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A reverse engineering process for mechanical engineering systems

Frank Tamarez-Gomez

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A REVERSE ENGINEERING PROCESS FOR MECHANICAL ENGINEERING SYSTEMS

By

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A Thesis Submitted in Partial Fulfillment of the Requirements for the

MASTER OF SCIENCE in MECHANICAL ENGINEERING

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Acknowledgments

I would like to express my extreme gratitude to all the persons who assisted me with the thesis and provide the necessary support for its completion: Dr. Edward Hensel, my thesis advisor, for being very patient, encouraging, understanding, supporting and a friend for the guidance of in the writing of this thesis in the past two years. He has been like a father in difficult and smooth times, without the help of Dr. Hensel, I may never have completed the thesis. Dr. Elizabeth DeBartolo, Dr. Marcos Esterman Dr. Alan Nye and MS. George Slack for providing professional and personal guidance that greatly enhanced and prepared my mind and ability to focus on this thesis and assistance to help minimize the stress of learning new things. Furthermore, I would like to express my deepest gratitude to my girlfriend, Lori Rosario, for her love, patience, understanding and support that always was there when needed. I express an overwhelming appreciation to my parents, Francisco and Ana, for always being there when I needed support and your numerous sacrifices extended far beyond the duties of parents, as well as friends, and I love and thank you. Finally, I would like to thank God for being beside me all the times and never abandoning me. Faith in him let me overcome all obstacles, thank God.
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Abstract

This thesis presents a literature review of current reverse engineering technologies and processes, with an emphasis on tools commonly used in Software Reverse Engineering (SRE). Using the foundation of the literature review, the thesis will then propose a standard process, referred to as “A Reverse Engineering Process for Mechanical Engineering Systems (REPMES).” The REPMES tool is intended to enable engineers to understand how current products work. Additionally, REPMES may allow engineering design teams to more effectively revise their product designs through competitive benchmarking. The REPMES is illustrated through application to case studies of a consumer flashlight and an automotive torque converter.

Unlike the field of Software Reverse Engineering (SRE), there is not currently a published standardized procedure to successfully implement reverse engineering of mechanical engineering systems. The REPMES process introduced here differs from SRE in that the target for SRE is to understand the inner workings of a computer program or system. However, REPMES has to account for the materials used, the limitations of the same materials, the physical conditions under which the system must operate, the mean time between failure, manufacturing processes and tolerances, and a variety of other factors not typically encountered in software systems.

Following the introduction and illustration of REPMES using the flashlight case study, the REPMES tool will be applied to the analysis of a traditional mechanical device, a torque converter, to evaluate the robustness of the REPMES in the context of a typical application. Use of the REPMES will be demonstrated to provide a thorough understanding of torque converter operation, design, and manufacturing. The REPMES
structure will be employed to provide a list of recommended improvements to the baseline torque converter, following benchmarking against competitive technologies.
Chapter 1 Introduction

Reverse engineering has several definitions, and at times can be easily confused with the definitions of engineering and re-engineering. Each of these terms has distinct meaning within the context of this thesis. “Engineering is the application of scientific and technical knowledge to solve human problems. Engineers use imagination, judgment and reasoning to apply science, technology, mathematics, and practical experience. The result is the design, production, and operation of useful objects or processes.” [1] Figure 1 shows a group of early 20th century engineering students from the US Military Academy at West Point analyzing a bridge structure to enhance their understanding. It is common practice for engineering students, and practicing engineers, to learn from prior examples of both good and bad design solutions to a particular problem.

![Figure 1 Engineering students learn through studying examples of designed systems [2].](image)

“Re-engineering is the process of examination, understanding and alteration of a system with the intent of implementing the system in a new form.” [3] An important
distinction between re-engineering and engineering, for the purposes of this thesis, is the process of iteration. Within this thesis, engineering refers to the first rendition, or initial release, of a product design, while re-engineering refers to a design variation based upon performance analysis of the preceding generation.

However, "Reverse Engineering (RE) is the process of discovering the technological principles of a mechanical application through analysis of its structure, function and operation. That involves sometimes taking something (a mechanical device, an electrical component, a software program, etc.) apart and analyzing its workings in detail." [4] In other words, reverse engineering help us to understand how a component functions. Figure 2 illustrates a humorous but sometimes accurate demonstration of how testing a product can help an engineer better understand the functions and properties of a product.

Figure 2 Reverse engineering requires testing and investigation of products under investigation. Cartoon taken from [5].
"A Technical Data Package (TDP) is a technical description of an item adequate for supporting an acquisition strategy, production, engineering, and logistics support. The description defines the required design configuration and procedures required to ensure adequacy of item performance. It consists of all applicable technical data such as drawings and associated lists, specifications, standards, performance requirements, quality assurance provisions, and packaging details." [6] The technical data package essentially contains all information required to manufacture a product. Figure 3 shows a drawing, a critical element of a TDP, of a lower receiving tube from Savit Corporation.

Figure 3 Drawing of a "lower receiving tube" taken from a Technical Data Package [7].

A Technical Data Package is made up of many elements. One general specification for TDP is described by the military specification MIL-DTL-31000C, which is approved for use by the Department of Defense. "This specification prescribes the
requirements for preparing a technical data package (TDP) composed of one or more TDP elements and related TDP management data products.”[8]

The military specification MIL-DTL-31000C [8] defines the list of items to be included in the TDP as follows:

- Engineering drawings
- Associated lists
- Specifications that define
- Function, performance, interfaces
- Physical geometry, other constraints
- Process descriptions
- Material composition
- Safety requirements
- Preservation and packaging requirements
- Test requirements data and quality provisions
- Preventative maintenance system/Maintenance Requirements
- Coordination, interchangeability, form fit, and function information

Three primary motivations for an engineer to perform reverse engineering include (1) expansion of knowledge and understanding, (2) competitive benchmarking, and (3) replacement of a lost or incomplete technical data package.

Competitive benchmarking is practiced by most modern engineering and product development organizations in an effort to continually improve their products and designs. The ancient Chinese warrior Sun Tzu taught his men to "know your enemy" before going into battle. For if "you know your enemy and know yourself," he wrote, "you need not
fear the result of a hundred battles." But, Sun Tzu warned, "If you know yourself but not the enemy, for every victory gained you will also suffer a defeat." [9]

Identifying the product, service and process from top competitors and comparing it with your own is the key to remain competitive in the market. Benchmarking does not only illustrate the features of another company’s products but also the engineering and customer’s satisfaction of the product by surveys conducted and explored by that specific company.

One example of a modern corporation that conducts competitive benchmarking is General Motors (GM). As of October 2006, “GM is the largest automobile maker in the world” [10], selling millions of cars per year. What tools do corporations employ to learn the desires of the customers in their market? How do large companies understand the engineering designs of products from other companies? How can manufacturers reduce the costs associated with production from one year to the next? Reverse engineering and benchmarking are essential tools used in answering each of these questions.

General Motors Corporation, like many other major manufacturers, has a formal program for benchmarking product made by competitors. GM operates the Vehicle Assessment and Benchmarking Activity (VABA), and prepares internal reports for dozens of vehicles annually. For example, in the interval between January - May 2006, GM purchased a $49,000 Silver Lexus RX 400h hybrid sport utility vehicle (SUV), similar to the vehicle illustrated in Figure 4.
The Lexus SUV, manufactured by Toyota, is highly regarded as a high end vehicle in the SUV market. GM disassembled their Lexus SUV at their GM Technical Center located in Warren, Michigan in an effort to understand every aspect of the vehicle, ranging from the parts used, to estimating the production cost. It is reported in the literature [12] the GM conducts teardowns on their own vehicles as well as the vehicles of their competitors such as BMW, Mercedes, Hondas, Lexus, Toyota, Chryslers, and Ford. It is estimated that about twenty vehicles are subject to the process known as a “full trim-saw cut” which is the process of cutting doors, roof pillars and fenders in 100-mm-wide cross sections, which are then scanned into digital blueprints for analysis by engineers. Results for 2007 include Chevy Malibu Hybrid (2007) which will have 822 propulsion parts compared with the 1,432 parts that make up the Toyota Prius. [12]

Is there any reason that a company uses reverse engineering on its own product(s)? Is that possible? Why would a company undergo that procedure internally? Engineers use reverse engineering to their own products as a tool when technical data are missing and to verify design intent of their engineering staff through independent validation. One way to recover missing technical data is with the help of reverse engineering. A good hypothetical example for replacing lost technical data is that of the Apollo series of
missions by NASA during the 1960's. In 1969, man first stepped on the moon, the Apollo rocket used is shown in Figure 5. If we want to accomplish this task again, what is the fastest way it could be accomplished? First, taking into account that at the time we traveled to the moon, the original technical data, and the Technical Data Package (TDP) was not created on computers because the Intel 1103 Computer Memory (The world's first available dynamic RAM chip) and Intel 4004 Computer Microprocessor (The first microprocessor) were available in 1970 and 1971 respectively - well after the design phase of the 1960's when the relevant engineering drawings and analyses were compiled.

![Figure 5 Apollo Rocket from the 1960's leaving the NASA headquarters [13].](image)

Second, at the current date of 2006, it is expected that many of the original design engineers' team may be deceased or at least retired from practice. Third, changes in design specifications, drawing practices, and technologies for reproduction have evolved dramatically over the five decade long history of space flight. Therefore, it may well be the case that the best way to begin designing a new lunar mission vehicle would be to take Saturn Rockets, Apollo Modules, and Lunar Landers from museums and conduct
reverse engineering to better understand how they function and then compare the knowledge with the technology we have available today.

Engineers can use reverse engineering to improve themselves to become better engineers, by learning best practices from the design of another engineer. For example, at the Rochester Institute of Technology in the summer of 2006, Professor Landschoot used reverse engineering with students enrolled in the cornerstone design class to understand how a solenoid valve, similar to those illustrated in Figure 6, functions and what fabrication process were used in their manufacture.

In order to understand the fabrication process Professor Landschoot was required to go to the GW Lisk Company, since they were the actual creators of the solenoid valve. The solenoid valve that Professor Landschoot is experimenting with is used to teach his students in the Cornerstone Design class. The reverse engineering processes that Professor Landschoot is using to teach the Cornerstone Design students include: functional and economic analysis, analysis of its structure, function and operation, disassembly procedures and engineering drawings.

This thesis will focus on development of a new standard process to implement reverse engineering methods for mechanical devices. This recurrent process will be
referred to as Reverse Engineering Processes in Mechanical Engineering Systems (REPMES). The baseline version of REPMES will be based upon an investigation of relevant literature from the software reverse engineering and mechanical and electrical design fields. A graphical representation of each reverse engineering method discussed in the literature will be created, to summarize and illustrate a variety of reverse engineering processes. Common elements will be inferred from the literature review investigation, resulting in the preliminary version of REPMES. The preliminary version of REPMES, \textit{REPMES}_1, will be applied to a simple product - the Rayovac flashlight V2D-B. This flashlight was chosen because it possesses detailed components all within a simple structure. Moreover, since its invention in 1898, the flashlight has undergone various changes and developments, specifically in terms of the technology, the material used as well as the relationship between humans and technological systems - ergonomics. Using knowledge gained through analysis of the flashlight, \textit{REPMES}_2 will be developed as a direct result of the analysis of the flashlight, \textit{REPMES}_2 will be a direct result of the steps unforeseen in the development of \textit{REPMES}_1. Once reverse engineering of the flashlight is complete, \textit{REPMES}_2 will inevitably need to be modified in order to account for its application to a real-world product. It is important to note that \textit{REPMES}_2 must be generic enough for any product’s analysis, yet detailed enough to be a truly implementable process. This improved version will take into account specific tools, technologies and theories that will apply to the product.

Following the development of the revised version, \textit{REPMES}_2 will be used to conduct a reverse engineering analysis of a torque converter, a fluid-coupling device used in numerous vehicle systems, to verify the consistency and completeness of the process.
The torque converter is an appropriate example for testing the REPMES, because it is a fully mechanical component; having mechanical and design features with unique manufacturing considerations, and material property constraints. Just as with the flashlight, the torque converter will be carefully disassembled to the last removable component (non-destructively) and then each of these components will be studied in detail using the REPMES₂ procedure. The development of a comprehensive technical data package includes a 3-D solid model and drawing package with fully detailed design and mechanical features, and material properties based on the coordinates obtained from a CMM (Coordinate-Measuring Machine). Upon completion of the torque converter case study, a final version of REPMES (REPMES₁nal) will be proposed for use with a wide variety of mechanical products. The resulting REPMES will be a tool useful for engineers wishing to expand their knowledge of product design, conduct competitive benchmarking of a baseline product against competitive products, and for replacing lost or unavailable technical data.
Chapter 2 Literature Review

Before introducing the Reverse Engineering Process for Mechanical Engineering Systems, one must first become familiar with the various resources of reverse engineering processes. This chapter will provide an overview of reverse engineering processes being applied in business, software, mechanical, mechatronics, industrial and other fields of applications. Detailed information on how reverse engineering is applied to both tangible items (such as products) and non-tangible items (such as processes and software) are discussed.

Though reverse engineering can be highly beneficial, it can also be used in more antagonistic terms. Reverse engineering may be used for a wide variety of applications. For example, the paper, “Data Rights Provisions Do Not Protect Your Products in Doing Business with the Government—Be Alert to the Need to Protect Yourself and Your Products Against ‘Reverse Engineering’” by Jacob B. Pankowski [15], is about a recent lawsuit case study, Night Vision Corporation vs. United States. The case study demonstrates how contracts with technicalities are essential with innovative products, in light of reverse engineering. Night Vision Corp. (NVC) introduced a new type of night vision goggles to the United States Air Force. The Air Force allegedly decided to take the physical product and pass it on to NVC’s competitor to reverse engineer the product. Though a contract was made between the two parties, the contract only protected the company’s technical data rights, and not the physical goggles themselves. NVC sued the Air Force for passing on their product. The government did not consider it as infringement since the night vision goggle prototypes are not considered technical data. The court found that the government did not violate any laws or agreements that were set
initially with NVC because it was not included in the written agreement. The court indicated that NVC should have pursued a patent on the product to avoid duplication of the product or allowing a competitor to reverse engineer the product. Reverse engineering is widely promoted, for example by the government, because it provides competition within companies and also an opportunity for innovative products to emerge. When making any type of contract or agreement with a business partner it is advised that all technical data, data rights, intellectual property, and physical products are protected.

2.1 Application of Reverse Engineering Methods in Business

Reverse engineering is a process to understand how a system works. Several tools have been developed to set the functionality of a business, however, to be able to set the business functionality it is required to first understand the business. Businesses cater to customer needs and to be able to satisfy those needs, they need to anticipate and adapt to customer demands. The proceeding two papers will show an example of how businesses may react using reverse engineering to anticipate and adapt to customer demands. The first paper, “Process reverse engineering for BPR: a form-based Approach” By K. H. Kim [16] describes and presents the Enterprise Process Reverse Engineering (EPRE) method for analyzing business processes and supporting process redesign tasks, sets a business functionality. The second paper, “Reverse engineering-modern tool for product-planning” by B. Schumacher [17], describes how he wanted to find out about the advantages and limitations of Reverse Engineering during stages of development and launching of mechatronic products, to develop and set product planning.
It is important to note that there is one major challenge facing Business Process Reverse Engineering implementation. The existing business processes have to be understood to enable the design team to identify the potential problem areas.

The Reverse Engineering part of (EPRE) method is involved in two stages as described in Figure 7. According to Kim, the first step in business process redesign is to define forms and form fields, which requires the identification and analysis of the candidate business processes to be redesigned, along with their related organizational units. Kim’s next step is to identify field set operations with field type. In this paper, Field Set Operation (FSO) is defined as a set of activities which processes from one or more fields and is performed at a single location during a single session for a specific customer service (Output Waiting Time, Processing Time, etc).

![Figure 7 Form analysis and Process Model Generation, inspired by Kim [16]](image)

The second stage of Kim’s Business Process Redesign method requires the user to generate the initial Event Process Chain (EPC) diagram based on the process-related and form-related information. When multiple FSO’s exist within a process, a proper FSO
selection order needs to be established. Each FSO can be inserted by the user to search the larger number of related common fields.

Figure 8 Event Process Chain Diagram from Kim [16]

Figure 8, from Kim [16] illustrates an example of EPC as a simulation of a hospital visit. In this example, the field set operations is represented by the “Consultation” room, the “Lobby Area”, and the “Pharmacy Center.” The set of activities - event, process, branch, and wait are represented by a circle, a rectangle, a diamond and a “W” respectively. In this simulation, the total process time is two hours; three processes, three events, and three different waiting times. The business process event starts when the patient enters the hospital to the lobby area, the registration process last a total of five minutes. The patient then walks over to the consultation room to wait for 60 minutes, followed by being consulted for fifteen minutes. After receiving the prescription, the patient returns to the lobby area for medicine payment, for a total time of
ten minutes, five minutes waiting and five minutes for the payment process. The patient then enters the pharmacy center, to put in the medicine request and wait for the prescription to be filled, for a total time of 30 minutes. At this point the entire event process is complete. Kim's reverse engineering process demonstrates that RE can be applied not only to tangible products, but also to many types of businesses and industries. This also demonstrates that information for a TDP can be represented by process tools for example EPC diagram.

Another example of where reverse engineering is applied to a business, is "Reverse engineering-modern tool for product-planning" by B. Schumacher [17]; where Schumacher realized that many individuals use this method but a systematic description is lacking. Scientific analysis of existing product is needed in order to achieve a new, improved, and cheaper product that is more market-oriented.

The process of reverse engineering as shown in Figure 9 starts with the "Scientific Analysis of existing products." In this paper, they concentrate on the technical functions, features and inner technical dimensioning of a product. They then continue with documentation. The third step is "New Planning," which concentrates on the market areas (cost attractive, innovative, reliable and rapid). In other words, this step concentrates primarily on what customers want. Next, a "Product Specification" is needed as a base for the new planning.

The fourth step is Product, this is where a prototype of the new product is obtained, and production is started. It is important to mention that this paper presents a graphical representation of the appropriate amount of time developmental elements should take. The paper presented a case study on a proposed new electronic product. In
their case study, the first group included a keyboard, antenna, wires, batteries, housing-injection mold, and assembly, all of which took 16 weeks. The second group included testing and trimming which took a total of 4 weeks. The last group included purchase of components and assembly, which took a total 3 weeks.

![Diagram showing the process of reverse engineering](image)

Figure 9 RE as a tool for product planning, inspired by Schumacher [17]

### 2.2 Application of Reverse Engineering Methods in Software

Another area for Reverse Engineering that has increased tremendously is Software: including the development of software like Rational Rose, Imagix 4D and Code Visual to Flowchart. Those three software programs help developers understand source code and then visualize it through flow chart modeling. SearchVB states that “software designer uses Rational Rose to visually create (model) the framework for an application by blocking out classes with actors (stick figures), use case elements (ovals), objects (rectangles) and messages/relationships (arrows) in a sequence diagram using drag-and-drop symbols.” Also, “Rational Rose documents the diagram as it is being
constructed and then generates code in the designer's choice of C++, Visual Basic, Java, Oracle8, CORBA or Data Definition Language.” [18]

The next six papers will show different approaches to software reverse engineering. The first paper, “Reverse Engineering Requirements for Process-Control Software” by Hildreth [19], discussed ways to develop a method to apply reverse engineering to process-control software. The results provided knowledge about what a system is doing. The second paper, “Analyzing the application of a reverse engineering process to a real situation” by F. Abbattista [20], describes a model in which the reverse engineering process, applied to a software system, interacts with the documentation of the software system in order to mutually improve one another. The third paper, “Domain analysis and reverse engineering” by J-M DeBaud [21] demonstrates how Domain Analysis can be used as a tool to aid the comprehensive process of reverse engineering. It discusses the relationship of application domain and reverse engineering by presenting two case studies. The fourth paper, “Characterizing Reverse Engineering Process component methodology (CREP)” by Maria Tortorella and Giuseppe Visaggio [22] is a method to formalize, characterize and evaluate reverse engineering process components. The fifth paper, “A reverse engineering methodology to reconstruct hierarchical data flow diagrams for Software Maintenance” by P. Benedusi, A. Cimitile, and U De Carlini [23] describes the methodology used to define a reverse engineering process that has been employed in an enhancement maintenance operation on a Pascal software system. The last paper, “Reverse Engineering: A Roadmap” by Hausi A. Muller et al. [24], presents four perspectives in the field of reverse engineering to provide a roadmap for other engineers.
Hildreth’s [19] goal was to maintain a system in control, which means defining system functionality in a language that is specific to the problem domain. The process in Reverse Engineering of the process-control system has four components, as described below by Figure 10. These include the process, sensors, actuators and controller.

![Diagram](image)

**Figure 10 Process control steps for RE, inspired by Hildreth [19].**

The first step is the process state estimation. In this step, the process is measured and operating condition inputs are used to determine an estimate of the current state of the process. The second step is the Supervisory Control, which is based on the review of computers outputs. Here control and process engineers would adjust set points in order to optimize efficiency, fine tune control, and maintain system operation within specified limits. The ability of computers to make such adjustments automatically is referred to as supervisory control.

The third step is Error Detection. The role of the error detector is to detect deviation between measurements of controlled process variables and their respective set
points. The final step is the Corrective Command Computation. In this step, the role of
the controller is to determine the corrective command needed to change the manipulated
process variable so that the deviation is within accepted limits.

To better explain this process, let’s say that a system is set with a certain range.
During the supervision step of the process, it is detected that the system surpasses the
range; the next step will be that the system is corrected to maintain control. Realizing, a
system control as a continuous reverse engineering process, due to the fact that the
system has to be understood to be corrected or redesigned.

The same occurs when industrial and manufacturing engineers analyze a system
process and use process capability. “Process Capability is required to be used by TS
16949 (ISO Technical Specification). Process capability compares the output of an in-
control process to the specification limits by using capability indices: a process capability
index uses both the process variability and the process specifications to determine
whether the process is ‘capable.’ The comparison is made by forming the ratio of the
spread between the process specifications (the specification "width") to the spread of the
process values, as measured by six process standard deviation units (the process "width").
There are several statistics that can be used to measure the capability of a process: Cp,
Cpk, Cpm. Most capability indices estimates are valid only if the sample size used is
'large enough'. Large enough is generally thought to be about 50 independent data values.
The Cp, Cpk, and Cpm statistics assume that the population of data values is normally
distributed.” [25]. Cp is the process capability and Cpk is an index which measures how
close a process is running to its specification limits. Generally, typical Cpk that is above
1.33 is preferred for customer satisfaction and to be able to be repeatedly produced. Cpm
is the process capability measured against performance of the target. Along with these are two limits that separate random variation and nonrandom variation. The larger value is the upper control limit (UCL), and the smaller value is the lower control limit (LCL). A sample statistic that falls between those two limits suggest randomness and those outside values are not randomness.

![Figure 11 Example of Process control step for RE, where LSL and ULS are the limits set to be in control](image)

As an example, a manufacturing team (MT) of the company AB had detected that the production line “KP12”, in July, produced three out of 25 laptop screens with 9.53 inches in width. Back in May, the process had a mean of 9.20 inches and a standard deviation of 0.30 inches. The lower specification limit was 7.560 inches and the upper specification limit was 10.50 inches with a Cpk=1.44 (Figure 11). After the MT analyzed the process, they determined that the problem was that machine A (for production line “KP12”) was not calibrated. After the machine was calibrated and corrected, the system came back to being in control. Hildreth’s overall goal in system control was to be able to
understand how a system works so that successful completion of supervision, detection and correction could be accomplished.

From another prospective, F. Abbattista [20] applied reverse engineering to a software system that interacts with the software documentation. The following process is described in Figure 12.

![Diagram](image-url)

**Figure 12** RE process and documentation for software system, inspired by Abbattista [20].

The first step is the Inventory Software System. Its inputs contain the Software system. This step aims to list and organize the logical parts of the software system,
returning outputs as Structure Charts and Logical Data Pre-models. The second step is to Reconstruct Logical Level of Data. Its inputs consist of Data Descriptions and Logical Data Pre-models. During this step, the data descriptions are analyzed against the logical data pre-models obtained from the inventory, and a logical data model is generated. Its outputs are in the form of a Logical Data Model.

The third step is the Analysis of Existing Information. Its inputs are Documentation and Experience in the Field. The purpose of this step is to identify the expected functions in the program being reversed using two types of information; static (documentation) and dynamic (experience) knowledge. The output is an Expected Functions List.

The fourth step is to Reconstruct Logical Level of Programs. Its inputs are Code and Structure Charts. In this phase, both dead data and dead instructions are identified. These are data that are not used by the program and include instructions which can not be run. The dead instructions are then erased from the chart, and a logical functions model is generated. The outputs are Logical Functions Models and Dead Data.

The fifth step is Abstract Data Modeling. Its inputs are Logical Data models and Dead Data. All data is analyzed and organized into a conceptual data model. The final output is a Data Conceptual Model. The sixth step is Abstract Functions Modeling. Its inputs are Logical Functions Models, Data Conceptual Models, Expected Functions Lists and Documentation. The purpose of this phase is to analyze the logical functions model against the expected functions and the documentation in order to create a conceptual model according to the data conceptual model. The output produces a final Conceptual Model.
On the other hand, J-M DeBaud [21] discusses the relationship of application domain and reverse engineering by presenting two case studies. The first case study uses a domain model to guide the reverse engineering effort by applying object-oriented frame-work to understand the concept of the domain. The second one studies how reverse engineering can be used to build a domain model.

![Diagram](image1.png)

**Figure 13** RE process by applying object-oriented frame working to understand the concept of the domain, inspired by J-M DeBaud [21]

The first case study uses object-oriented technology as the domain model representation mechanism as a reference to guide the reverse engineering method (Figure 13). This technique made it possible to identify patterns that reflected a purpose token in the source code. Object-oriented frameworks provide a clear and normative structure to guide the reverse engineering effort through feature expectations and purpose patterns.

![Diagram](image2.png)

**Figure 14** Synchronized refinements in order to implement design, inspired by J-M DeBaud [21]
In the second case study, the target program was reverse engineering and the domain model that resulted was studied. The method used to reverse engineer, (Figure 14) the program was Synchronized Refinement. This technique analyzes the program text from bottom up, looking for stereotypical cues that signal implementation of design decisions. It also synthesizes an application description from the top down, using expectations derived from the various domains relevant to the program.

Tortorella and Visaggio’s [22] method to formalize, characterize and evaluate reverse engineering process components uses the CREP method. CREP methods have two phases; the first one formalizes the process components, and constructs the process models, while the second phase characterizes the process components, highlighting their most peculiar concepts and grouping the homogenous information. The following process is described in Figure 15.

Figure 15 Characterizing and evaluating RE process components, inspired by Tortorella and Visaggio [22]
The first CREP Step is the Build Process Model phase, which formalizes the reverse engineering process components to analyze the order to represent them in a uniform way. This task receives input of all the documentation available of the process components to analyze and compare to develop a process model for each of them. The second model is the Validate Process Model, which analyzes and checks the process models obtained in the previous task to verify if internal consistencies exist. The third model is the Modify Process model, which modifies the inconsistencies possibly discovered during the previous task. The fourth step is Characterize Process Component, which determines the evaluation schematic of the reverse engineering process components whose process models have been obtained in the previous step.

Benedusi, Cimitile, and De Carlini [23] describes the methodology used to define a reverse engineering process that has been employed in an enhancement maintenance operation on a Pascal software system. They define the Reverse Engineering (RE) process in three phases as shown in Figure 16. The first phase consists of (i) analysis of the reasons for which it was set up, (ii) the reference software maintenance and development cycle and, therefore (iii) the goals of the RE process.
Analyze Requirements and Software Production cycle

Define Goals

Define Models and Data Structures

Define Information Abstractors

Figure 16 RE Methodology to reconstruct data flow diagrams, inspired by Benedusi [23]

The second phase is to define models on the basis of the goals. These are the specification functions that the RE process must develop: 1) identifying the operations to be carried out, and 2) the inputs on which to work and the outputs to be produced for each function in a clear manner.

The last phase in RE process design is the definition of an information abstractor that can automatically produce or support the production of the documents to be formed and a conceptual description of the information they contain.

The last paper by Muller et al. [24], presents four perspectives in the field of reverse engineering to provide a roadmap for other engineers (Figure 17). Also, the authors offer peer support as they follow the same pattern as the other papers. The reverse engineering of software always begins with having a product at hand.
In the first field, “Data Analysis” the design team (engineers, domain expert, developer, etc.) analyze the code, schema catalog, obstacle documentation and data so they can have a better understanding of how the process should be carried out. The next field, “Logical Data Model” is one that involves Taxonomy. Taxonomy is a classification of things (answers, February 10, 2006), so in this stage organization and classification of the analyses is done for better understanding and usability.

The third field, “Abstraction”, is produced through a transformation of the analyzed logical data model and the feed back of the Design Team. In other words, it is the design verification of the data. The last field is the conceptual design which involves all areas that are concerned with re-design and re-engineering procedure. In mechanical engineering terminology, this will include the Design for Manufacturing and Assembly (DFMA) Process which includes integration, assessment, distribution, etc.
2.3 Application of Reverse Engineering Methods in Mechanical Components

Typical application for mechanical components to implement reverse engineering is through using various computer aided programs and mechanical systems. Examples of computer aided design programs include Pro-E and Solid Works, which provide detailed drawings that are manually inputted into the computer. Examples of mechanical systems include Coordinate Measuring Machines (CMMs) and Range Imaging machines that move a measuring device to determine the coordinates of points on the surface of a piece/component to obtain a technical description of the component.

The next four papers will discuss reverse engineering applied to a component using computer aided and mechanical systems. The first paper, “Reverse engineering of mechanical components within a computer-aided design/computer-aided manufacturing environment” by V. Kalra [26], defines the reverse engineering process within a computer-aided manufacturing environment using computer-aided design. The second paper, “On generating solid models of mechanical parts through fuzzy clustering” by Girish Phansalkar and Rajesh N. Dave [27], describes how using reverse engineering is used to generate a solid model. The third paper, “Feature-based reverse engineering of mechanical parts” by William Thompson et al. [28], describes a prototype of a reverse engineering system which uses manufacturing features as geometric primitives. The fourth paper, “Reverse Engineering: A Tool for Process Planning” by Abella Daschbach and McNichols [29] describes how to use the Coordinate-Measuring Machines (CMM) as reverse engineering tools.

Kalra [26], defines the reverse engineering process within a computer-aided manufacturing environment using computer-aided design. The steps for the reverse
engineering process consist of measurement of the part geometry by a contact or non-contact measurement device, the development of a computer aided geometric model from the measurement data, and possible engineering refinements of the part design. Development of the manufacturing plan includes selection of materials and the actual production of the part as shown in Figure 20.

![Diagram of reverse engineering process](image)

**Figure 20** Reverse engineering of mechanical components for CAM / CAD, inspired by Kalra [26].

To illustrate this process as an example, let’s suppose Person A who lives in California wants to produce a product, and is forced to get information about the product from Person B, who lives in New York. What is the fastest way that Person B can get the information about the product or the TDP of the product to Person A? Well, in today’s innovative and technological world, after Person B completes the steps described in Figure 20, Person B will then send the engineering drawings, associated lists, and files to Person A. The CAD drawings are essential because it explicitly explains the product and its properties, and now Person A can produce the product.
As described previously, reverse engineering is a process to understand how a product functions. Therefore, the last step for reverse engineering of mechanical components within a computer-aided design/computer-aided manufacturing environment, which is titled “Production” should not be included as part of the reverse engineering process. A production of any component will be part of the RE process only if what is being produced is a prototype to validate prior assumptions, certification of a function and producibility of a product.

Girish Phansalkar and Rajesh N. Dave [27], describes how using Reverse Engineering to generate a solid model using computer aided design (CAD) software can be a laborious procedure. To overcome this problem, an automated procedure is proposed by the authors. Their proposed approach is to segment the range image of the object using fuzzy clustering, and then construct a solid model.
Figure 21 RE to generate a solid model using CAD, inspired by by Girish Phansalkar and Rajesh N. Dave [27]

An interesting topic in this paper is the series of steps shown in Figure 21 that are used to implement reverse engineering. The first step they took was to bring in a part, which presupposes that a part already exists to implement Reverse Engineering. Next, they made a Critical Analysis of what they wanted and what they needed to get the Solid Model. Two tools that were necessary to solve this problem included the coordinate measuring machine (CMM) and the complex Range Image. The Range Image is a set of data points on the surface of an object represented in a 3D Cartesian coordinate system. The Range Image must be processed to generate the desired mathematical model. This
task is divided into two general steps (i) Segmentation of the range image and (ii) Processing of these surface patches. This will produce the Solid Model. Even though there are multiple approaches to solve this problem, this paper has shown that Reverse Engineering follows the same step.

William Thompson et al. [28], describes a prototype of a Reverse engineering system which uses manufacturing features as geometric primitives. This is important because a desired feature-based CAD application directly from any model, will give results without the loss of any characteristics of the part using human factor for refinement. Also, this method can facilitate highly accurate models, even though the original part could contain significant errors.

This idea was produced when it was realized that CAD Models are often unavailable or unusable for parts that must be duplicated or modified. Reverse Engineering techniques were used to create CAD models of a parts based on sensed data acquired using three-dimensional (3-D) position digitization techniques. The process works when reverse engineering of solid objects traces its roots back to the pantograph, which uses a mechanical linkage to duplicate arbitrary geometric shapes at any predetermined scale. It is important to note that the way that they validate the final result of the Reverse Engineering was they first found the part that they wanted to work with and found the original CAD models to compare the result.

This reverse engineering system provides a substantial advantage in usability and accuracy. It is also beneficial to know that reverse engineering can be use to re-construct a part of an element that does not have history information such as a CAD Model.
Daschbach and McNichols [29] defined reverse engineering as the process of accurately and quickly measuring dimensions, calculating solid geometry shapes, (i.e., areas, volumes and displacements), and evaluating the geometric tolerances of an existing part. In essence, this is accomplished through appropriate software; typically available on CMM equipment. This software produces the exact description of a part in the absence of the original engineering drawings.

“The CMM are mechanical systems designed to move a measuring probe to determine the coordinates of points on the surface of a work piece. Coordinate-measuring machines consist of four main components: the machine itself, the measuring probe, the control or computing system, and the measuring software.” [30]

For this thesis, the appropriate software along with the CMM equipment could produce a representation of the Torque Converter which would facilitate in the Design Feature of “Reverse Engineering Process for Mechanical Engineering Systems (REPMES) Component First Step”. It is obvious that the CMM is not merely useful just on the shop floor as an inspection tool, but is valuable as a reverse engineering tool as explained in this paper.

2.4 Application of Reverse Engineering Methods for Mechatronics

In this section, an introduction of the implementation of reverse engineering to mechatronic components and the methodologies used in engineering in undergraduate education is accomplished. “Mechatronics is the synergistic integration of physical systems, electronics, controls, and computers through the design process, from the very start of the design process.” [31]
The following two papers will show different approaches to Mechatronic reverse engineering. The first paper, "Reverse engineering and re-engineering of avionics legacy components" by Ted Riffle [32], describes a general process for Re-engineering avionic components where detailed engineering data is not available on the component. The second paper, "Reverse engineering: An Effective approach to studying Mechatronics at Undergraduate tertiary education" by Mohamad Saleh [33] describes the methodologies of engineering in undergraduate tertiary education.

Ted Riffle [32] describes many times that data is insufficient to re-engineer a system component without first reverse engineering the existing component. Due to the diminishing manufacturing sources, this is typically necessary to replace a high cost component or replace an item that can no longer be procured as a direct replacement component.

Figure 22 below represents the steps followed to implement reverse engineering. Following this procedure will enable the engineers to determine what is necessary for Re-Engineering to replace low Reliability and Maintainability (R&M) legacy components. The process begins with identification of component problems, and then isolating those component problems. These steps produce a list of components that could be used. The next step is collecting as much information as possible from existing documentation. Due to the process of justifying a new component costing a large amount of money to formulate, development and validation models will be mandatory.
Determine R&M Problem

Isolate Problem to Components

List of legacy Components (LCs) to Re-Engineer

Collect existing Data for LCs

Formulate Model of LCs

Develop LC Validation Capability

Validate Validation Capability

Validate LC Models

Engineering Model of Legacy Components (s)

Figure 22 Reverse engineering and re-engineering of avionics legacy components, inspired by Riffle [32]

The most important validation steps are (1) generate a large number of test scenarios for the legacy component (LC), (2) execute the test scenarios using different statistics, (3) observe any differences in the expected functional performance of the state, (4) postulate cause for the difference and make changes to the LC, and (5) repeat steps 1 through 4. Mohamad Saleh [33] discusses an implementation of reverse engineering as an approach to studying Mechatronics. The paper defines Mechatronics as the synergic combination of precision Mechanical Engineering, electronic control and systems
thinking in the design of products and processes. The following process is described below in Figure 23.

![Diagram](image)

**Figure 23** Steps for reverse engineering as an approach to studying Mechatronics, inspired by Saleh [33]

The First step suggested by the authors is evaluating the product following a generalized process. This helps evaluate the product so that the engineers can have a clear idea about the functionalities of the product. In the second step, the engineers should carefully determine the functions that are carried out by a specific part and the product as a whole. This would provide a basic scientific knowledge of the engineering function used for the smooth functioning of the product.

The third step is to identify the various assemblies and sub-assemblies of the product. This helps to understand how a product can be disassembled in a way that it can be later reassembled to carry out its original function. The fourth step is the actual disassembly. In this step all the components are separated or broken down into individual components. The fifth step is where the details of each component are carefully noted,
starting from the product’s geometrical information (i.e. size, length, color, weight and other similar features), and then moving to the technical information which not only includes the functionality that it performs as a part of the product but also other functionalities it contains separate from the product.

2.5 Application of Reverse Engineering Methods in Industrial Engineering and Miscellaneous

Reverse Engineering has played an important role in both design and in manufacturing to accelerate product and process development. For example the paper, “Development of a Step-based Collaborative Product and Process Development system for Manufacturability evaluation with Reverse Engineering” by Rong Shean Lee and Jo Peng Tsai [34], discussed a system based on the product data exchange standard STEP (STandard for Exchange of Product) model data [35] which has been developed to integrate the new technologies such as network and videoconferencing to form innovative strategy in enhancing the competitiveness of an enterprise. Overall, this paper combined the product data modeling and CSCW (computer supported Cooperative Work) technologies to develop a rational, extensive and in-time collaborative reverse engineering system to catalyze and improve product and process development.

The next five papers will show the importance the roles of both the design and manufacturing application have in accelerating the product and process development. The first paper, “Reverse Engineering process: A Competition Engineering Perspective” By A.J. DiMascio [36], describes an overview of some of the principal technical, management and economic considerations which should be factored into the planning,
decision-making, and control processes when applying reverse engineering techniques to a Re-Plenishment Spares Breakout program. The second paper, “A Reverse Engineering and Redesign Methodology for Product Evolution” by Kevin Otto and Kristin Wood [37], begins with Reverse Engineering and ends with Redesign. The third paper, “Design for Assembly Techniques in A Reverse Engineering and Redesign: ASME design engineering technical conferences and design theory and methodology conference” by Douglas D. Lefever and Kristin L. Wood [38] describes how to implement reverse engineering and redesign methodology to the three DFA (Designs for Assembly). The book, Reverse Engineering by Kathryn A. Ingle [39], describes Reverse Engineering as a four – stage process (Figure 28) in the development of technical data to support the efficient use of capital resources and to increase productivity. And also the book, Product Design Techniques in Reverse Engineering and new Product Development by Kevin Otto and Kristin Wood [40], describes the preparation of high-quality documentation in order to understand the market and customers’ likes and dislikes of the product.

DiMascio’s [36] process is described below in Figure 24. The first step is to have a Preliminary Plan to implement RE. The second step is Functional and Economic Analyses, which includes: Documentation, Evaluation of Data, Requirement and Developing and understanding of functional characteristics. The next step is Disassembly Procedures, which includes initial inspection, testing, and comparison with documentation and part identification.
Next, the Hardware must be analyzed to determine the dimension, materials specification and electrical/electronic operation characteristics. The sixth step is Drafting, which simply includes the drawing package. The seventh step is producibility analysis, where studies are conducted to determine if the initial draft drawings and specifications are adequate for competitive production. Next, Prototype Review is done to determine estimates, schedules, intrinsic values and should-cost estimates. The ninth step is the

Figure 24 Preliminary plan for reverse engineering techniques for Re-Plenishment of a Spares Breakout program, inspired by DiMascio [36].
Prototype Production, where the prototype is built. When all of the steps are completed, the TDP is finalized.

This RE process consists of the ingredients a RE process should have, but on the other hand there was one step that stood out from the rest – the building of a prototype. But wait, in the introduction, section 1, it was stated that reverse engineering is a process to understand how a product functions. So why does this process create a product prototype? Well, this RE process is used to validate and to be in accordance with the developed technical documentation to certify function and producibility of a product.

Kevin Otto and Kristine Wood [37], begins with Reverse Engineering and ends with Redesign, but the main focus is on the Reverse Engineering procedure. Reverse Engineering is defined in two blocks, 1) investigation, prediction & hypothesis, and 2) Concrete Experience: function & form. The following process is described in Figure 25

![Figure 25 Reverse Engineering and redesign accord to Otto [37]](image)

In the top block, the product is treated as a black box, experienced over its operating parameters, and studied with respect to customer needs and predicted or hypothesized functionality, product components, and physical principles. More detail may be found in Figure 26.
Investigation, prediction, and hypothesis

- Develop Black box model
- Use/Experience Product
- Gather and organize customer needs
- Perform economic feasibility of redesign
- State process description or activity diagram
- Hypothesize refined functional decomposition hypothesize product features
- List assumed working physical principles

Figure 26 Investigation, prediction, and hypothesis tools for RE, taken from Otto [37].

In the bottom block, the current product architecture must be understood in detail. Important customer needs must be compared with the product’s functionality and the design parameters. This also includes the full disassembly of the product, design for manufacturing analysis, further functional analysis and the generation of final design specification. More detail may be found below in Figure 27.

Concrete Experience: Function & Form

- Plan and execute product disassembly
- Create BOM, exploded view, and parameter list
- Execute and document subtract operate procedure
- Experiment with product components
- Develop force flow Diagrams
- Create refined function structure of actual product
- Create morphological matrix
- Identify function sharing and compatibility
- Transform to engineering specs. & metrics (QFD)

Figure 27 Concrete Experience: Function & Form – tools for RE, taken from Otto [37].

Lefever and Wood [37] describe how to implement Reverse Engineering and redesign methodology to the three DFA (Design for Assembly) techniques that are described in this paper. The techniques include component elimination procedure, component combination analysis, and techniques that establish a logical approach for revealing more abstract component elimination or combination opportunities. Various
investigations have been made in the Reverse Engineering procedure and redesign Methodology. This is also reflected on Kevin N. Otto and Kristin L. Wood, 1996’s “A Reverse Engineering and redesign methodology for product evolution.” [37] For example, an appreciation on how to use the force flow diagram from a staple and Slide-out Auxiliary visor which is included in the first step “investigation, prediction & hypothesis” of the reverse engineering procedure of Kevin N. Otto and Kristin L. Wood.

It is important to note that they clearly demonstrated the first two step of the Reverse engineering by 1) investigation, prediction & hypothesis, and 2) Concrete Experience: function & form. This was used to provide a means of not only understanding the physical product that is being analyzed, but also a mode for understanding the design rationale that motivated the existing design. Lefever and Wood (1996) said that there are at least five possible motivations in existence behind reverse engineering of a product. These motivations include, (1) Benchmarking, (2) Critical study, (3) Quality Improvements, (4) Cost Reduction, and (5) Pure Understanding.

As explained before, the book, Reverse Engineering by Kathryn A. Ingle [39], describes Reverse Engineering as a four – stage process. The stages, all of which are conducted after a rigorous prescreening, consist of data evaluation, data generation, design verification and design implementation (Figure 28).
The "prescreens" are the design team's information in the form of detailed drawings or specifications and failure data after having reviewed the economics, logistic, and technical complexity.
Stage 1 requires multidisciplinary teams to combine work and stage 2, 3, 4 are dependable of the result of the stage 1. The book identifies stage 1 as the most demanding and crucial part of the reverse engineering process. The second stage has the entire tool ready to be elaborated on. This is the step where the missing or inadequate technical data will be generated as engineering drawings are incorporated in a preliminary drawing set.

When prototypes are built, they must pass both the operational and systems test in stage 3. In stage 4, the finalization and project implementation are produced. After stage 4, the prototype can be sent back to stage 1, as this is a cyclical process of continuous improvement.

Otto and Wood [40] have prepared high-quality documentation in order to understand the market and customers likes and dislikes in the product. Additionally, the book suggests how to make intelligent estimates as to what the functional model ought to be, using the modeling in Chapter 5. This step is important to clarify our preconceived notions of how the product ought to function and to adopt a functional view of the design task. This will be very useful to make a Prescreen step of the REPMES.
Figure 29 Five steps to product development, Otto and Wood [40]

Figure 29 describes the process for product teardown, which is the process to dissect the product and understand how its operation either satisfies or fails the customer.

In step 1, the design team has a clear understanding of what problems and opportunities they face on the current project. However, if it is a new project, the design team issues may be unknown, but could still be related to the customer needs.

In step 2, the designers must identify all tools that will be required to complete teardown. The goal of step 3 is to acquire parts, contain them, ship, distribute, and market the product. Step 4 contains the obvious step of teardown, where the product is dismantled. However, here the disassembly is combined with measurements and experimentation. The final step is, as the title suggests, the formation of the bill of materials, the process where a bill of materials and details about the product is produced.
2.5 Literature Review Summary

All of the papers researched under the literary review stated that direct observation in terms of having the product physically available or visually observing the process, for reverse engineering is important. Various disciplines have unique graphing and drawing tools to describe the product or process, but nonetheless every discipline/paper provides a graphical representation. Other differences alluded in the papers is that some discussed validation, offered applications to other fields, used reverse engineering to support re-engineering, and only one discussed the creation of a prototype to understand functionality. None of the papers included a clear critical analysis and none stated objectives of reverse engineering explicitly.

At this point, literature reviews have been completed. The REPMES process will be created in Chapter 3 based on previous investigation from the literature reviews, at a level of detail sufficient to be applied to the first case study the Flashlight V2D-B. In the next chapter, the REPMES process will be fully discussed, evaluated, and analyzed. Suggestions will be made for revising the REPMES process after its application to the first case study.
Chapter 3.0 Reverse Engineering Process for Mechanical Engineering Systems (REPMES₁)

The objective of this work is to create a reverse engineering process, or recipe, that mechanical engineers can use to investigate mechanical products and components. Using the methods discovered through the literature review, which describes engineering, re-engineering and reverse engineering problems, in all types of operational areas, a new REPMES process emerges through consolidation of these ideas. Figure 30 shows the relationship between engineering, re-engineering, and reverse engineering and how the technical data package (TDP) is used to control the flow of information between these processes.

**RE-Engineering**

![Diagram](image)

**Figure 30** A pyramid illustrating the relationships and flow of information between engineering, re-engineering, and reverse engineering.

Referring to Figure 30 there is no flow of information from the TDP coming into reverse engineering, which means that if you have the complete technical data package of a component, there is no need to apply the tools of reverse engineering, while you may
indeed be engaged in either process of engineering or re-engineering. If part of the TDP is available, it can be used to aid with the completion of the TDP.

On the other hand, in order to effectively re-engineer a product or a component, a TDP is needed - and can be provided either from the original engineering design process, or it can be inferred from the reverse engineering process. Before altering (re-engineering) any existing system, an understanding of the system is also needed, a component cannot be redesigned without knowledge of how it works. Engineers use reverse engineering as tool when the technical description of a component is desired. The reverse engineering process in this case may include replacing information missing from the technical data package, and may also include benchmarking for a competitive market assessment.

While the Re-engineering process may obtain a TDP from two inputs, engineering and reverse engineering, as shown in Figure 30, engineering on the other hand, receives TDP from two inputs, reverse engineering and re-engineering. In this case, it is assumed that the reverse engineering inputs to engineering are primarily from a competitive benchmarking study. To conclude the pyramid shown in Figure 30, note that the engineering process may send and receive data information to the re-engineering process.

As the late Japanese Engineer, Dr. Shigeo Shingo once stated, “We think we know certain things we perceive. This doesn’t mean that we really understood them. Understanding demands more than simply knowing. Understanding results from a multi-faceted examination which includes the realization of why the phenomenon in question must be the way it is.” [41] From this saying, it is evident that though one thinks they know, for example a product; a product must be fully examined and analyzed to gain
complete knowledge and to know all of its functionalities. Dr. Shingo has exceeded many great advances in the manufacturing business during his lifetime. He revolutionized the Toyota production system and has written extensive novels about process and manufacturing.

Dr. Shingo’s insight describes the reverse engineering process with stating that “Understanding results from a multi-faceted examination . . .” [41] meaning to analyze a problem based on answering and implementing these five elements: 1) the object; what 2) the agent; who 3) the method; how 4) the space; where 5) the time; when. Dr. Shingo notes that it must not be forgotten to observe both the process and the operation. The process is the course of change in the object and the operation is the course of change in the agent. Translating Shingo’s method to analyze a problem or, in the case of reverse engineering a product, should result in a better understanding of the product. So, if the problem is to implement the RE method to understand how a flashlight works, the five elements will be defined as: 1) the object; a flashlight 2) the agent; design team 3) the method; REPMES\textsubscript{1} 4) the space; Rochester Institute of Technology Laboratories and finally 5) the time; from 2005-2006. According to this information, the method (REPMES\textsubscript{1}) is the one element that needs further explanation.

From the literature review, an initial process for RE which will be denoted as REPMES\textsubscript{1} was compiled, REPMES\textsubscript{1} is defined below shown in Figure 31 and 32. This process, as you can see, is by no means complete, however it is a basic frame work which will be expanded through case studies
REPMES 1

![Diagram of REPMES 1 process]

**Figure 31** Preliminary phases of REPMES1 as presented in the original thesis proposal.

**REPMES 1**

![Diagram of REPMES 1 process]

**Figure 32** Later phase of REPMES1 as presented in the original thesis proposal.

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1. REMPES 1 was formulated by the literal reviews in Chapter 2. The process will be implemented on the Rayovac Flashlight V2D-B
3.1 Management Decision, select a product for RE and define goals

Reverse engineering processes always start with a decision of what to reverse engineer. It is followed by its reasons (objectives and sub objectives). The management group of a company selects a product to reverse engineer and define all the goals they want to achieve. The management decision is based on information gathered on needs and the feasibility to enhance current products. The reverse engineering objectives will be based on the management decision. For example a company X makes a decision to use reverse engineering to understand how the Cellular VB-2 works, but why? To remain competitive in the market, to expand their knowledge or to replace lost technical data package. A well defined objective is important, as it presents the facts in a manner that clearly outlines the requirements and the real need for reverse engineering. This would help focus on the particular aspects of the reverse engineering process. As explained previously in the introduction in Chapter 1, the three main objectives for reverse engineering are Competitive Benchmarking, Replace Lost Technical Data Package, and Knowledge Expansion.

3.2 Competitive Benchmarking

Competitive Benchmarking is an important objective for REPMES because many companies approach their competitive market by applying RE. Many companies use competitive benchmarking for innovation, to reduce cost, and to fully understand the customer needs. It is defined as: "Benchmarking is the process of identifying, understanding, and adapting outstanding practices from organizations anywhere in the world to help your organization improve its performance." [42] Benchmarking helps
understand how competitive companies make their products and the process used. Key components of benchmarking are to conduct need assessments, establish engineering specifications, and finally select a product. REPMES uses competitive benchmarking to define the sub-objective(s). The sub-objective(s) is based on customer needs after assessments have been completed and engineering specifications.

3.3 Need assessment

Being one of the preliminary components of benchmarking, need assessment defines customer needs, as defined internally and externally. The internal aspects are the employees of that company, for example engineers, technicians, etc. The external aspects are users or customers.

Companies need to understand how other companies are staying dynamic in the market. It also needs to be understood that no matter how good your product or service is, the reality is that the product will not sell if a customer does not want or feel they need it. To put this in perspective, Company X will not be able to persuade customers to buy its products, if Company X does not clearly understand what it is customers really want or need.

Knowing and understanding customer needs is the key for any business to succeed, whether it’s to sell directly to individuals or other businesses. Once the company has this knowledge, it can use it to persuade potential and existing customers that buying from the company is in their best interests.

The steps shown in Figure 33 are as follows: first it is necessary to gather needs information, then grouping the needs to rank their importance, after that it is important
that the design team creates questions that help engineers establish engineering specifications, followed by a good documentation of those needs for future innovations or improvement of the product re-design.

Gathering customer needs: There are several methods available for a design team to understand the customer needs. Different techniques developed and applied to construct a customer needs list include: directly using the product, circulating questionnaires, holding focus group discussions, and conducting interviews. [40]
Customer interviews require that a design team member(s) discusses the needs with a single customer, one at a time. Such interviews are usually held in the customer’s environment, where the customer uses the product. The design team member records the customer responses. [40] The tool that will be used herein is the like/dislike method. The simplest approach that proves reasonably effective in practice is to interview customer as they use the product. During the interview a team member asks the customers to describe what they like and do not like about the product at their site of usage. During the process more detailed questions may be asked to explore different facets of the product. At the same time, a reasonable list of customer needs is developed. It is important when holding interviews to have the customers run through their process of using the product. [40]

After knowing what a customer wants, it is essential to translate that into engineering specification. With this, the reverse engineering and design team can focus on a specific area.

3.4 Establishing Engineering Specifications

Establishing engineering specifications is an important part of benchmarking. The goal is to provide the design team with specification related with the customer needs and compare them with other products in the markets. This REPMES will use QFD as the methodology for relating this specification with customers needs.
The process of establishing engineering specifications is defined in three stages shown in Figure 34. First, it is vital to interpret the customer needs in terms of quantity specification. For example, customer A wants Flashlight to illuminate far distances, these needs to be interpreted by engineers in quantity terms, such as “customer will be satisfied if the flashlight illuminates 3 meters.” The next step is to find additional competitive companies with similar products to understand what competitors are doing and how did they create the products, as far as machines used and process for the product. The process of benchmarking can be used to understand mechanical features, design features, and manufacturing processes. Finally, establish the engineering specification. It is very important to know that it does not matter the tool or methodology used to establish engineering specification, as long as you understand and establish those needs.
More information about QFD may be found in the book *Product Design: Techniques in Reverse Engineering and New Product Development* by Kevin Otto and Kristin Wood.

### 3.5 Select Products to RE

This step in benchmarking is where you select a series of products to reverse engineer. In most cases, these selections of the products are based on the competitive companies. Product selection occurs after assessments and engineering specifications have been completed.

Selection of product will be based on the following categories (Figure 35): Customer Needs, Engineering Specifications, or Same Specification. If the category is Customer Needs, all investigation to select the product will be specifically based upon the desired or similar needs from the customer. The same goes for Engineering Specifications. The category for Same Specification is based on the product that was assessed by the customer initially, for example, if the initial product was a domestic flashlight, the category type that would searched will be under the same category, domestic flashlight.
Selecting a product for reverse engineering is the result of the business plan analysis and customer input. At times this process could be very difficult or very easy depending on the type of product, for example if the product is easily accessible. If Company T, a multimedia company, wants to re-design or create a new product, for example a digital music player, and wants to analyze other company’s products and its customer needs, Company T would probably choose the iPod to understand its
functionality. The iPod is a well known portable media players designed and marketed by Apple Computer Inc., therefore Company T will definitely compare products amongst them and other companies. Often on the basis that a company has high quality, their products are more likely to be chosen for reverse engineering, for example the iPod. That is mainly due to the customer's input," It took Apple six weeks to sell 120,000 of the original iPod when it came out in 2001. Apple has now sold over 2 million and has a 70.4% share of digital music player revenue, according to market trackers NPD Group.” [43] This information is useful because it demonstrates a high customer satisfaction and needs in the entertainment industry.

When customer's input information can not be obtained easily, like the example of the iPod, it is necessary to analyze those businesses that have similar products and look for key factors (quality, economical incomings and selling of a product, etc.), that can help your company select a product for RE.

3.6 Replace Lost Technical Data Package

Replace lost technical data package is the process of using RE when a fraction of the TDP is lost or the company wants to replace a part of the product for reductions in maintenance cost. For a better explanation, the average age of US military aircraft is 20+ years and the avionics systems in aircraft are becoming increasingly more expensive to maintain and operate. Typically, the root of the problem can be traced to a few “bad acting” components within legacy avionics system. These bad acting components are characterized by low reliability and high repair cost. The high repair costs are due to the age of the components (multiple past repairs make new repairs more difficult) and high
cost or non-availability of replacement parts. These reliability and maintainability problems lead to high and increasing cost ownership. [32]

Implementing RE with the objective of replacing a lost technical data package is to replace old technology components and take full advantage of life cycle savings for the remainder of the system life. Basically, the RE team will be in charge to compare, analyze and understand functionality of available technology in the market for the re-design team to combine and integrate the legacy components.

3.7 Knowledge Expansion

Knowledge Expansion is a process to not only better understand how a product works but also be a better engineer as a whole. REPMES defines this objective that a combined effort is much better than just one individual effort: if many different ideas are posted from many different people it is much better because many different points of views are expressed. Everyone’s knowledge will expand because many different ideas are being said about the product given. It is a fact that the product analyzed was already analyzed and tested by other engineers and while it is analyzed again, other ideas and knowledge can and are being transferred.

When using reverse engineering with the objective to expand knowledge it is as if working together with two or more people, organizations or things, especially when the result is greater than the sum of their individual effects or capabilities. In other words, knowing everything there is to know about the product and mixing ones own idea can expand your knowledge on the functions of that product. This objective focuses on knowing the entire product, in terms of electrical, mechanical, design, manufacturing
features, and material properties. The conclusion of knowledge expansion is when the engineer feels that enough information has been acquired, and their learning objectives have been met.

3.8 RE sub-objective(s)

Reverse engineering sub-objectives process will be different to a certain point but will be joined together to accomplish a common task which is to understand the functionality of the products based on the objectives. All of the objectives have something in common and that is that they all need a sub-objectives. A well defined sub-objective (s) is important, as it presents the facts in a manner that clearly outlines the requirements and the real need for reverse engineering. This would help focus on the particular aspects of the product that would help save time and money. Figure 36 is a REPMES\textsubscript{1} segment of the flowchart pertaining to RE sub-objective(s).
As previously stated, Figure 36 shows the steps for defining the RE sub-objective(s). All sub-objectives are based on the objectives, therefore they vary depending on what is defined for the objective. To remain competitive in the market (benchmarking), a critical assessment analysis is completed to fully understand what the customer wants and then ranking the users potential sub-objective. Identification and selection of the sub-objective is then based on the engineering specification. For both the objectives of
knowledge expansion and replace lost TDP, identification of the reasons why each objective is chosen is analyzed to then select the sub-objective.

3.9 Getting the Product (s) for RE

As an essential step in the reverse engineering process, is acquiring the physical product (s) for analysis. Having the physical product can help evaluate the product and reverse engineer it. In this step of the RE process for getting the product (Figure 37), the product must be obtained. In the case that the product is unavailable, find a similar product. If the similar product is unattainable, create a prototype.

![Flowchart for Obtaining the Product(s) for RE](image)

Figure 37: Obtaining the Product(s) for RE
3.10 Getting Product Documentation

Design or product planners, probably create documents of some kind to capture the design decisions and solutions for a product. Documentation is a crucial component to successful reverse engineering planning and implementation. Gathering all necessary product documentation is very important because it will help save time and money. Since the product has already been out in the market, there is no need to conduct certain experiments if the documentation is readily available. REPMES defines the information as objective information, useful information, and usage information (Figure 38).

![Figure 38 Getting Product Documentation](image)

Heavy research is completed to find all product documentation based on the sub-objective(s). A careful analysis of information found follows the research, answers to
doubtable questions will be answered, and new questions will arise. Throughout the research, there were other useful and usage information obtained, at this time analysis of that information is requisite.

3.11 Design Team Selection and RE plan

Design team selection is based on the sub-objectives of the selected product to be reversed engineered. Figure 39 displays the steps to the selection of the design team. After identification of the product features and characteristics is completed, areas of the product are selected to be analyzed. The various areas of a product include but are not limited to mechanical, electrical, etc. All personnel that comprise the design team will be essential in different areas but there will be a continued collaboration within the team. Multitalented individuals offer a particular advantage in their ability to synthesize the variety of elements for RE. Documentation of each personnel and corresponding function is also completed in this step of the RE process.
Scheduling and creating a plan is important to enable order and a better use of time so that set goals are achieved. Figure 40 displays the steps for creating an RE plan. It begins with the design team stating a deadline for each part of the RE project. A detailed RE plan is compiled and depending on the plan, a schedule is created accordingly. This schedule ensures that all objectives are achieved in a timely manner as well as to write the product will be transported or located at any given time. Documentation and distribution of the schedule is given to the design team. It is important to make a critical analysis of what to do to accomplish the task and write a detailed reverse engineering plan for engineering: following this may include all transportation of the product, tools use, strategy, details, logistics and material handling.
3.12 Product Functionality

The product functionality section begins with asking the question, "How does this product work?" (Figure 41) First, identify the root cause of the problem based on the sub-objective(s) using the "5 Whys." The 5 Whys establish how the relationships among the root cause of a problem are obtained with simply five questions. Establish the system functionality using the FAST method, Function Tree, and the Block Box. More information on some of these methods may be found in Appendix A. It is important that communication is as effective as possible. Good organization, complete information, and clear writing are key to the success of any design document.
3.13 Visual inspection of the product and understand how it operates

The visual and dimensional inspections constitute the first task before dissembling a product. The visual inspection is a review of the overall condition of the part in terms of functionality and quality. This process helps to assess where to begin the process of Reverse Engineering. The inspection requires the answer to several questions to document if the product is adequate for reverse engineering. Figure 42 is a REPMES\textsubscript{1} segment of the flowchart pertaining to Visual Inspection of the product and understanding how it operates.

The process of visual inspection begins with a simple inspection, for example, to make sure the product works properly. This simple inspection is useful because it will not be worthwhile to reverse engineer a product that does not work properly initially.
Another attribute of inspection is that it can determine if the product received matches with the technical data.

Next, gathering basic information of the product: for example, tolerance, primary functions, cost per part or subassembly, other notes, color finish, and any other information that will help you interact with the product. Gather tools to use and prepare for product teardown. Disassemble product, make measurements accordingly, take necessary pictures, and analyze all assemblies. Finally, create a Bill of Materials.
Start of visual inspection of the product

Inspection

List the design matters

Prepare for product teardowns

Disassemble, Measure and analyze data by assemblies

Bill of material

End of visual inspection of the product

Gathering basic information

Tools to use for teardown

Take apart the assembly, take picture and an exploded view and take measurements on the parts and assemblies

Ishikawa diagram and Interconnection description

Figure 42 Visual inspections, Kevin Otto and Kristin Wood [40]
3.14 Design Feature

The design feature section constitutes the most important part of reverse engineering of a mechanical and electrical component based on the military specification MIL-DTL-31000C. "That specification states that 2D and 3D document should be in a detail or content sufficient for the support of production, and engineering and logistics support based on 2D and 3D engineering drawing" [6]. Figure 43 is a REPMES₁ segment of the flowchart pertaining to the Design Feature of the product and understanding how it operates.

![Flowchart](image)

**Figure 43 Design Features**
The first step in the design feature section is to create a design feature model and describe all of the design feature attributes of the component; this could be mathematical or graphical, with its associated feature. Graphical could be classified as 2D or a 3D type drawing. Next, recognize special geometrical shapes and also simple or complex surfaces to determine the type of computer aid needed; for example, CMM, Range Image, or a CAD program (Solid Works, Pro-E, etc.). Finally, a solid model will be created and other characteristics will be based on MIL-DTL-31000C.

3.15 Electrical Feature

The electrical feature section constitutes the application of electricity in technology. The model process for the electrical feature includes the electrical drawing and the electrical description of the mechanical component.

The first step in the electrical feature section is to create a electrical feature model that helps engineers interpret the product’s functionality; this could be mathematical or graphical, with its associated feature. Each electrical drawing includes an electrical circuit and corresponding component specifications. The Electrical Feature process is shown in Figure 44.
3.16 Mechanical Feature

The mechanical feature section constitutes areas of physical features as shown in Figure 45. The model process for the mechanical feature is heat treatment, mechanical structure, failure analysis, and quality evaluation reports.

The first step in the mechanical feature section is to create a mechanical feature model; this could be mathematical or graphical, with its associated feature. The difference between mechanical feature and design feature is that mechanical feature is associated with Newton’s second law; which are the features that affect the functionality of a product. An example of mechanical feature is a flat surface placed on a cylindrical body, to stop it from rolling on a surface. An example of design feature would be the
color of the flat surface, to distinguish it from the cylindrical surface, and highlight the mechanical feature to make the product more marketable. A feature may have both mechanical and design attributes. In this work, the mechanical feature refers to the functional attribute, while the design feature refers to the aesthetic attributes.

3.17 Technical Implementation

It comes to a point when the reverse engineering team receives information from product documentation, product functionality, and analysis of features and properties. Then technical implementation, critical analysis, validation, and design verification make sure that all of the information received matches with one another. Technical implementation is a process that depends on the sub-objective (s) (Figure 46). First, technical implementation starts with defining a field set operation. Field set operation focuses on the areas of analysis, features, and properties. For example on metals, in terms of material property, their structures, what they are composed of, properties, design detail, electrical characteristics and application will be analyzed and compared with documentation.
The interrelation of properties, structure, processing, and performance is studied.

The technical implementation is divided into two procedures: Destructive and Non-Destructive. If the non-destructive procedure is applied then the subtract and operate procedure will be conducted, which means that the component will be examined in full range and re-examined until all of the information of the product functionality and
product documentation matches with the component. If destructive procedure is applied then the component is tested to its maximum capabilities to test if the documentation matches. Then a report is made so it could be critically analyzed.

3.18 Critical Analysis

Critical analysis is a method of understanding and thoroughly identifying all aspects of the product in terms of design, electrical, and mechanical features and material properties based on the sub-objectives. At this point, research has been collected and will be evaluated in detail. The data desired for reverse engineering will be defined in this section as well.

A problem may arise when the available documentation about a product does not agree with the observed function or features of the product. The process described in Figure 47 demonstrate how to resolve the problem of a conflict between the available documentation and the observed performance. The procedure starts with listing all of the components of the part examined to re-examined. Next, confirm the component functionality, collect existing data of components and then answer the questions and create new questions. Then functional and economic analysis is done if a new test or analysis is required for the comparison of data and product. Then an engineering judgment is done following a Go /No Go decision, which means whether or not the additional test or analysis, will be conducted. If the conflict between previous documentation and observed product function has been resolved, then no further work is needed. If the conflict remains, we repeat the process again, or decide that the conflict does not warrant further analysis.
3.19 Validation

To validate data is to construct a premise that is jointly asserted and the conclusion cannot be denied without contradiction. The validation process in this section is as follows: first generate a vast number of test scenarios, and then perform the test scenarios using a similar unit, observe any differences, postulate the cause for the
differences and make changes accordingly, and finally repeat the steps. Validation is done to make sure the information from critical analysis is concise and accurate. Stated another way, validation serves to insure that the information derived from reverse engineering truly is an accurate representation of the product.

![Diagram of validation process](image)

**Figure 48 Validation, Riffle [32]**
3.20 Design verification

Design verification as explained in Figure 49 is the process of establishing the validation capability by the investigation and evidence confirmed by the critical analysis and validation sections. This section will answer initial questions and new questions will arise, along with the creation of the TDP. There is a section within the design verification for a manufacturing process if it is needed.

![Design verification flowchart](image)

**Figure 49 Design verification**

Within this section, examination of the documents to be produced and a conceptual description of the information they contain will be included. Collecting all the technical data and arranging them in a data structure will be dependant on the sub-objectives (s).
3.21 Process State Estimation “Inconsistency”

The process for resolving inconsistencies (when RE information contradicts each other) is shown in Figure 50. This occurs most often when technical data is compared with the validation process data. During the RE validation, when the mechanical, electrical features and material properties have been analyzed, assume that an inconsistency is found. In this case, it is necessary to backtrack in the REPMES process, and repeat the critical analysis and validation once again until no inconsistencies remain.

![Figure 50 Process State Estimation](image)

Now that the primary version of REPMES is developed, it is necessary to test this version through application to an actual product. The Rayovac Flashlight V2D-B was chosen because it possesses detailed components all within a simple structure, but yet realistically multifaceted in its attributes. REPMES on the Flashlight V2D-B will be thoroughly explained in the following case study.
Chapter 4 Case Study: REPMES\textsubscript{1} Applied to a Flashlight

REPMES\textsubscript{1} is used to conduct a reverse engineering case study of a Rayovac Flashlight, Model V2D-B to demonstrate the REPMES process. For the purpose of the case study, the design team assumes that the objective of the reverse engineering process was to gain knowledge about the function and operation of the flashlight and to conduct product benchmarking from the perspective of customer's perceptions, and manufacturing cost reductions. The REPMES\textsubscript{1} case study required 1,119 hours to complete, with a task breakdown as illustrated in Table 4.1.

Table 4.1 REPMES\textsubscript{1} Case Study Task Breakdown

<table>
<thead>
<tr>
<th>Task</th>
<th>Labor Hours</th>
<th>Start Date</th>
<th>End Date</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interviewing Customer</td>
<td>53</td>
<td>02/06/06</td>
<td>02/13/06</td>
<td>RIT campus</td>
</tr>
<tr>
<td>Importance of customer needs</td>
<td>44</td>
<td>02/16/06</td>
<td>02/20/06</td>
<td>RIT campus</td>
</tr>
<tr>
<td>Establishing engineering specification</td>
<td>22</td>
<td>02/22/06</td>
<td>02/24/06</td>
<td>ME and IE Lab</td>
</tr>
<tr>
<td>Competitive companies</td>
<td>18</td>
<td>02/25/06</td>
<td>03/2/06</td>
<td>Internet and the Home Depot</td>
</tr>
<tr>
<td>House of quality and establishing RE sub-objectives</td>
<td>24</td>
<td>03/2/06</td>
<td>03/5/06</td>
<td>ME lab</td>
</tr>
<tr>
<td>Obtaining products for benchmarking</td>
<td>29</td>
<td>03/9/06</td>
<td>03/15/06</td>
<td>Amazon, the Home Depot and Wal-mart</td>
</tr>
<tr>
<td>Get products documentation</td>
<td>53</td>
<td>03/25/06</td>
<td>04/7/06</td>
<td>Internet, Modeling system Lab and RIT Wallace library</td>
</tr>
<tr>
<td>Select and identify engineering functions</td>
<td>10</td>
<td>04/7/06</td>
<td>04/8/06</td>
<td>ME department, RIT</td>
</tr>
<tr>
<td>Establishing system functionality</td>
<td>50</td>
<td>04/8/06</td>
<td>04/12/06</td>
<td>ME and IE Lab</td>
</tr>
<tr>
<td>Dissecting the product, understand how it operates and gathering basic information</td>
<td>120</td>
<td>04/14/06</td>
<td>04/25/06</td>
<td>Engineering building, RIT</td>
</tr>
<tr>
<td>Inspection</td>
<td>20</td>
<td>04/14/06</td>
<td>04/25/06</td>
<td>Engineering building, RIT</td>
</tr>
<tr>
<td>Teardown implementation</td>
<td>98</td>
<td>04/21/06</td>
<td>05/1/06</td>
<td>Engineering building, RIT</td>
</tr>
<tr>
<td>Analysis of the design, electrical and mechanical feature</td>
<td>212</td>
<td>05/2/06</td>
<td>05/17/06</td>
<td>Engineering building, RIT</td>
</tr>
<tr>
<td>Critical analysis and validation</td>
<td>88</td>
<td>05/18/06</td>
<td>05/25/06</td>
<td>Engineering building, RIT</td>
</tr>
<tr>
<td>Writing description documentation and answer questions</td>
<td>72</td>
<td>05/25/06</td>
<td>06/10/06</td>
<td>ME lab and grad office</td>
</tr>
<tr>
<td>Analysis of useful and usage data</td>
<td>30</td>
<td>06/8/06</td>
<td>06/11/06</td>
<td>Engineering building, RIT</td>
</tr>
<tr>
<td>Creating technical data package (TDP)</td>
<td>166</td>
<td>05/4/06</td>
<td>06/12/06</td>
<td>Engineering building, RIT</td>
</tr>
<tr>
<td><strong>Total (hours)</strong></td>
<td><strong>1119</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 The table 4.1 is a REPMES\textsubscript{1} segment of the flowchart pertaining to RE plan
Throughout the balance of Chapter 4, the reader is referred to Figure 31, the flow chart illustrating the steps of REPMES$_1$. Each section of this chapter represents various steps in the flow chart of Figure 31.

### 4.1 Management Decision

The first step of the REPMES$_1$ is to select the product or products for reverse engineering analysis, and to clearly establish the goals and objectives of the case study. The primary motivation for conducting the case study is to exercise the REPMES$_1$ proposed process through application to an actual product so that the REPMES process can be further refined and developed. The chosen product must be simple enough to create a replicable process, yet realistically multifaceted in its attributes. The Rayovac Flashlight Model V2D-B, illustrated in Figure 51, was chosen because it possesses detailed components all within a simple structure.

![Rayovac Flashlight Model V2D-B](image)

**Figure 51 Rayovac Flashlight Model V2D-B used in Case Study.**

Since its invention in 1898, flashlight devices have undergone various changes and developments, specifically in terms of the lighting technology, the materials used in construction, and the ergonomic relationships between humans and the device. Therefore, the topic Rayovac Flashlight V2D-B is a good subject device for a reverse engineering case study with a focus on competitive benchmarking.
The objectives of the case study are to

1. Demonstrate REPMES$_1$ on a simple electromechanical device
2. Demonstrate REPMES$_1$ as a tool for competitive benchmarking
3. Demonstrate REPMES$_1$ as a tool for establishing customer needs and engineer specifications that will help drive redesign efforts directed towards cost reduction

4.2 Competitive Benchmarking and Product Improvement

Referring to Figure 31, the competitive benchmarking branch of the flow chart refers to three sub-steps, each of which will be investigated sequentially.

4.2.1 Need assessment

Two methods were employed to demonstrate a needs assessment activity for the Rayovac Model V2D-B flashlight – a focus group using a “Like-Dislike” assessment, and an “Importance Questionnaire” assessment, as described in Section 3.3: Need assessment. For actual reverse engineering processes, a wide variety of needs assessment tools are available. The data resulting from this case study is not intended to be exhaustive, but rather demonstrative. The targeted focus group was that of adult college students who use a flashlight for domestic use. Before continuing to the interviewing steps, the flashlight must be obtained, to physically show the interviewees the product. Two flashlights were acquired for use with the case study. The first Rayovac Flashlight V2D-B (black) was provided by the Mechanical Engineering Department of the Rochester Institute of Technology, and was used for mechanical investigations in conducting REPMES$_1$. A second Rayovac Flashlight V2D-B (blue) was obtained from Amazon for US$ 4.99 plus shipping, for modeling purposes and survey demonstration in the original
market packaging. The following are the results of the various methods are all located in Appendix B.

4.2.2 Establish Engineering Specifications

In this section, the engineering specifications will be established, by first interpreting the voice of the customers that was analyzed in the previous section, then analyzing the current companies that make the same or a similar product to the flashlight. This is done to understand how the competitive companies make their product and how they cater to customer needs. Then compare the Flashlight V2D-B with those companies using a common tool called “The House of Quality” which only focuses on the sub-objective obtained from the need of assessment. Based on the results of the need assessment, it was determined that one of the main priorities for the customer is for the flashlight to illuminate more than two meters. The engineering design team must interpret the needs expressed by the voice of the customer, to establish engineering metrics to quantify areas of importance in the design. These analyses and the results are located in Appendix B.

4.2.3 Select n Products for Reverse Engineering

Based on Section 3.5: Select n product for RE, similar products will be obtained for reverse engineering to compare with the Flashlight V2D-B. This will help identify features from other companies’ customers as shown in Appendix B. These similarities should include price, simplicity and type of features. Then, establish engineering metrics base on the customer desire. As explained previously, the house of quality may be used to
compile the results of competitive benchmarking by comparing the baseline product versus a set of competing products from the marketplace. In this stage of the case study, three remarkable companies were selected that manufactured a flashlight similar to the V2D-B. The competitive companies for the domestic flashlights were Eveready Industries, Garrity Lites, and Dorcy. Appendix B includes summary information about the competitive companies and their products. Products selected and extra information may be found in the Appendix as well.

4.3 Reverse Engineering Sub-Objectives

Based on the results of Section 4.2, it has been determined that the single reverse engineering sub-objective (s) for the Flashlight V2D-B is to improve far distance illumination. Therefore, the implementation of RE to the Flashlight V2D-B case study will only focus on understanding how the flashlight’s illumination works, taking into account all components related to the illuminating parts. As other sub-objectives may be determined by the team, additional details may be determined by the RE investigation. 3D Drawing package regarding the flashlight and operating information may be found in Appendix B.

4.4 Acquire the Product(s) for Reverse Engineering

A comprehensive reverse engineering case study requires acquisition of one or more artifacts of each competing product selected for benchmarking. In the interest of brevity, the case study here will present RE results for a single sub-objective (far distance illumination) for a single artifact (The Rayovac V2D-B). After obtaining the two
flashlights V2D-B as explained in the above section and selecting the competitive companies, one product from each company was chosen for comparison, as summarized in Appendix B. Each of the selected products share similar engineering specifications (SE) and customer needs (CN) with the case study flashlight V2D-B, which includes all flashlights that use 2 D-cell batteries, with price ranging from US $1.72 to US $7.45, plastic material, and a non-rechargeable feature. The first unit, called Eveready 1251 has pre-focused light beams, weighs 255.44 grams, and has an impact-resistant polypropylene case, for a retail price of $6.23. The second unit, the Garrity No. G500GST06H, weighs 120 grams, has a soft grip handle for a comfortable hold, and has a retail price of $5.99. The Garrity design incorporates bigger reflectors compared with the Eveready 1251. The third domestic flashlight is the Dorcy 41-2380, which has blinking LED light locators, weighs 90 grams, and has a retail price of $6.70.

4.5 Get Product Documentation

A thorough history of the common “flashlight” or “torch” is presented in the paper, "Lighting: The Way to Flashlights" by Mike Roux [44] and the following two websites that discuss history and background information of the flashlight, Answers.com [45] and TheLEDLight.com [46]. The reader is referred to these three references for a fascinating historical summary documenting the development of the flashlight since the invention of the “Electric Hand Torch” by Conrad Hubert demonstrated in New York City in 1896 and patented in 1898 [47]. The following sections are product history, documentation, and specification from extensive hours of research. Recent significant developments of the flashlight include the use of light-emitting-diodes (LEDs) in place of
incandescent or fluorescent bulbs, as documented by TheLEDLight.com, and illustrated in Figure 52, below [46].

![LED flashlight image]

Figure 52 Electronically regulated, variable output LED flashlight [46]

### 4.6 Design Team Selection

For the flashlight case study, a team of three individuals was relied upon as the core team, as listed in Table 4.2. Additional personnel may contribute to the case study, but will be called upon as needed. This core team will not change from case study 1 to 2 to maintain a consistency in the application of the reverse engineering philosophy governing the way projects are handled, and insure that the accumulated knowledge will not be lost from case study to case study.

<table>
<thead>
<tr>
<th>Core Team</th>
<th>Description</th>
<th>REPMES Function(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frank B. Tamarez G.</td>
<td>Student at Rochester Institute Of Technology</td>
<td>Analysis Management</td>
</tr>
<tr>
<td>Dr. Edward Hensel</td>
<td>Professor of Mechanical Engineering</td>
<td>Validation and Process Management</td>
</tr>
<tr>
<td>Dr. Marcos Esterman</td>
<td>Assistant Professor of Industrial and Systems Engineering</td>
<td>Process and Identification Management</td>
</tr>
</tbody>
</table>

### 4.7 Product Functionality

There are many techniques available to establishing system functionality that engineers can use to understand the systems more efficiently. The techniques in this
chapter that REPMES uses may improve the thinking process, communication with other people, and ultimate decision making. The tools used may accelerate and increase results when properly used, perhaps even involve situations where a high order of results is needed.

After gathering and analyzing the product documentation and selecting the design team, product functionality needs to be set, as explained in Section 3.12. The tools used to understand the functionality of the Flashlight V2D-B were the Set Mode, 5 Whys, FAST method, Function tree and Black box; the results may be found in Appendix B.

4.8 Visual inspection of the product and understand how it operates

In this step, it is important to note that destructive testing was avoided during teardown and dissection of the flashlight. A careful disassembly of the Flashlight V2D-B "Rayovac" was completed, so that it can still function properly.

4.8.1 Inspection, Dissection, and Bill of Materials

After the system functionality is set, it is essential to know that the product works properly. The visual inspection helps to establish quality control and to establish a nomenclature to be used during the subsequent steps of the reverse engineering process. This step is necessary because at times products may not come directly from its manufacturing plant, in this case Rayovac, and design team would rather not analyze a component that was modified by the customer. Furthermore, at this stage during dissection, the reverse engineering team will establish a first draft definition of the subassemblies on an overall design intent of the original engineering design team. For the Flashlight V2D-B, it was necessary to obtain another black Flashlight V2D-B to make
sure all the data measurements were accurate and the electrical properties were not affected by the flashlight that has been used by several customers.

The design team knows that like other companies, Rayovac conducts inspections on their products at three times during production: before production, during production, and after production. The logic of checking conformance before production is to make sure inputs are acceptable. The logic of checking conformance during production is to make sure that the conversion of inputs into outputs is proceeding in an acceptable manner. The logic of checking conformance of output is to make a final verification of conformance before passing a good product on to the customers.

The REPMES inspection starts with an inspection form, as shown in Figure 53. The form prompts the inspector to answer a few questions about the product, the condition of the product, if the product was properly received, and whether the product received matches the documentation provided with it. At this point, and depending on the answers given, the team will know what parts to change or buy to obtain a better result for understanding the product. The inspector’s questions and responses are presented in the Appendix B.
LOCATION (include building and room number)

COMPONENTS MANUFACTURER MODEL

SERIAL NUMBER

VISUAL INSPECTION EQUIPMENT

ITEM FOR VISUAL INSPECTION ANSWER OR DESCRIPTION

Figure 53 Sample inspection form to be used by the inspector during dissection. Additional details are presented in the Appendix B.

4.9 Design Features

As explained in Section 3.14, the design feature section constitutes the most important part of reverse engineering of a mechanical and electrical component based on the military specification MIL-DTL-31000C. That specification states that "2D and 3D document should be in a detail or content sufficient for the support of production and engineering and logistics support based on 2D and 3D engineering drawing." [6]

Based on the objective and sub-objective, for example, mathematical modeling of the product was created because it was not required to understand any part of the flashlight's illumination. The first step for the design team in the design feature section was to recognize special geometrical shapes.
and simple or complex surfaces to determine the type of computer aid program needed. With a simple inspection it was noticed that the flashlight’s shape was mostly circular with a flat smooth surface. Based on this observation, the design team decided to use a CAD program (Pro-E Wildfire) to create a solid model and obtain the technical description of the flashlight V2D-B. No CMM or Range Image was needed to obtain the technical description. The technical description and design feature of the Flashlight V2D-B are presented in Appendix B. The following 2D drawing is an example of the CAD program use (Pro-E Wildfire 2.0).

![2D drawing of the Base of the Flashlight V2D-B](image)

Figure 54 the 2D drawing of the Base of the Flashlight V2D-B

### 4.10 Electrical Features

The electrical feature section constitutes the application of electricity in technology. The model process for the electrical feature includes the electrical drawing and the electrical description of the mechanical component. The Flashlight V2D-B is a simple electrical device that contains a source of electro-chemical energy (the dry cell batteries),
a bulb that changes the electro-chemical energy into a more functional form of energy (visible light), and a switch to control the energy delivered to the bulb. The electrical analysis of the flashlight is represented by the simple schematic shown in Figure 55. Detail information of electrical feature is presented in Appendix B.

![Electrical Circuit of the Flashlight V2D-B "Rayovac"](image)

Table 4.3 illustrates a functional analysis of the electrical performance of the flashlight. The simple analysis presented herein for the case study suggests that a circuit analysis, simulation, PCB layout, and similar investigations may be appropriate for a particular product reverse engineering analysis. In the interest of brevity, and to simply illustrate the process, the electrical analysis is intentionally limited herein.

**Table 4.3 Electrical feature Flashlight V2D-B at 1 Meter**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Two Batteries D (In Series)</th>
<th>Bulb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ampere</td>
<td>Base on the Chapter 2.8.4 is 15 Ampere *Hour</td>
<td>0.5 Amp.</td>
</tr>
<tr>
<td>Voltage</td>
<td>3</td>
<td>2.4 Volts</td>
</tr>
<tr>
<td>Power</td>
<td>45.5 Watts/hour</td>
<td>1.2 Watts</td>
</tr>
<tr>
<td>Estimated time that Flashlight V2D-B will remain on</td>
<td>30 hours</td>
<td></td>
</tr>
</tbody>
</table>
4.11 Mechanical Features

For this case study of the flashlight, no mechanical features were analyzed due to the fact that it was not required by the reverse engineering objectives of the Flashlight V2D-B. The objective of the Flashlight V2D-B was to understand how the flashlight’s illumination functioned. The mechanical feature of a component constitutes areas of physical features in relation with any other component of that product. As explained in Section 3.16, the model process for the mechanical feature is heat treatment, mechanical structure, failure analysis, and quality evaluation reports. The design team included in the report and the TDP of the flashlight in Appendix B a section of extra information that will include mechanical features of those components that had features that interact with other components for example the base thread and the light cover attach to each other and therefore interact with one another. Also, the lens and reflector interact with one another to influence far-distance illumination.

4.12 Material Properties

For the flashlight case study, there was also no material properties process conducted because it was not required by the reverse engineering objectives and sub-objective. Additional information obtained in the research analysis of the material property of the Flashlight V2D-B is presented in Appendix B and in the following section.

4.13 Critical Analysis

4.13.1 Assembly Analysis
Figure 56 displays the solid model design of the Flashlight V2D-B in exploded view using Pro Engineering Wildfire 2.0. Each component in the flashlight was modeled as a solid model, and then assembled using the Pro-E package. More 3D models are presented in Appendix B.

![Figure 56 Assembly view of the solid model flashlight](image)

4.13.2 Mechanical Analysis

Figure 57 displays the solid model of the flashlight base using Pro Engineer Wildfire 2.0. Several mechanical features provide useful functions for the user. For example, feature (a) provides the right placement for the batteries, so that it can connect correctly to both poles. The two bars are good enough to hold the batteries in the center. Feature (b) is a base-stand (0.15 inch height and 1.15 inch width) which makes the base to be static on any surface and inhibits the flashlight from rolling on flat surfaces. Feature (c) does several things, including provision of a recessed space to connect the rubber band to the base, while allowing the flashlight to stand upright on its heel, and provide a mechanical attachment point for the spring-bottom pole. Feature (d) in the central region of the base has nine roots which provide a good grip. The roots
are on the one side only, and are not surrounding the base, which most likely provides the basic gripping need while making the molding process economical. It is not surrounding the base because the nine roots will cover the basic needs and make it probable for an economical mold. Feature (e) provides a path for the switch to connect both poles together while insuring that the batteries do not make contact with the metal switch.

![3D model of the flashlight base created using Pro-E wildfire 2.0](image)

Figure 57 3D model of the flashlight base created using Pro-E wildfire 2.0

For the sake of this case study, additional mechanical analyses of each part could be conducted. In the interest of brevity, these details are not presented here but refer to in Appendix B.

### 4.13.3 Material Properties Analysis

The material of the base is an ABS thermoplastic housing which makes the product light weight. It is not as resistant to impact as an aluminum casing; however due to its material it will not have problem with corrosion. It has a circular body with roots on one side which makes it easy to grip and portable. REPMES uses validation to check the documents searched and engineering judgment against the formal standards. Through the “non-destructive process” some of the materials in certain parts of the flashlight were
identified and explained more explicitly below. Depending upon the application, the reverse engineering investigation team may choose to secure additional artifacts of the product under investigation, so that more thorough material properties analysis, including destructive evaluation, may be completed. Again, the simplistic analysis presented in this case study is to illustrate the process only. Many different tools are available for materials analysis. It is noticed that the whole flashlight is composed of seven different materials. Initially it is observed that plastic and metal are both present. Following investigation, those materials are further identified as copper, aluminum, rubber, glass, plastic, metal alloy (iron and steel), and tin.

By studying the response of the bulb to magnetism and heat, it was confirmed that the bulb is made of aluminum and tin. The bulb cover is divided into three components. The top one was obviously made up of plastic with a shiny aluminum layer. Initially, the assumption made with the second part was that it was composed of aluminum due to its appearance, but after applying a magnet to it and having it connect to the magnet, it was concluded that the second part was not aluminum. The conclusion of the second part was that it must be iron and carbon, a metal alloy. The third and final part of the bulb cover was made of some type of plastic. A thorough investigation to determine what type of plastic was not completed, in the interest of time. Similar investigations may be conducted on each part within the assembly, to determine the material properties, coatings, and surface treatments applied to each part in the assembly.
4.14 Technical Data Package for the V2D-B Flashlight

The complete technical data package (TDP) for the flashlight case study is presented in Appendix B. The purpose of a Technical Data Package (TDP) is to provide a technical description of the object undergoing reverse engineering (in this case study, the Flashlight V2D-B) that helps engineers understand how it functions, how to manufacture it, and to make recommendations for redesign to improve the flashlights illumination based on the customer needs. The contents of the TDP vary greatly depending upon the objective of the reverse engineering project. For example, if the desire is to manufacture thousands of artifacts based on the reverse engineering on reverse engineering of the specimen, then complete manufacturing drawings are required. If the intent is to upgrade and modernize a subsystem (such as an electronics board) within a large integrated system (such as an aircraft), then and interface specification may suffice for the TDP. The US military specification MIL-DTL-31000C (approved for use by all departments and agencies of the Department of Defense) provides an outline for defining the contents of a technical data package. According to this MIL-DTL-31000C, the TDP presented in Appendix B for this case study would be categorized as a 2D type TDP, which will contain 4 TDP elements and 2 TDP data management products. The need for the level of detail needed in the TDP varies greatly depending upon the REPMES application objectives, which may from knowledge expansion to become better engineers to a competitive benchmarking to remain competitive in the market. The TDP in this case study does not include financial, management, or contract administrative data.
The TDP for the flashlight case study presented in Appendix B consists of the following elements:

B.i Title Page

B.ii Executive Summary

B.iii Reverse Engineering Objectives and Statement of Work

1. Introduction

2. Product Dissection and Inspection Report
   a. Product inspection
   b. Gathering Basic information
   c. Mass of the flashlight components
   d. Photographic Bill of Materials
   e. Assignment of Names and Numbers to Parts and Subassemblies

3. Background Information “Know the flashlight”
   a. Operation instructions for the Rayovac V2D-B flashlight
   b. Important safeguards for end users

4. Design Features Analysis
   a. User Needs Assessment
      i. Customer Surveys
         1. Like / Dislike Assessment Method
         2. Questionnaire Method
      ii. Illumination
      iii. Applications
      iv. Priority of customer needs
      v. Priority of Design Level
      vi. Ergonomics
   b. Competitive Benchmarking
      i. Comparison Products
      ii. House of Quality

5. Mechanical Features Analysis

6. Electrical Features Analysis
   a. Schematic diagrams
b. Circuit simulations
c. Component Specification
d. Manufacturing Process Information

7. Materials Properties Features Analysis

8. System Functionality Analysis
   a. Set Mode
   b. Identifying the root cause using the Five Whys
   c. FAST Diagram Method for the Flashlight V2D-B
   d. Function tree for the Flashlight V2D-B “Rayovac”
   e. Black Box analysis for the Flashlight V2D-B

   a. 3-D Solid Model of the Device
   b. 2-D Drawing Package

10. Extra information

**4.15 Case Study Summary**

At this point, the case study of the Rayovac Flashlight V2D-B is complete. The REPMES process has been applied to the flashlight, at a level of detail sufficient to indicate where the REPMES process works well, and where it falls short. In the next chapter, the performance of the baseline REPMES process will be evaluated in the context of this case study, and suggestions will be made for revising the REPMES.
Chapter 5 Revisions of REPMES$_1$ to implement REPMES$_2$

Within this chapter, as shown in Figures 59a, 59b and 60, when implementing REPMES$_1$ to the first case study, the “Flashlight V2D-B”, several implementation problems were encountered. These implementation problems and re-ordering of some process steps (in contrast to the sequences observed in the bibliographic search) resulted in REPMES$_2$. The changes from REPMES$_1$ to REPMES$_2$ are explained in the next three sections. The first and second sections describe some inconsistencies found in REPMES$_1$ with the objective of “Competitive Benchmarking” and “Replace Lost Technical Data Package and Knowledge Expansion.” The third section describes a series of process steps that were included in the “Technical Data Package.”

*Competitive Benchmarking*

As stated before, one of the objectives of REPMES is Competitive Benchmarking. Within this objective lies Need Assessment; when conducting the interviews and surveys, it was encountered that the actual product was needed to display it to the customers that were interviewed so that they can provide areas for improvement and recommendations. This brings us to the first problem at hand. Initially, the product needed to be obtained after the sub-objective(s) are defined, as shown previously in Figure 31, but after applying the REPMES to the Flashlight V2D-B, it was discovered that the product needs to be obtained before gathering the assessments, as shown in Figure 59a. In other words, the product is physically needed before analyzing the market.

The second problem encountered within Competitive Benchmarking was that before the Engineering Specifications could be completed, “Selecting a Product” had to
be done. In order to compare the Engineering Specifications of the product that will undergo reverse engineering, it is needed to select a number of products that have the same characteristics based on the Need Assessment segment. Therefore, after Need Assessment is "Select n Product," and then Engineering Specifications.

Along with difference in order of certain process steps, some steps were added as well. After the Engineering Specifications, the RE sub-objective(s) are defined and the project cost are estimated. RE project cost are based on the "... technical complexity of the part and the amount of available data" [39] and the sub-objective(s) defined. Mainly, the sub-objective(s) will lower the project cost in general because lets say that you have a product and you are focusing on RE the material of the product, well instead of attributing all the parts of the product, the main focus is the material. Therefore defining the sub-objective(s) is important to have before calculating the RE project cost. These changes and new process steps can be seen on Figure 59a.

**Replace Lost Technical Data Package (TDP) and Knowledge Expansion**

Another objective of REPMES is Replace Lost Technical Data Package. Initially, this objective was followed by the sub-objective(s). Now, the addition of identifying missing data and selecting the product to RE is included into REPMES2 (Figure 59a).

Initially, after the third objective was defined, being Knowledge Expansion, the sub-objective(s) followed thereafter. Now, after the main objective is defined, a product selection is made based on economic factors. Figure 58 shows the product selection based on the economic factors, beginning at "Start" and continues with the series of process steps.
How are the products chosen? Well, economic factors are essential when a product is chosen to reverse engineer. A high probability of success is needed before investing time and effort into each project, taking into account that success is measured by return on investment. Even though RE is a process that can help companies to remain competitive in the market, it is still a business venture.

Engineering judgment is the process of analyzing all available technical and economical data. After all assessments have been done and reviewed, the engineer will use their best judgment to select the product to reverse engineer. The decision is then made to see if the product is or is not going to be selected for RE, in other words the “Go / No Go decision.” After the decisions are made, the question posed is if the product is feasible for RE. If the product is feasible for RE then a final selection is made of the
product based on the economic factors. But if the product is not feasible for RE, then other possibilities need to be considered, and follow the process steps again until a product is chosen with RE feasibility. This goes along with the next process which is to obtain the product to RE.

In the analysis of features shown in Figure 59a, Manufacturing Requirements was added. A “... critical manufacturing process descriptions shall be prepared to describe manufacturing processes, which are critical to meeting the design requirements of the item.” [6] This feature is significant because the product characteristics and specifications should be known in terms of manufacturing and cost estimation to RE any product.

An additional change to the process was made in the features section. The double lines represents that more than one process can be done simultaneously. For example, while one group within a company is working on the electrical feature of the product another group could be working on the material property. Also, instead of having a general critical analysis for the features, each one will have a critical analysis, validation, and design verification within the feature.

REPMES₁ that was applied to the Flashlight V2D-B is shown in Figure 31 and Figure 32 in Chapter 3. The revised and updated RE process is defined as REMPES₂, is shown below in Figure 59a and Figure 59b.
Figure 59a REPMES$_2$ – Revised Process
Figure 59b REPMES2 – Revised process continued. REPMES 1 referred from Figure 37.
Technical Data Package

A Technical Data Package (TDP) includes a series of process steps. Figure 60 prescribes the requirements for preparing the TDP based on the REPMES sub-objective(s). A TDP provides explicit technical description for the product that is to be reverse engineered. The technical data needs to be generated in the final stage of REPMES and may include engineering drawings, functionalities, specifications, and requirements based on the sub-objectives(s).

The TDP process begins by defining the contents desired for each Feature Category, including: Design Features, Electrical Features, Mechanical Features, Material Properties, and Manufacturing Requirements. The desired TDP contents for each Feature Category should be specified during the sub-objective process earlier in the flow chart.

The physical form of the TDP may be expressed as multimedia (video and audio) content, electronic computer documents, or as printed materials. All three formats of documentation are valid and follow the same underlying process. The three formats may be combined to provide a more complete TDP. For example, some computer documents may include multimedia content for the reader to get a better prospective of the product.

The first step within the process is to write the general information of the product. This includes the purpose, specifications, various standards, etc. Following is the Bill of Materials where all components of the product are identified. A complete labeled diagram is composed after the Bill of Materials is constructed. The complete labeled diagram, or in other words an exploded view of a CAD drawing of the product, explicitly labels all components, design and mechanical features, and other important details of the product. This is only included if the sub-objective(s) requires it to be included.
An instructions manual of the product is also included in a TDP, this user guide can help any company understand the proper operating instructions of a product. The engineering drawings and associated information provide the adequate design, engineering, manufacturing, and quality assurance requirement information necessary to understand how a product functions. The “product drawings shall reflect the level of design maturity that the item has attained.” [6] A distribution statement is a declaration of a technical document to justify the extent of availability of the distribution, release, or disclosure without permission or approval.

Performance characteristics and component specifications are specific information about the product and its components: in terms of electrical, mechanical, and design features and the material properties. This will all be included in the TDP as long as it is required by the sub-objective(s).

The final step in the TDP process is to identify if manufacturing requirements are needed. If the sub-objective(s) define that the product is going to be manufactured, information for manufacture needs to be obtained. This includes manufacturing information such as: important safeguards, preservation, packaging and packing information, quality information, special tooling, and inspection information. In other words, any information that aids to duplicating the physical and performance characteristics of the original product, without additional design engineering effort to the original design activity. This is the conclusion of a Complete Technical Data Package (Figure 60).
Figure 60 Final Complete Technical Data Package
Chapter 6 Implementing Reverse Engineering Process for Mechanical Engineering System (REPMES$_2$) to Torque Converter “Ford”

Now let’s move on to the second case study: Implementing the Reverse Engineering Process for Mechanical Engineering Systems (REPMES$_2$), to a Torque Converter manufactured by Ford, Serial No. Ys7PAA1121. As explained in the abstract, a thorough understanding of how a torque converter works to expand knowledge will be achieved with this case study.

Engineers are, by necessity, innovative. There is a constant need to learn new things every day. With a simple product, an engineer can learn an infinite amount of information about the product. A given product compiles ideas from many different engineers, again, in terms of design, mechanical, electrical, manufacturing features, and the products material properties. Synergies of ideas make reverse engineering “knowledge expansion” an exponential curve of learning.

A bit of history about the torque converter, is that it was incorporated by Dynaflow transmission in 1948 and later to other automatics [51]. Just like the manual transmission cars use clutches to be able to come to a complete stop without damaging the engine, automatic transmission cars use a torque converter. Throughout this case study more information is going to be gained by learning more about the torque converter’s functionalities and features.

Within Chapter 6, it will be seen how REPMES$_2$ is implemented to the torque converter. The entire process took 804 hours to be implemented; with the objective of knowledge expansion and to reach a sub-objective of providing a technical data package that would be easily understood and could be utilized in the future. The way the
implementation of RE will be presented is in a total of 804 hours, which is the total number of hours it took to use REPMES$_2$. Table 6.0 shows the task, estimated time and location necessary to understand the functionalities of the torque converter.

### Table 6.01. Reverse engineering plan schedule and location

<table>
<thead>
<tr>
<th>Task</th>
<th>Estimate time</th>
<th>Start</th>
<th>End</th>
<th>Where</th>
</tr>
</thead>
<tbody>
<tr>
<td>Define Goals</td>
<td>11</td>
<td>07/12/06</td>
<td>07/13/06</td>
<td>RIT campus</td>
</tr>
<tr>
<td>Product Selection based on economic factors</td>
<td>10</td>
<td>07/14/06</td>
<td>07/16/06</td>
<td>RIT campus</td>
</tr>
<tr>
<td>Get the Product</td>
<td>14</td>
<td>07/17/06</td>
<td>07/19/06</td>
<td>Rochester, NY</td>
</tr>
<tr>
<td>Product Documentation and Critical Analysis for Data</td>
<td>40</td>
<td>07/19/06</td>
<td>07/26/06</td>
<td>RIT campus, Wallace Library, Internet</td>
</tr>
<tr>
<td>Design Team Selection and RE Plan</td>
<td>31</td>
<td>07/27/06</td>
<td>08/1/06</td>
<td>RIT campus</td>
</tr>
<tr>
<td>Visual Inspection</td>
<td>13</td>
<td>08/1/06</td>
<td>08/5/06</td>
<td>RIT campus</td>
</tr>
<tr>
<td>Product Functionality</td>
<td>54</td>
<td>08/5/06</td>
<td>08/18/06</td>
<td>RIT campus</td>
</tr>
<tr>
<td>Critical Analysis of features</td>
<td>453</td>
<td>08/18/06</td>
<td>12/20/06</td>
<td>RIT campus</td>
</tr>
<tr>
<td>Creating technical data package (TDP)</td>
<td>178</td>
<td>09/23/06</td>
<td>12/17/06</td>
<td>Engineering building, RIT</td>
</tr>
<tr>
<td><strong>Total (hours)</strong></td>
<td><strong>804</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6.0 Management Decision, select a product for RE and define goals

REPMES$_2$ was developed and it is now time to apply this version to an actual product. The product chosen was the torque converter because it has detailed components and intricate attributes. Since its incorporation in 1948, the torque converter has undergone many changes, especially given that different automobiles have advanced tremendously since then. Presently, there is a wider range of vehicles compared to those in the late 40’s; there are very small, fast vehicles for example the Porsche, and very large, powerful vehicles like the Hummer.

---

1 The Table 6.0 is a REPMES 1 segment of the flowchart pertaining to RE plan
The topic of the second case study of REPMES will be reverse engineering to a torque converter with a focus on knowledge expansion. The following case study, very similar to the flashlight case study, will be an example of the reverse engineering process in its entirety. The project selection sheet and economic factors will be based on the sub-objective(s) defined. Now that a topic and product have been selected, it is time to implement REPMES$_2$ to the torque converter.

The objectives of the case study are to

1. Demonstrate REPMES$_2$ on a complex mechanical device
2. Demonstrate REPMES$_2$ as a tool for knowledge expansion
3. Demonstrate REPMES$_2$ as a tool to easily understand the torque converter and to provide a technical data package that would be easily understood and that could be utilized in the future.

6.1 Product Selection based on economic factors

Now that the sub-objective(s) are defined, an analysis of the product selected and its economic factors are researched. In Chapter 5, Figure 58 shows the flowchart for product selection based on economic factors. The process begins with selecting a product for reverse engineering. Functional and economic analysis is completed after the selection of the product. A focus in risk factors, calculation of the return on investment, a full economic analysis and production unit cost estimates, is also completed. Then, engineering judgment is applied followed by the Go/No Go decision. A REPMES Project Recommendation Sheet (Figure 61) is filled out with the required information.
This sheet is to be filled out last because all of the appropriate information would have been analyzed and completed by this time.

<table>
<thead>
<tr>
<th>PROJECT SELECTION RECOMMENDATION SHEET</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOCATED: (must be filled out on cover)</td>
</tr>
<tr>
<td>DATE: 9/14/00 (for copy)</td>
</tr>
<tr>
<td>description: (to be filled in)</td>
</tr>
<tr>
<td>YSTERSALIS</td>
</tr>
<tr>
<td>COMPONENTS: FORD</td>
</tr>
<tr>
<td>MANUFACTURER: N/A</td>
</tr>
<tr>
<td>NOTE: N/A</td>
</tr>
<tr>
<td>MANUFACTURER: N/A</td>
</tr>
<tr>
<td>CARDINAL NUMBER: YSTERSALIS</td>
</tr>
<tr>
<td>TECHNICAL DATA AVAILABLE:</td>
</tr>
<tr>
<td>DETAILED DRAWINGS (SD, SD)</td>
</tr>
<tr>
<td>COMPONENT SPECIFICATION</td>
</tr>
<tr>
<td>MEDIA DIGITAL TECHNICAL DATA</td>
</tr>
<tr>
<td>RESTRICTIONS</td>
</tr>
<tr>
<td>MECHANICAL ELECTRICAL OR SIMILARITY</td>
</tr>
<tr>
<td>ECONOMIC INFORMATION</td>
</tr>
<tr>
<td>DETERMINATION OF PROJECT TYPE</td>
</tr>
<tr>
<td>Use Case: $275.00 USD</td>
</tr>
<tr>
<td>Use Case Detail: Implanted</td>
</tr>
<tr>
<td>Actual Cost: $275.00 USD</td>
</tr>
<tr>
<td>Lab Case Design: $275.00 USD</td>
</tr>
<tr>
<td>Project Cost in % of $275.00 USD</td>
</tr>
<tr>
<td>Project Return as Investment:</td>
</tr>
<tr>
<td>ECONOMIC FACTORS</td>
</tr>
<tr>
<td>DECISION OF PROJECT TYPE:</td>
</tr>
<tr>
<td>ELECTRICAL INTEGRITY</td>
</tr>
<tr>
<td>ELECTRICAL INFORMATION</td>
</tr>
<tr>
<td>MANUFACTURING DETAILS</td>
</tr>
<tr>
<td>DESIGN DETAILS: N/A</td>
</tr>
<tr>
<td>MANUFACTURING REPORT</td>
</tr>
<tr>
<td>DESIGN REPORT: N/A</td>
</tr>
<tr>
<td>ECONOMIC REPORT: N/A</td>
</tr>
<tr>
<td>COMPLETED BY Frank B. Tahara, G.</td>
</tr>
</tbody>
</table>

Figure 61 Sample project selection recommendation sheet to be used by the design team during Economic analysis. Additional details are presented in Appendix C.

Economic factors and other logistics are identified about the product and are essential in selecting a product. Sometimes, companies must evaluate the reverse engineering project cost to make a wise decision concerning the fate of a product. A reverse engineering project can be very expensive and it is necessary for the company to see if it is a feasible investment as far as time and money on a particular RE project. An example was explained in Chapter 1, when GM invested their time and money every year to purchase around forty vehicles and implement RE to understand new features and operations of those brands of vehicle.
The military specification "MIL-T-31000C" (Pg 19) shows a TDP Selection Worksheet that helps the design team obtain the objective(s) and sub-objective(s) for implementing RE to a product. The Selection Worksheet does not include an economic factor but for most companies it should be in their best interest to gain that information. The REPMES Product Selection Recommendation Sheet is a form that will help understand what the RE team receives before using RE. Within this sheet, one can determine the complexity of the project, projected costs, project type and available data, this may change throughout the RE project and preferences of the company.

There are many ways to analyze if a project is worthwhile and feasible. Functional and economic analysis is a very delicate process because even the minor details are needed to reflect a good economic analysis. The factors used to calculate if a project is worthwhile usually includes: Return on Investment (ROI), Rate of Return, Net Present Value, Benefit Cost, etc. For better explanation, REPMES2 will use the factor of ROI. Return on investment is a very popular metric because it is adaptable and simple. The ROI calculation can be tailored to suit the situation because it depends on what is to be included as returns and as costs. ROI is taking the Life Cycle Savings and subtracting the RE cost and then divide by the RE cost. Life Cycle Savings is the gain from investment of the project, and RE cost is the initial investment amount. The equation is listed below:

\[
ROI = \frac{LCS - RE \text{ cost}}{RE \text{ cost}}
\]

*Figure 62 Return on Investment (ROI) equation, taken from [39]*
Let's take General Motors once again. As stated in Chapter 1, GM invested in a large number of vehicles. For 40 vehicles and under the assumption that the average cost per vehicle of $30,000, that alone is a total of $1.2 million per year that GM is spending. Now let's add the cost of approximately 50 engineers earning an average of $70,000 per year, which totals $3.5 million dollars. Facility cost \((Y)\), electricity cost \((X)\), equipment cost \((Z)\), and any other costs for the project \((F)\), are additional costs that GM will have to invest for the project as well. For this project to be worthwhile, all of these costs need to be greater than and equal to the Life Cycle Savings \((LCS)\) as shown below.

\[ LCS \geq 1.2\, \text{MM} + 3.5\, \text{MM} + Y + X + Z + F \]

It is important to know that if the RE Cost is $10 million per year for GM and they are selling each vehicle for $20,000, they have to sell more than 500 vehicles per year of that same vehicle to recover their capital. For example, if the company has a gross margin of 10% on each vehicle sold, then they would have to sell 5,000 incremental vehicles per year to break even on their investment, or demonstrate a similar cost savings in manufacturing.

The project cost for the torque converter was calculated upon a percentage of machines used, professor’s time, design team, etc. Economic recommendation regarding the Torque Converter’s information may be found in Appendix C.
6.2 Acquire the Product(s) for Reverse Engineering

After getting in contact with many companies and researching various places, the torque converter was donated by an automotive shop, whose name will remain undisclosed. The Torque Converter obtained was manufactured by Ford, Serial No. Ys7PAA1121. Information regarding the condition of the torque converter may be found in Appendix C.

6.3 Design Team Selection

For the torque converter's case study, a multitude of personnel will be needed to form the entire reverse engineering team. The core team that was stated in Chapter 4 did not change from case study 1 to 2 to maintain a consistency in the application of the reverse engineering philosophy governing the way projects are handled. Also, one will learn that with each case study, the accumulated knowledge will not be lost from case study to case study. Other team members were added due to the complexity of the torque converter. The following table represents the design team, their descriptions and role in the RE functions.

<table>
<thead>
<tr>
<th>Core Team</th>
<th>Description</th>
<th>REPMES Function(s)</th>
</tr>
</thead>
</table>
| Dr. Edward Hensel        | • Professor at Rochester Institute of Technology  
                          • Degree(s): Ph.D., New Mexico State University    | Validation and Process Management   |
| Dr. Marcos Esterman      | • Assistant Professor at Rochester Institute of Technology  
                          • Degree(s): MS: MIT, Ph.D.: Stanford University  
                          • Specialization(s): Product Development & Design Robustness | Process and Identification Management |
| Dr. Elizabeth DeBartolo  | • Associate Professor at Rochester Institute of Technology                  | Material Science and Properties     |
6.4 Reverse Engineering Plan

A reverse engineering plan is created to make sure that the main objective is accomplished. An example of a plan would be similar to the one explained above in Table 6.0. There are many ways to create a plan: for example mark a calendar, create a timeline with various computational tools, etc. For REPMES2 what was used was a timeline table which is explained in detail in Table 6.0.
6.5 Get Product Documentation

A thorough history of the common “Torque Converter” is presented in the book, “The Motor Vehicle,” 12th edition by Newton, K. W. Steeds, and T K Garrett [48] and two websites articles “Automatic Transmissions: What Makes Them Work”, by Scott Memmer [49] and “Shifting through the years: A brief history of transmissions” by Jim Bohen [50]. All resources discuss history and background information of the torque converter. The reader is referred to these three references for a fascinating historical summary documenting the development of the torque converter and its incorporation by Danaflow transmission in 1948. The following sections discuss the torque converter’s history, documentation, and specification from extensive hours of research. Recent significant developments of the torque converter are included throughout the case study.

6.6 Product Functionality

As stated in previous chapters, there are many techniques available to establish product functionality that engineers can use to understand the system or product more efficiently. The tools used to understand the functionalities of the torque converter are the same as the ones applied to the first case study with the Flashlight V2D-B and additional tools were also used. As stated in the first case study, more information on how to use the various methods could be found in Appendix A. Since the torque converter is a more complex product than the flashlight, other tools used for this case study were system dynamic equations and event process chain diagrams. The results regarding the torque converter functionality may be found in Appendix C.
6.7 Dissect the product and understand how it operates

In this step, unlike the Flashlight V2D-B case study, it is important to note that destructive testing was conducted during teardown and dissection of the torque converter. Since no careful disassembly of the torque converter could be completed and destructive testing was performed on the torque converter, it could not be reused.

6.7.1 Inspection

As learned in Chapter 4 a visual and dimensional inspection is needed to check the overall conditions in terms of quality and functionality. To inspect the torque converter, a handsaw and electrical band saw were used to open it and check all of the internal components. When the torque converter was opened, a good amount of Automatic Transmission Fluid (ATF) leaked out, therefore indicating that the product documentation was in sync with what was found: that the torque converter functioned with fluid. Other facts that were observed when the torque converter was opened were that there were a total of four assemblies within: the impeller, the stator, the turbine, and the torque converter base. In the interest of brevity, the details as far as inspector’s questions, responses, bill of material and inspection form sheet are presented in the Appendix C.

For demonstrative purposes, an example of the visual inspection form that was completed for the torque converter is presented below in Figure 63.
### REPMES VISUAL INSPECTION WORKSHEET

(Use additional sheets for remarks. Identify item by number)

<table>
<thead>
<tr>
<th>LOCATION (include building and room number)</th>
<th>Date and time of Inspection</th>
</tr>
</thead>
<tbody>
<tr>
<td>RIT Mechanical Engineering Department</td>
<td>2/10/06 10:16 AM</td>
</tr>
</tbody>
</table>

#### EQUIPMENT IDENTIFICATION

<table>
<thead>
<tr>
<th>COMPONENTS</th>
<th>MANUFACTURER</th>
<th>MODEL (Include type, style, size, etc.)</th>
<th>SERIAL NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque converter</td>
<td>Ford</td>
<td>N/A</td>
<td>Y57PAA1121</td>
</tr>
</tbody>
</table>

#### VISUAL INSPECTION OF EQUIPMENT

**ITEM FOR VISUAL INSPECTION**

<table>
<thead>
<tr>
<th>Product have an excellent physical appearance</th>
<th><strong>Answer or Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="#" alt="Yes" /> <img src="#" alt="No" /></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Is functioning properly</th>
<th><strong>Could not be tested</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="#" alt="Yes" /> <img src="#" alt="No" /></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Does it match the product documentation</th>
<th><strong>Answer or Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="#" alt="Yes" /> <img src="#" alt="No" /></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Is the product corroded</th>
<th><strong>Answer or Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="#" alt="Yes" /> <img src="#" alt="No" /></td>
<td></td>
</tr>
</tbody>
</table>

**COMPONENTS FOR VISUAL INSPECTION**

(Are the following in good condition?)

<table>
<thead>
<tr>
<th><strong>Answer or Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Scratch marks</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>The impeller</th>
<th><strong>Scratch marks</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="#" alt="Yes" /> <img src="#" alt="No" /></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>The turbine</th>
<th><strong>Some minor bendings</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="#" alt="Yes" /> <img src="#" alt="No" /></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>The stator</th>
<th><strong>Some minor bendings</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="#" alt="Yes" /> <img src="#" alt="No" /></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Torque converter clutch</th>
<th><strong>Some minor bendings</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="#" alt="Yes" /> <img src="#" alt="No" /></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Turbine hub</th>
<th><strong>Some minor bendings</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="#" alt="Yes" /> <img src="#" alt="No" /></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Torque converter base</th>
<th><strong>Some minor bendings</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="#" alt="Yes" /> <img src="#" alt="No" /></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stator one way clutch</th>
<th><strong>Some minor bendings</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="#" alt="Yes" /> <img src="#" alt="No" /></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ring bearings</th>
<th><strong>Some minor bendings</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="#" alt="Yes" /> <img src="#" alt="No" /></td>
<td></td>
</tr>
</tbody>
</table>

Additional Information:

A small metal piece was attached for rotational stability

**INSPECTED BY (Type or print name)**

Frank G. Tamagawa, C.  

**SIGNATURE**

---

Figure 63 Example inspection form for the Torque Converter

The REPMES inspection form for the torque converter asks a few questions about the product, conditions of the product, and if it was properly received, this includes if the product received matches with the documentation. This form will be given to the design team, and at this point and also depending on the answers given, the team will know what parts to change or buy to obtain a maximum result for understanding the torque converter.
6.8 Design feature

As explained in Section 4.9, the design feature section constitutes the most important part of reverse engineering of a mechanical and electrical component based on the military specification MIL-T-31000C. Based on the objective and sub-objective for design feature, a mathematical model is needed. The first step is to create a design feature model; this will be mathematical and graphical, with its associated features. Graphical information included is 2D or a 3D type drawing. Next, because the torque converter is a complex device with special geometrical shapes and also simple and complex surfaces, it is known that computational tools are needed. To determine the type of computer aid needed, the design team decided that all of the parts of the torque converter could be easily duplicated as CAD drawings therefore it was determined by the design team to use the CAD program Pro-E Wildfire. Finally, a solid model of the torque converter was created using the program. As stated previously, all technical descriptions will be based on MIL-DTL-31000C. The below drawing (Figure 64) is an example of a technical 2D drawing description of the Impeller Case and shows all dimensional specifications. The torque converter's complete drawing package may be found in Appendix C. Some parts of the torque converter may have two or three drawings due to its complexity; therefore the part is shown at different views.
6.9 Technical Implementation (Design feature)

As introduced in Chapter 3, technical implementation is a process that depends on the sub-objective(s). First, technical implementation starts with defining a field set operation. Field set operation emphasizes on metals, their structures, what they are composed of, properties, design detail, electrical characteristics and application. The interrelation of properties, structure, processing, and performance for non-metallic materials was studied. Also, as explained before, the technical implementation is divided into two procedures: Destructive and Non-Destructive. For the design feature no destructive testing was needed. All of this information and analysis of the technical implementation regarding the torque converter is presented in Appendix C.
6.10 Critical analysis of torque converter (Design Feature)

![Torque Converter](image)

**Figure 65 Vehicle display of location for Torque Converter**

One of the most important design features of the torque converter is that for an automatic transmission it takes the place of the clutch found in any manual shift vehicle. It allows the engine to continue running when the vehicle comes to a stop. As shown in Figure 65, the torque converter is located between the engine and transmission and is filled with Automatic Transmission Fluid (ATF). "A torque converter uses fluid to smoothly transfer engine torque to the transmission." [51] The torque converter is a type of fluid coupling that connects the engines crankshaft to the transmissions input shaft. [52] The torque converter allows some slippage between the engine and the transmission, "so that the engine will remain running when the vehicle is stopped while it is in gear. The torque converter also multiplies torque when the vehicle is under load to improve performance." [53]
The torque converter is a doughnut-shaped component and has three main parts: the impeller, the turbine, and the stator. Each of these has blades that are curved to increase torque converter efficiency.

**Impeller**

Figure 66 3D model of the Torque Converter

Figure 67 Actual picture of the torque converter Impeller showing the guide rings and its fins
The impeller is the drive member of the unit and its fins are attached directly to the converter cover. Therefore, the impeller is the input device for the converter and always rotates at engine speed.

The impeller has 31 fins adequately positioned to allow the fluid to impel. The fins are positioned on the impeller hub, and it is stabilized with the help of the guide ring. The fins have a total of five membranes: two are attached to the guide ring and the other three are attached to the impeller. The guide ring serves two main purposes, one is to stabilize the fins and the second is to help the fluid flow smoothly. The guide ring and fins are displayed in Figure 67 above.

Figure 68 shows a quick display of Newton’s Second Law applied to the torque converter system and the equations demonstrate the relationship between members mathematically. For the sake of this case study, the complete design feature analyses and research of each part was conducted and are presented in Appendix C.

Figure 68 – Mathematical equations of three components of the torque converter
6.11 Electrical Feature

Unfortunately, no electrical feature for the torque converter was conduct due to the fact that the torque converter is a full mechanical device that does not possess any electrical characteristics. For more detail refer to design and mechanical features of the torque converter, in the following sections.

6.12 Mechanical Feature

As explained in Chapter 3, the difference between mechanical feature and design feature is that mechanical feature is associated with the interaction of two components, for example the torque converter's stator has mechanical features. Things roll better than they slide, for example one of the functions of the stator is to act as a bearing between the impeller and turbine. The stator is like one big bearing that rotates in one direction. It has friction eliminating plates to eliminate friction between the impeller and the stator clutch. The stator has a clutch protector for the one-way clutch to contain the stator blades, spares, springs and guide rings as shown in Figure 69 and also allows the rotation of the stator. In the absence of a stator in a torque converter, the torque converter would be more difficult to rotate and to translate the rotation into output efficiency. The reason is because when parts slide, the frictional force is higher than when parts or surfaces roll. Since the stator acts as a rolling device in the torque converter, the frictional force is greatly reduced. Additional mechanical details are presented in Appendix C.
Friction eliminating plate

One-way clutch

Clutch protector plate

Spares

Figure 69 Stators three components

6.13 Critical Analysis (Mechanical Feature)

Figure 70 Exploded view of the Torque Converter that shows all parts and components

Figure 70 displays the solid model design of the torque converter in exploded view using Pro Engineering Wildfire 2.0. It shows the impeller, the stator, the turbine and the converter clutch. As shown in Figure 71, the impeller is controlled by the engine and thrusts fluid flow against the turbine blades, forcing them to rotate and
drive the transmission’s input shaft. Between the impeller and the turbine, the stator is located, and returns fluid from the turbine to the impeller, so that there could be repetition in the cycle. Each component in the torque converter was modeled as a solid model, and then assembled using the Pro-E package. More 3D models are presented in Appendix C.

![Fluid flows in the torque converter](image)

Figure 71 Fluid flows in the torque converter

### 6.14 Material Properties

The material composition of the torque converter varies with the different parts the torque converter is composed of. Various experiments were conducted to test what type of material the torque converter is since material specifications were not given at the time when the inspection form was completed.
The Rockwell and Brinell hardness tests, the Metallography test and the analysis of volume fraction by image were the various material testing experiments that were performed for steel material. The experiments were performed on the turbine and the impeller. Specifically, the tests were done to one of the turbine blades and to the case of the impeller. All results of the material property analysis regarding the torque converter are presented in Appendix C. It must be remembered that the materials analyses and tools used for the torque converter material property investigation are based on the earlier hypothesis (from the visual inspection) that the material is steel due to its magnetic characteristic. Often, the visual inspection and preliminary critical analysis will help to guide which tools should be used for the material property investigation. For example, if the visual inspection suggested that the casing was made of plastic, then different materials test would be performed.

6.15 Critical analysis (Material Property)

Two steel rods, one 4340 alloy steel and one 1045 carbon steel will be tested to narrow down the option of what carbon content steel the impeller is composed of, therefore a Jominy Hardenability test will be used. The goal of this experiment is to determine the hardenability curve for the two steels that are going to be used. First, the steel 4340 and 1045 need to be heated above the austenizing temperature, due to that the critical analysis is simulating the torque converter under its normal conditions. After an hour being heated, the two specimens were removed and end-quenched to provide a cooling gradient. The specimens were then dried and the Rockwell hardness test was performed along the cooled specimens. The next step is to compare the hardenability
curve obtained from the experiment results with published hardenability curves. After that is accomplished, microscopic grain structure were taken and examined of the Jominy end quench. The graph below displays the Rockwell Hardness versus the distance starting from the quenched up to the cooled end of the specimens. A part of the torque converter was taken and also quenched along with the other two rods and then Rockwell hardness test was performed at each given distance.

![Distance vs. Hardness Graph](image)

**Figure 72 Distance versus Hardness Graph for Torque Converter’s impeller case**

The graph in Figure 73 is a published hardenability curve for alloy steel and carbon steel.
Comparing the two graphs, it shows that the impellers hardenability is closer to that of the carbon steel specimen. A table with the results of the chemical composition of plain carbon steel and an alloy steel and with other useful information is covered in Appendix C.

6.16 Technical Data Package for the Torque Converter “Ford”

The complete technical data package (TDP) for the torque converter case study is presented as video multimedia and report form in Appendix C. The purpose of a Technical Data Package (TDP) is to provide a technical description of the object undergoing reverse engineering (in this case study, the Torque Converter “Ford”) that would be easily understood and could be utilized in the future. This interactive Multimedia TDP helps engineers understand how it functions, provide ideas of how to manufacture it, make recommendations for redesign to improve the torque converter and
to easily teach other engineers/students to understand how the torque converter works in just 12 minutes. As explained in the previous case study, the contents of the TDP vary depending on the objective of the reverse engineering project. For example, if what’s desired is to manufacture thousands of artifacts based on the reverse engineering objectives of the specimen, then complete manufacturing drawings are required. If the intent of the project is to upgrade and modernize a subsystem (such as an electronic board) within a large integrated system (such as an aircraft unit), then interface specifications may be sufficient for the TDP. The US military specification MIL-DTL-31000C (approved for use by all departments and agencies of the Department of Defense) provides an outline for defining the contents of a technical data package. According to this MIL-DTL-31000C, the TDP presented for the Torque Converter will be divided into a multimedia video CD that explains how the torque converter works in just 12 minutes and a TDP that is included in Appendix C. Similar to Appendix B, this case study would be categorized as a 2D type TDP, which will contain 4 TDP elements and 2 TDP data management products. The level of detail needed in the TDP varies greatly depending on the REPMES application objectives, which may vary from knowledge expansion to become better engineers to a competitive benchmarking to remain competitive in the market. The TDP in this case study does not include financial, management, or contract administrative data.

The TDP for the Torque Converter case study presented in Appendix C consists of the following elements:

C.i Title Page

C.ii Executive Summary

C.iii Reverse Engineering Objectives and Statement of Work
1. Introduction
2. Economic factors
3. Product Dissection and Inspection Report
   a. Product inspection
   b. Gathering Basic information
   c. Mass of the torque converter components
   d. Photographic Bill of Materials
4. Torque Converter Functionality
   a. Event process chain diagram
   b. Identifying the root cause using the Five Whys
   c. FAST Diagram Method for the Torque Converter
   d. Function Tree for the Torque Converter
   e. Black Box analysis for the Torque Converter
5. Design Features Analysis
   a. Mathematical modeling of the Torque Converter and Fluid Coupling
   b. Analyzing the torque converter in terms of fluid and clutch friction
   c. Critical analysis design feature
      i. Torque Converter Impeller
      ii. Torque Converter Turbine
      iii. Torque Converter Stator
6. Mechanical Features Analysis
   a. Torque Converter Operations
   b. Torque Converter Multiplication
7. Electrical Features Analysis
8. Materials Properties Features Analysis
   a. Rockwell Hardness test
   b. Brinell Hardness Test
   c. Metallography
   d. Research and Comparisons
   e. Analysis of volume fraction by image
   f. Critical analysis for narrowing down options
9. System Functionality Analysis
   a. Set Mode
   b. Identifying the root cause using the Five Whys
   c. FAST Diagram Method for the torque converter
   d. Function tree for the torque converter
   e. Black Box analysis for the torque converter

10. Final Technical Data Package for the Device
    a. 3-D Solid Model of the Device
    b. 2-D Drawing Package

11. Extra information

6.17 Case Study Summary

At this point, the case study of the Torque Converter is complete. The REPMES process has been applied to the Torque Converter, at a level of detail sufficient to indicate where the REPMES process works well, and where it falls short. In the next chapter, the performance of the baseline REPMES2 process will be evaluated in the context of this case study, and suggestions will be made for revising the REPMES2.
Chapter 7  Revisions of REPMES$_2$ to Final REPMES

When implementing REPMES$_2$ to the second case study, the "Torque Converter" there were additional implementation problems encountered that added steps to the final REPMES. There were some steps that were rearranged to improve the final REPMES. For example, for knowledge expansion, the RE sub-objective should be defined before the economic factors are stated. This change is due to the fact that a purpose for RE should be defined before researching potential costs for the RE project as a whole.

Figure 74 below, Material Property, is a process that was added to the features section after Mechanical feature. It is needed to have a material property section as one of the features in the reverse engineering process to fully understand the composition of the product as a whole and if the sub-objective(s) requires doing so. Also, to RE a product, all aspects of the product should be accounted for: for example its hardness, strength, ability to withstand certain temperatures, grain structure, etc.
Depending on physical property:
Weight, color, texture, size, and density

Start of material property

Make list of assumptions

Collect specimen data

Eliminate some assumptions w/ non-destructive test

Destructive experiments

Collect material information

Research and compare w/ published data

Narrow down assumptions

Analyze best match

Generate material composition

Document

End of material property

Figure 74 – REPMES material Property Process
The material property process was specifically applied to a metal component (Torque Converter) for the sole purpose of demonstrating a general process that can be applied to any material. While the general process will remain the same, the specific tools used for the materials investigation will depend on the basic composition of the material (such as metal, plastic, ceramic, organic) and its state (such as liquid, gaseous, or solid). This material property process for reverse engineering helps completely understand what the material composition is. The process begins with stating a list of assumptions of the material in terms of its weight, color, texture, size and density. Collect specimen data as far any physical data; for example if any scratches or if it is bent, heat treated areas, etc. Next, conduct some non-destructive tests, for example for steel, holding a magnet near the material to see if it’s magnetic and for plastic material a visual inspection of areas of where welding has occurred to check for dimensions and appearance, and then eliminate some assumptions based on the non-destructive test. Then, conduct destructive tests, for example Rockwell and Brinell Hardness, Microstructure, etc. to learn more about the material and its composition for metal materials, and for other materials bending test and tensile strength and impact test. Collect all material information and research and compare the data with published data. This will help narrow down assumptions of what the material is and what is composed within the material. A full analysis is then performed for the best match of the data collected with the published data. From the best match, then generate the material composition and document all findings. This concludes the material property feature.

The final REPMES could be found in Appendix F.
Chapter 8 Conclusion

A Reverse Engineering Process for Mechanical Engineering Systems (REPMES) has been developed and presented. This reverse engineering process will aid engineers to understand how a product was made, and how it functions. The reverse engineering process can provide insight about why the original engineers made design decisions on the product.

Though there are many reverse engineering processes in industry today, none is quite like this one. Other processes focus on a particular area of a product whereas REPMES embodies a unique process which combines many reverse engineering ideas into one complete process. This process analyzes a product in terms of design, electrical, and mechanical feature, manufacturing requirements, material property and product functionalities. A critical analysis of each of the features is completed, followed by creating a Technical Data Package.

This work is important because by implementing this reverse engineering process, engineers can learn an extensive amount of information about a product. A product compiles ideas from many different engineers, and other engineers can use those ideas to improve or innovate a new product.
Chapter 9 Recommendation for Future Developments

A step toward further development in applying REMES to any product or component is to select several products; for example for a Senior Design Group to select a product and apply REMES to it and provide feedback about the process. As discussed previously, it is important to test the process to various different products to provide a solid reverse engineering flow. This will insure that a RE process could be applied to any product to fully understand its functionalities and how it could be improved. As seen from the initial REMES to the final REMES, new tools or steps can be developed from every case study applied. This leaves room for future developments to be applied to REMES, since different products function differently.

As software has increased tremendously within RE, it can also be implemented as a software program. REMES was intentionally created as a flowchart because similar to programming code, where codes are create simulated by flowcharts, the REMES process could be translated into code that help the design team understand the product and visualize it through flow chart modeling. Likewise to software programs such as Rational Rose and Imagix 4D which take source codes and create a visual framework for applications (programming), this could be taken to the mechanical level and prompt users to input information.
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Appendix A: Explanation Tools

This Appendix includes explanation tools for some of the methods used in this thesis. How to create, apply and use the House of Quality, the Ishikawa Diagram, the FAST method, and the Five Whys will be accomplished.

A.1 Steps for the creation of the “House of Quality”

The House of Quality has two main areas which make up the x and y axis of the table, the “Customer Requirements” tells us what to do, and the “Functional Requirements” tells us how to do it. The relationship between the Functional requirements and the Customer requirements is shown in center, “Relationship Matrix.” Figure A.1 displays a preliminary format of the House of Quality. Two examples of this method are shown in Appendix B and Appendix C.
The following steps are the steps to creating the House of Quality, partially taken from the book *Product Design Techniques in Reverse Engineering and new Product Development* by Kevin Otto and Kristin Wood [40].

1. Identify the Customers (Both internally and externally) - Three people were selected for create the "House of quality" for the Flashlight V2D-B.
   a. Ankur Abrol is from India and is completing a Master’s degree in Information Technology.
   b. Abraham Janne is from Colombia and is completing a Master’s degree in Information Technology.
c. Frank Tamarez is from the Dominican Republic and is completing a Master of Science in Mechanical Engineering.

The individuals selected to complete the House of Quality were chosen because they came from countries that have frequent problems with electricity and that do not utilize nuclear plants like the United States. In addition, the individuals use the flashlight for domestic use only.

2. Determine the customer Needs (or wants).

   a. With the advantage of having the customer in person, I could ask them personally what they want from a flashlight and 16 needs were gathered which are:

      i. Plastic material
      ii. Portable
      iii. Inexpensive
      iv. Look nice
      v. Illuminate far distance
      vi. Turn on fast
      vii. Compact
      viii. Easy to change bulb
      ix. Easy to maintain
      x. Easy to find and operate
      xi. Easy to handle
xii. Last longer

xiii. Water proof

xiv. Anti-shock

xv. Halogen light

xvi. Unbreakable

3. Determine the relative importance or priority of the customer needs.
   
a. Using a scale of 1-10, the customers could rank the importance of that feature on the flashlight.

4. Translate customer needs into measurable engineering (functional) requirements
   
a. Determine how the product can be changed as far as performance to better meet customer needs, for example
   
i. Ergonomic
   
ii. Weight
   
iii. Illuminates at 2 meters
   
iv. Effort to adjust
   
v. Time to change batteries
   
vi. Design level
   
vii. light intensity
   
viii. Operation time

5. Determine relationship of engineering design requirements to customer needs.
a. Indicate the relationship and the strength of the relationship between the engineering requirements and the customer needs.

6. Rank the technical difficulty of each engineering requirement. Again, from a scale of 1 – 10, comparison can be used to determine ranking.

7. Set engineering requirement targets for the product design. One can do this by comparing the requirement measurements of each of the benchmarking products and positioning the new product amongst this specification.

A.2 Determining the Root Cause: 5 Whys

The 5 Whys is a technique used in the Analyze phase of the Six Sigma DMAIC methodology. It's a great Six Sigma tool that doesn't involve data segmentation, hypothesis testing, regression or other advanced statistical tools, and in many cases can be completed without a data collection plan. [55]

By repeatedly asking the question "Why" (five is a good rule of thumb), you can peel away the layers of symptoms which can lead to the root cause of a problem. Very often the ostensible reason for a problem will lead you to another question. Although this technique is called "5 Whys," you may find that you will need to ask the question fewer or more times than five before you find the issue related to a problem. [55]
Benefits of the 5 Whys, taken from iSixSigma.com [55]

- Help identify the root cause of a problem.
- Determine the relationship between different root causes of a problem.
- One of the simplest tools; easy to complete without statistical analysis.

How to complete the 5 Whys, taken from iSixSigma.com [55]

1. Write down the specific problem. Writing the issue helps you formalize the problem and describe it completely. It also helps a team focus on the same problem.

2. Ask why the problem happens and write the answer down below the problem.

3. If the answer you just provided doesn't identify the root cause of the problem that you wrote down in step 1, ask Why again and write that answer down.

4. Loop back to step 3 until the team is in agreement that the problem's root cause is identified. Again, this may take fewer or more times than five Whys.

5. Example of the 5 Whys

Problem Statement: You are on your way home from work and your car stops in the middle of the road.

1. Why did your car stop?
   - Because it ran out of gas.

2. Why did it run out of gas?
- Because I didn't buy any gas on my way to work.

3. Why didn't you buy any gas this morning?
   - Because I didn't have any money.

4. Why didn't you have any money?
   - Because I lost it all last night in a poker game.

5. Why did you lose your money in last night's poker game?
   - Because I'm not very good at "bluffing" when I don't have a good hand.

As you can see, in the example the final Why leads the team to a statement (root cause) that the team can take action upon. It is much quicker to come up with a system that keeps the sales director updated on recent sales or teach a person to "bluff" a hand than it is to try to directly solve the stated problems above without further investigation.

A.3 FAST Method

The function analysis system technique (FAST) is used to define, analyze, and understand product functions, how the functions relate to one another, and which functions require attention to increase the product value. It is used to display functions in a logical sequence, prioritize them, and test their dependency (Figure A.2). [40]

The first step is to brainstorm all the functions the product will serve in the eyes of the customer. One needs to ask “what the product does” rather than “what the product is” to define the functions, a simple verb and noun structure should be used or a verb followed by a noun phrase. When choosing words that define a function, they should be made as broad and generic as possible, such as produce torque, generate light, and shape material. [40]
During this process, it becomes obvious that these functions have different levels of importance. Out of all of the functions, one function that is the overall product function has to be selected. The product function, again, represent the main reason that the product exist in the eyes of the customer. [40]

![Figure A.2 FAST Method, inspired by Kevin Otto and Kristin Wood [40]](image)

### A.4 How to create a precedent result diagram “Ishikawa Diagram”

The Ishikawa diagram is a graphical method for finding the most likely causes for an undesired effect. The method was first used by Kaoru Ishikawa in the 1960s. [56]

Because of its shape, it is also known as the fishbone diagram. Another name for this technique is: the cause-and-effect diagram. The fishbone diagram is a method/tool used in a root cause analysis. [56]
Ishikawa's Cause & Effect diagram ("fishbone")

Figure A.3 Ishikawa Diagram, taken from Answers.com [56]

How to make the diagram

Take a sheet of paper and draw a box on the right side of the paper. Draw a horizontal line from the left side of the box to the right. Write in the box the effect for which you want to find the causes. Starting from the horizontal line, draw four to six short diagonal lines in the direction the left upper and left lower corner of the paper. These are the main bones of the diagram. Label them with categories you know will span the whole problem space. For example, a business may use: management, manpower, machines and materials (the 4 M's). [56]

Next, start filling the diagram with causes. Put them as arrows pointing to any of the main bones of the diagram. After you feel you have named most causes, identify the most likely causes for the effect in the box on the right side. [56]
Appendix B: Reverse Engineering Report and Technical Data Package for the Rayovac Flashlight V2D-B

This appendix presents the end results of the REPMES case study from Chapter 4. At the conclusion of the REPMES process, the reverse engineering team would prepare a comprehensive TDP as their report of results. This appendix simulates that report.

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   d. Photographic Bill of Materials
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   b. Important safeguards for end users
B.4. Design Features Analysis
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      i. Customer Surveys
         Like / Dislike Assessment Method
         Questionnaire Method
      ii. Illumination
      iii. Applications
      iv. Priority of customer needs
      v. Priority of Design Level
vi.  Ergonomics
   b.  Competitive Benchmarking
      i.  Comparison Products
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B.5. Mechanical Features Analysis
B.6. Electrical Features Analysis
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B.7. Materials Properties Features Analysis
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   a.  Set Mode
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   c.  FAST Diagram Method for the Flashlight V2D-B
   d.  Function tree for the Flashlight V2D-B "Rayovac"
   e.  Black Box analysis for the Flashlight V2D-B
   a.  3-D Solid Model of the Device
   b.  2-D Drawing Package
B.10. Extra information
The technical data package and engineering reports are typically presented to management in the form of a formal technical report. Normally, the TDP report includes the names of the REPMES engineering team, the product under investigation, date of the review, and other relevant information. An example of a report cover is illustrated below in Figure B.1.

![Figure B.1 Flashlight V2D-B technical report title page](image-url)
B.ii Executive Summary

That reports will include the results and information of the analyses of the market and companies that make domestic flashlights. The report provides a detailed description of the study with the intent to improve the illumination of the Flashlight V2D-B and provide detailed information about the flashlight that will help engineers understand the illumination component and other features of the flashlight or a similar developed device. This is done to understand how other companies do it and what their customers wanted on the flashlight; this could include for example, the cost range that went from US $ 3.00 to US $7.50. The customer research conducted is used to obtain the customer needs on this specific product, “Flashlight V2D-B” and some other essential tools that use these needs and engineering specifications for engineering analysis. Also, information such as the 2D Drawing package, 3D package, bill of material and mechanical design will be discussed and included. Electrical and manufacturing features and material property that will help replicate the Flashlight V2D-B and manufacture it will be discuss and thoroughly shown. Though this report and the technical documentation focuses on the flashlight’s illumination, it will also include safeguard, usage instructions, and background information of the flashlight that will aid in the requirements of the manufacturing process of the product.
B.iii Reverse Engineering Objectives and Statement of Work

The purpose of this Technical Data Package (TDP) is to provide a technical description of the Flashlight V2D-B that helps engineers (1) understand how it functions and (2) make recommendations for redesign to improve the flashlights illumination based on the customer needs. The primary focus of this TDP is on those parts that affect the illumination of the flashlight. Of the parts that affect illumination, mechanical and electrical features and material properties will also be analyzed. This TDP does not include financial, management, or contract administrative data. This TDP will use the SI system of units.

B.1 Introduction

The V2D-B flashlight is a device that many use to for illumination. This device possesses detailed components all within a simple structure. This product, manufactured by Rayovac Corporation, includes the following features:

- A total of 14 parts including the two batteries
- A price of $3.72
- Non-Roll Feature
- Bright Pre-Focused Beam
- Uses 2 D batteries
- Unconditionally warranted for life

B.2 Product Dissection and Inspection Report

a. Product inspection

The inspector’s questions and responses are presented below, for the flashlight case study:

1) Does the sample function properly?
Yes. The flashlight illuminates properly, and came with batteries.

2) Does the product received match the technical documentation?

No technical documentation was obtained from the Rayovac Company, but the flashlight did match several documents from internet sources.

3) Define drawing requirements such as assembly and detail drawings.

The flashlight V2D-B does not require Machining Aid CAD procedures like CMM or Range Image because of its simple surface. The Pro Engineering Wildfire CAD package will be used. The majority of the parts of the flashlight are circular, however, three components are not circular but they have planar surface, which means drawings may be easily made.

b. Gathering Basic Information

1) Quantity of parts per product unit

The Flashlight V2D-B has 14 parts, this includes the two batteries. It is important to note that without batteries the flashlight components would be 12 parts. In addition, the flashlight does not work only with 1 battery so the two batteries are needed.

2) System of Dimensional Measurements

The Metric International System (SI) of Units will be use to measure any element of the flashlight.

3) Maximum, minimum and average material thicknesses - Dimensional Measurements
The maximum thickness is 0.30 centimeters, the minimum thickness 0.05 centimeters and the average thickness is 0.17 centimeters. These results do not include battery thickness.

c. **Mass of the flashlight components**

The mass of each part was measured during dissection, and tentative names and part numbers were assigned to each component at this time as well. The part number assigned during this dissection will be subsequently used during the next steps of the REPMES process. The results are presented in Table B.1, below.

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Part Name</th>
<th>Unit Mass (g)</th>
<th>Quantity</th>
<th>Extended Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Base</td>
<td>48.0</td>
<td>1</td>
<td>48.0</td>
</tr>
<tr>
<td>5</td>
<td>Bulb Cover</td>
<td>11.7</td>
<td>1</td>
<td>11.7</td>
</tr>
<tr>
<td>2</td>
<td>Spring</td>
<td>4.7</td>
<td>1</td>
<td>4.7</td>
</tr>
<tr>
<td>3</td>
<td>Bottom Pole</td>
<td>3.1</td>
<td>1</td>
<td>3.1</td>
</tr>
<tr>
<td>8</td>
<td>Bulb</td>
<td>2.6</td>
<td>1</td>
<td>2.6</td>
</tr>
<tr>
<td>1</td>
<td>Protector Washer</td>
<td>1.45</td>
<td>1</td>
<td>1.45</td>
</tr>
<tr>
<td>5</td>
<td>Light Cover</td>
<td>10.15</td>
<td>1</td>
<td>10.15</td>
</tr>
<tr>
<td>10</td>
<td>Switch</td>
<td>1.5</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>13</td>
<td>Copper Connector</td>
<td>2.2</td>
<td>1</td>
<td>2.2</td>
</tr>
<tr>
<td>4</td>
<td>Bulb Base</td>
<td>3.15</td>
<td>1</td>
<td>3.15</td>
</tr>
<tr>
<td>7</td>
<td>Convex Lens</td>
<td>3.95</td>
<td>1</td>
<td>3.95</td>
</tr>
<tr>
<td>12</td>
<td>Plastic Rub</td>
<td>4.8</td>
<td>1</td>
<td>4.8</td>
</tr>
<tr>
<td>11</td>
<td>D Cell Battery</td>
<td>98.85</td>
<td>2</td>
<td>197.7</td>
</tr>
</tbody>
</table>

d. **Photographic Bill of Materials**

Upon completing the disassembly, REPMES employs an Ishikawa Diagram to illustrate the hierarchical relationships between components, with the principal or top level being the final V2D-B Flashlight product. The Ishikawa Diagram shown in Figure

---

1 More information about how to create this diagram may be found Appendix A.
B.2 is a cause and effect diagram that can be used to illustrate how all of the parts of the flashlight are related to each other. Seven main components are combined to make the V2D-B flashlight operate. The first component is the case. This is the tube that guards the other components, including the batteries and the bulb. Next will be the contacts. This is a very thin spring or strip of metal, which is located throughout the flashlight. This metal makes the electrical connection between the batteries, the bulb and the switch. The contacts conduct electricity and complete the circuit making everything work properly. The switch activates the flow of electricity when pushed to the "ON" position. Pushing the switch to the "OFF" position interrupts the flow and the light turns off. To protect the bulb, which is a very fragile glass device, a lens is placed over the filament in a flashlight. Last but not least are the batteries. The batteries store the electricity needed to make the filament glow, thus producing the light. All of the components are shown in Table B.2.
Figure B.2 Ishikawa Diagram or "Assembly Precedence Diagram" for Flashlight Model V2D-B.
As the inspector is conducting the dissection of the product, determining each part's mass, and relationship to the other parts of the assembly, it is also convenient to create a photographic inventory of the parts list, or in other words a Bill of Materials. The photographic Bill of Materials shown in Table B.2 describes the Flashlight V2D-B in terms of its base components, and serves as a useful reference table for other engineers engaged in their reverse engineering project, to ensure that consistent terminology is used throughout the REPMES.

Table B.2 Photographic Bill of Material of the Flashlight V2D-B

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Part Name</th>
<th>Photographic Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>9, 12</td>
<td>Base and Rubber Band</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Bulb Cover</td>
<td></td>
</tr>
<tr>
<td>2, 3</td>
<td>Spring Bottom Pole and Spring Base</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Bulb</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>1</td>
<td>Protector Washer</td>
<td><img src="image1.png" alt="Protector Washer" /></td>
</tr>
<tr>
<td>5</td>
<td>Light Cover</td>
<td><img src="image2.png" alt="Light Cover" /></td>
</tr>
<tr>
<td>10, 13</td>
<td>Switch and Copper Connector</td>
<td><img src="image3.png" alt="Switch and Copper Connector" /></td>
</tr>
<tr>
<td>6</td>
<td>Bulb Base</td>
<td><img src="image4.png" alt="Bulb Base" /></td>
</tr>
<tr>
<td>7</td>
<td>Convex Lens</td>
<td><img src="image5.png" alt="Convex Lens" /></td>
</tr>
<tr>
<td>11</td>
<td>D Cell Battery</td>
<td><img src="image6.png" alt="D Cell Battery" /></td>
</tr>
</tbody>
</table>
Assignment of Names and Numbers to Parts and Subassemblies

The following figure is an exploded view of the solid model for the Flashlight V2D-B in which the use of the arrow and number feature were used, and subassemblies and parts name are assign for user and manufacturing purpose. The lists of name are detailed below with their respective number.

1. Flashlight Base (Cylindrical body)
2. 9 ridges (makes it easy to grip and easy portability)
3. Spiral spring (help keep both batteries together and conduct current)
4. Base notch (rubber band placement)
5. Rubber band hook
6. Fillet edges (non sharp corner)
7. Switch button placement area
8. Rubber band
9. Upper base slope (bulb cover reflector incline)
10. Pressure washer limit stop (helps create pressure against light cover)

11. Base-stand (help stop from rolling over and to be static on surface)

12. Threads for the light cover (tightly seals light cover)

13. Aluminum bottom pole (contact with copper (18) and steel (3))

14. Hole cutout for copper contact (22) with switch (23) at placement area (7)

15. Spring base (supported by notch (4))

16. Rubber band head (connects to rubber band hook (5))

17. Batteries (connected ‘+’ to (20) and ‘-’ to (3))

18. Copper pole (serves as weld isolator between aluminum (13) and steel (29))

19. Pressure washer (seals the light cover and the base together)

20. Bulb base (attaches bulb to reflector (28))

21. Copper strip (allows current flow from bulb to batteries)

22. Copper bulge (attach to switch (23))

23. The switch

24. Switch bulge (help move on and off position)

25. Bulb and cover reflector placement area

26. Protuberance attachment for copper bulge (22)

27. 12 ridges (makes it easy to grip)

28. Bulb-cover reflector

29. Metal alloy cover

30. Cover reflector threads

31. Aluminum plated plastic (allows a steady light beam)

32. Bulb aluminum base
33. Bulb “kpr102”

34. Convex lens (creates a focus point)

35. Light cover

36. Lens limit stop

37. 32 ridges (better grip to tighten cover)

38. Spring fastener

39. 2 plastic shaft (maintain the copper and aluminum poles static)

40. 2 small post (help keep aluminum still in switch area (7))

41. Top rim of pressure washer

42. Plastic convex mirror

B.3. Background Information “Know the flashlight”

a. Operating Instructions for the Rayovac Flashlight V2D-B

An understanding of the Flashlight V2D-B is not limited to knowing only how to turn it ON and OFF, but it’s like a car, everyone knows how to turn it ON, drive it and how to turn it OFF, but in most instances, the individual does not know how it completely functions, but nonetheless they know how to use it. The next step will explain how to assemble and operate the flashlight, and which parts attach to one another for the flashlight to operate correctly. The part numbers described below are taken from Figure B.3. For a more explicit understanding of the functionality of each part of the flashlight V2D-B refer to the functionality section below.

When assembling and using the Flashlight V2D-B, it is important to know that the batteries and cover reflector are subject to wear during normal use. Always inspect for
corroded parts. If parts are damaged, discontinue using the flashlight. Also, make sure the flashlight has 14 parts including the two batteries (base, spiral spring, light cover, bulb, convex lens, bulb-cover reflector, switch, bulb base, pressure washer, spring-bottom pole, rubber-band, copper pole and batteries). Place all the parts on a clean, dry surface to keep foreign water particles from being pulled inside the flashlight base during normal operation. Make sure the bottom aluminum pole (13) and spiral spring (3) are attached together with the spring fastener (38). The bottom aluminum pole must lie flat at the bottom of the flashlight base firmly. Set the copper pole (18) into place on switch (23). The copper pole should be in place on the bottom aluminum pole, underneath of the copper strip (21) and through the hole cutout for copper contact (14). The copper strip must have direct contact with the copper pole. If not, the charges can not move continuously through the circuit loop. Set bulb (33) and bulb-cover reflector (28) into the bulb base (20) on the bulb and cover reflector placement area (25), making sure it is securely screwed. If not, gently rock the bulb-cover reflector until completely screwed in. Set the plastic convex mirror (42) into the light cover (35), making sure it is securely seated. Screw components A and B together. Set the batteries (17) in the base on the spiral spring. Screw components C and D together. Push the ON button to start illuminating. Remember to always turn flashlight OFF after use. To change batteries remove the light cover by unscrewing it. If it does not easily removed, gently rock, twist, and retry.
b. **Important safeguards for end users**

When using an electrical flashlight, basic safety precautions should always be followed, including the following:

- Keep this documentation for manufacturing references
- Do not use AAA, AA and C household batteries
- Verify that the voltage in the two D batteries are in a range of [0.72-4.08]
- To protect against risk of corrosion and create an electrical hazard, **do not** submerge the flashlight into water
- Turn off the appliance when not in use
- **Do not** use the appliance after 1 year if it was in a damp place
- **Do not** use the appliance after 2 years if it was in a dry place
- When the flashlight is corroded, seal the top cover of the base. **Do not** throw the flashlight open into the garbage. Keep hands and other exposed skin away from the cover opening to prevent possible burns. Be sure to dispose of flashlight when it is closely sealed
- Do not use appliance for any other purpose than illuminating
- This flashlight must **not** be used in potentially dangerous locations such as flammable, explosive, chemical-laden or wet atmospheres where gasoline, paint or flammable liquids are used or stored.
- **Never** operate the flashlight with a corroded batteries
- This appliance is intended for domestic use only. Use for home/auto only.
- This appliance is equipped with a Non-Roll Feature.
- The convex lens used on this appliance was selected to pre-focus the beam.
Do not place flashlight next to the stove. This could make the batteries explode and damage the flashlight materials.

B.4. Design Analysis
a. User Needs Assessment
i. Customer Surveys

Like / Dislike Assessment Method

As explained previously, two methods were used to obtain the user needs: Like / Dislike Assessment and Importance – Questionnaire Assessment Method. The question posted for all users for the Like / Dislike Assessment Method was “This is a flashlight from Rayovac: model number V2D-B. This is a domestic flashlight and it was designed for all purposes. So, please let me know what do you think about it? What do you like/do not like about it? Any suggestions for improvement?” Four individual interviews were conducted with RIT students: an MS in Information Technology, a BS in Photojournalism, a BS in Mechanical Engineering Technology and a MS in Mechanical Integration. Figure B.4 through B.7 shows the results of a sample like/dislike survey. Each survey included general questions about flashlights and their use, as well as questions specific to the design and features of the subject flashlight. Based on the interpretation of the raw data from the four surveys, this tool yields four specific product “likes” or preferences: (1) compact, (2) bright, (3) unbreakable, and (4) cheap or low-cost. The survey results yielded two “dislikes” or shortcomings of the case study product: (1) poor focus of the light beam, and (2) its portability. The following are the results of the Like / Dislike survey based on the flashlight.
<table>
<thead>
<tr>
<th>Question</th>
<th>Customer Statement</th>
<th>Interpreted Need</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical uses</td>
<td>While hiking, camping</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power cut</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Likes</td>
<td>Size</td>
<td>Compact</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>Color</td>
<td>Bright Base</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>Durable</td>
<td>Unbreakable</td>
<td>Must</td>
</tr>
<tr>
<td></td>
<td>Affordable</td>
<td>cheap</td>
<td></td>
</tr>
<tr>
<td>Dislike</td>
<td>Small focus portability</td>
<td>Range</td>
<td>Must</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Foldable</td>
<td>Good</td>
</tr>
<tr>
<td>Suggested</td>
<td>Improve light focus</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improvements</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure B.4 Ankur Abrol like/dislike survey
<table>
<thead>
<tr>
<th>Question</th>
<th>Customer Statement</th>
<th>Interpreted Need</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical uses</td>
<td>Emergency light (Car) Hard to see/dark places (Home)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Likes</td>
<td>Compact/small Easy to operate Inexpensive</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>Dislike</td>
<td>Grip/handle Battery efficient Looks Material Far lighting ability</td>
<td>Should</td>
<td></td>
</tr>
<tr>
<td>Suggested Improvements</td>
<td>Rubber handle (easier grip) On/Off button (push instead of slide) Metal frame for durability (insulated)</td>
<td>Should</td>
<td></td>
</tr>
</tbody>
</table>

Figure B.5 Lori Rosario like/dislike survey

<table>
<thead>
<tr>
<th>Question</th>
<th>Customer Statement</th>
<th>Interpreted Need</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical uses</td>
<td>• To illuminate. • To inspect the interior or exterior of something</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>Likes</td>
<td>• Can be use in all weather conditions. • Easy handling.</td>
<td>Must.</td>
<td></td>
</tr>
<tr>
<td>Dislike</td>
<td>• Consume too much battery. • Have to change bulbs.</td>
<td>Nice.</td>
<td>Nice.</td>
</tr>
<tr>
<td>Suggested Improvements</td>
<td>• Water resistant. • Uses of diodes instead of bulbs.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure B.6 Juan M. Garcia like/dislike survey
### Customer Data: Flashlight

**Customer:** Stephanie Piro (photojournalism major)

**Interviewer(s):** 

**Address:** 

**Willing to do follow up?** 

**Currently:** 

<table>
<thead>
<tr>
<th>Question</th>
<th>Customer Statement</th>
<th>Interpreted Need</th>
<th>Importance</th>
</tr>
</thead>
</table>
| Typical use | -Emergency light in power outage  
-Walking outside at night  
-Extra light when doing repairs (e.g., fixing a computer) | -Affordable  
-Powerful illumination  
-User friendly | -Good  
-Must  
-Good |
| Likes | -Inexpensive  
-Good illumination  
-Simple to operate | -Affordable  
-Powerful illumination  
-User friendly | -Good  
-Must  
-Good |
| Dislike | -Hard to grip  
-Battery dies quickly  
-Too heavy | -Better handle  
-More battery efficient  
-Lighter | -Nice  
-Good  
-Should |
| Suggested Improvements | -Adjustable brightness  
-Comfortable handle or wrist attachment  
-Low battery warning | - | - |

**Figure B.7 Stephanie Piro like/dislike survey**

While not a comprehensive survey or data set, this simple set of interviews demonstrates how focus groups and customer interactions can be valuable tools in assessing product needs.

**Questionnaire Method**

After compiling the results of the Like/Dislike method, a questionnaire was prepared to assess the relative importance of each need identified previously. Figures B.8 through B.11 displays an example of the questionnaire method used with customers, where the importance of certain features ranged from 1 – 5. The first respondent noted that though the flashlight could come with lifetime warranty and its cost was inexpensive, it was a feature that would be nice to have but not necessary. That the flashlight could illuminate more than two meters, it is a compact size and easy portability, can be used in
all weather conditions and has a comfortable grip are all features that were judged to be critical for a flashlight, and would be required for a purchase decision. The lightweight plastic construction was determined to be desirable, but not critical for the respondents.

The second part of the questionnaire was for the respondents to classify various features of the flashlight as unique, exciting, and/or unexpected. One respondent classified that if the flashlight could illuminate more than two meters and had a comfortable grip that would classified as an exciting feature. If the flashlight could be used in all weather, that would be a unique feature, and if it comes with lifetime warranty that would be an unexpected feature.

Determining need importance
Questionnaire Method

------------------------------------------
Flashlight V2D-B Survey

Name: Lori Rosario
Major: Mechanical Engineering Technology

For each of the following criteria written below please indicate of scale of 1 to 5 how important the feature is to you. Please use the following scale.

1. Feature is undesirable. I would not consider a product with this feature.
2. Feature is not important, but I would not mind having it
3. Feature would be nice to have, but is not necessary.
4. Feature is highly desirable, but I would consider a product without it
5. Feature is critical. I would not consider a product without this feature

In the right indicate if you feel that the feature is unique, exiting, and/or unexpected

<table>
<thead>
<tr>
<th>Importance of feature on scale of 1 to 5</th>
<th>Check if feature is unique, exciting, and/or unexpected</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Flashlight V2D-B comes with lifetime Warranty</td>
<td>Unexpected</td>
</tr>
<tr>
<td>3 Cost of the flashlight V2D-B US$ 4.00 plus two 2D battery</td>
<td></td>
</tr>
<tr>
<td>3 The flashlight can illuminate more than 2 meter</td>
<td>Exciting</td>
</tr>
<tr>
<td>3 Compact size and easily portable</td>
<td></td>
</tr>
<tr>
<td>5 Flashlight V2D-B can be use in all weather</td>
<td>Unique</td>
</tr>
<tr>
<td>5 Flashlight V2D-B comfortable grip.</td>
<td>Exciting</td>
</tr>
<tr>
<td>4 Flashlight V2D-B is made of Polymeric material which makes it light in weight</td>
<td></td>
</tr>
</tbody>
</table>

Figure B.8 Lori Rosario Questionnaire method
Determining need importance
Questionnaire Method

------------------------
Flashlight V2D-B Survey

Name: Ankur Abrol
Major: IT Major

For each of the following criteria written below please indicate of scale of 1 to 5 how
important the feature is to you. Please use the following scale:

1. Feature is undesirable. I would not consider a product with this feature.
2. Feature is not important, but I would not mind having it.
3. Feature would be nice to have, but is not necessary.
4. Feature is highly desirable, but I would consider a product without it.
5. Feature is critical. I would not consider a product without this feature.

In the right indicate if you feel that the feature is unique, exciting, and/or unexpected.

<table>
<thead>
<tr>
<th>Importance of feature on scale of 1 to 5</th>
<th>Check if feature is unique, exciting, and/or unexpected</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Flashlight V2D-B comes with life time Warranty</td>
<td>u</td>
</tr>
<tr>
<td>4 Cost of the flashlight V2D-B US$ 400 plus two 2D battery</td>
<td>unex</td>
</tr>
<tr>
<td>5 The flashlight can illuminate more than 2 meter</td>
<td>unex</td>
</tr>
<tr>
<td>5 Compact size and easily portable</td>
<td></td>
</tr>
<tr>
<td>4 Flashlight V2D-B can be use in all weather</td>
<td>e</td>
</tr>
<tr>
<td>4 Flashlight V2D-B comfortable grip</td>
<td>u</td>
</tr>
<tr>
<td>3 Flashlight V2D-B is made of Polymenic material which makes it light in weight</td>
<td></td>
</tr>
</tbody>
</table>

Figure B.9 Ankur Abrol Questionnaire method
# Determining need importance

## Questionnaire Method

**Flashlight V2D-B Survey**

**Name:** Stephanie Piro  
**Major:** Photojournalism Major

For each of the following criteria written below please indicate scale of 1 to 5 how important the feature is to you. Please use the following scale.

1. Feature is undesirable. I would not consider a product with this feature.  
2. Feature is not important, but I would not mind having it.  
3. Feature would be nice to have, but is not necessary.  
4. Feature is highly desirable, but I would consider a product without it.  
5. Feature is critical. I would not consider a product without this feature.

In the right indicate if you feel that the feature is unique, exciting, and / or unexpected.

<table>
<thead>
<tr>
<th>Importance of feature on scale of 1 to 5</th>
<th>Check if feature is unique, exciting, and / or unexpected</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Flashlight V2D-B comes with lifetime Warranty</td>
<td></td>
</tr>
<tr>
<td>4 Cost of the flashlight V2D-B US$ 4.00 plus two 2D battery</td>
<td>X</td>
</tr>
<tr>
<td>3 The flashlight can illuminate more that 2 meter</td>
<td></td>
</tr>
<tr>
<td>2 Flashlight V2D-B Can be use in all weather</td>
<td></td>
</tr>
<tr>
<td>3 Flashlight V2D-B comfortable grip.</td>
<td></td>
</tr>
<tr>
<td>5 Flashlight V2D-B is made of Polymeric material which makes it light in weight</td>
<td></td>
</tr>
</tbody>
</table>

**Figure B.10 Stephanie Piro Questionnaire method**

---

# Determining need importance

## Questionnaire Method

**Flashlight V2D-B Survey**

**Name:** Juan M Garcia.  
**Major:** Mechanical System Integration.

For each of the following criteria written below please indicate scale of 1 to 5 how important the feature is to you. Please use the following scale.

1. Feature is undesirable. I would not consider a product with this feature.  
2. Feature is not important, but I would not mind having it.  
3. Feature would be nice to have, but is not necessary.  
4. Feature is highly desirable, but I would consider a product without it.  
5. Feature is critical. I would not consider a product without this feature.

In the right indicate if you feel that the feature is unique, exciting, and / or unexpected.

<table>
<thead>
<tr>
<th>Importance of feature on scale of 1 to 5</th>
<th>Check if feature is unique, exciting, and / or unexpected</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Flashlight V2D-B comes with lifetime Warranty</td>
<td>X</td>
</tr>
<tr>
<td>4 Cost of the flashlight V2D-B US$ 4.00 plus two 2D battery</td>
<td></td>
</tr>
<tr>
<td>3 The flashlight can illuminate more that 2 meter</td>
<td>X</td>
</tr>
<tr>
<td>3 Compact size and easily portable</td>
<td></td>
</tr>
<tr>
<td>5 Flashlight V2D-B Can be use in all weather</td>
<td>X</td>
</tr>
<tr>
<td>4 Flashlight V2D-B comfortable grip.</td>
<td></td>
</tr>
<tr>
<td>4 Flashlight V2D-B is made of Polymeric material which makes it light in weight</td>
<td>X</td>
</tr>
</tbody>
</table>

**Figure B.11 Juan M. Garcia Questionnaire method**
The left column of Table B.3 represents the summation value of all flashlight users ranking of importance resulting from the questionnaire method, with a maximum possible score of 20. From Table B.3, it can be concluded that the most important feature is for the flashlight to illuminate more than two meters. If this feature is not part of the flashlight, the customer will not be satisfied.

Table B.3 Summation importance of the questionnaire method

<table>
<thead>
<tr>
<th>Summation value</th>
<th>Item</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>Flashlight V2D-B comes with life time Warranty</td>
<td>6</td>
</tr>
<tr>
<td>15</td>
<td>Cost of the Flashlight V2D-B US$ 4.00 plus two 2D battery</td>
<td>5</td>
</tr>
<tr>
<td>17</td>
<td>The flashlight can illuminate more that 2 meter</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>Compact size and easily portable</td>
<td>2</td>
</tr>
<tr>
<td>16</td>
<td>Flashlight V2D-B can be use in all weather</td>
<td>2</td>
</tr>
<tr>
<td>16</td>
<td>Flashlight V2D-B comfortable grip</td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>Flashlight V2D-B is made of Polymeric material which makes it light in weight</td>
<td>6</td>
</tr>
</tbody>
</table>

Interviewing customers also constitutes for researching various survey methods, creating survey forms, preparing interview settings, looking for volunteers to interview, actual interview, gathering and interpreting information, follow up from interview, compile and record/document all survey data, etc. As mentioned previously, while these results do not constitute a comprehensive data set, this simple set of questionnaire results
demonstrates how survey data may be compiled to assess the relative importance of various product features.

ii. Illumination

The Flashlight V2D-B has a KR102 bulb, this bulb is a regular incandescent bulb that is used for any purpose. The KR102 bulb is designed to work at 2.4 Volts and 1.2 Amps and approximately 1.68 Watts. The approximation mean spherical candela is 1.3 and the filament design nation is C-2R. More importantly, the KR102 bulb has the characteristic of illumination of "16.5 Lumen." More information may be found below in the Electrical Feature analysis.

iii. Applications

The Flashlight V2D-B was made for domestic use only, which will be used in a place where a person or family spends most of their time (home) or any other comfortable place. The flashlight can be used for car emergencies but one must be aware that temperatures vary when inside/outside of the car; outside weather and use can affect the performance of the flashlight and diminish the life of the flashlight along with corrosion and deterioration.

iv. Priority of customer needs

The priority of customer needs, in terms of the need of assessment, is the priority level that may be assigned to the House of quality to compare and relate features from customer needs to engineering specifications. The order of features that were provided was arranged in random order and was obtained from both the design team and the end
users, as shown in Table B.4. This table contains 4 columns and 17 rows. The first column has the flashlight features are perceived by the design team and end users. All of the individuals were told that the purpose was to create a cheap flashlight that could satisfy the customer needs. The features that the customers desired, do not have an asterisk ("*") indicated, as shown in Table B.4. Following are three columns that have three different users and their features ranked from 1 to 10 with 10 bring the maximum (excellent) and minimum being 1 (satisfactory). Following each feature is an average of the ranking that the three users noted for each feature. After the needs are prioritized, the features with low relative importance were excluded from the House of quality.

Table B.4 Priority of customer needs

<table>
<thead>
<tr>
<th>Feature</th>
<th>Ankur Abrol</th>
<th>Abraham Janne</th>
<th>Frank Tamarez</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>*Look nice</td>
<td>5</td>
<td>4</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>*Inexpensive</td>
<td>9</td>
<td>6</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>*Portable</td>
<td>7</td>
<td>8</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Plastic material</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Illuminate far distance</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>*Turn on fast</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Compact</td>
<td>8</td>
<td>7</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>Easy to change bulb</td>
<td>9</td>
<td>5</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>*Easy to maintain</td>
<td>7</td>
<td>5</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>
v. **Priority of Design Level**

For benchmarking purposes, the design level of the Flashlight V2D-B was required along with the other domestic flashlight companies. The way the design team measured this design was by selecting the design feature defined by the team and users. Then ranked the results from 1 to 10, with 10 being the maximum (excellent) and 1 being the minimum (poor), and obtained the sum of the rankings from the user’s responses. This information is displayed in Table B.5 below.

<table>
<thead>
<tr>
<th>Flashlight Metrics “Design level” Max point 10 (Excellent) and Min 1 (poor)</th>
<th>Ankur Abrol</th>
<th>Abraham Janne</th>
<th>Frank Tamarez</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Look nice</em></td>
<td>10</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td><em>Turn on fast</em></td>
<td>9</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Plastic material</td>
<td>9</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Water proof</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Anti-shock</td>
<td>7</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>Halogen light</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>42</td>
<td>36</td>
<td>44</td>
</tr>
</tbody>
</table>
Ergonomics

The ergonomics of the Flashlight V2D-B was measured in the same manner as the design level of the flashlight. It is important to note that the same users were used for the flashlight to maintain consistency in the benchmarking investigation.

Table B.6 Priority of ergonomics

<table>
<thead>
<tr>
<th>Flashlight Metrics</th>
<th>Ankur Ahrol</th>
<th>Abraham Janne</th>
<th>Frank Tamarez</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Ergonomic&quot; Max point 10 (Excellent) and Min 1 (poor)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>*Portable</td>
<td>8</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>*Turn on fast</td>
<td>9</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Compact</td>
<td>5</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Easy to change bulb</td>
<td>9</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>*Easy to maintain</td>
<td>4</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>Easy to find and operate</td>
<td>7</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Easy to handle</td>
<td>8</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>
| Total                               | 50          | 35            | 50            | **135**
b. Competitive Benchmarking

i. Comparison of Products

The information displayed in Table B.7 and Table B.8 show detailed information about the companies that manufacture domestic flashlights similar to the flashlight V2D-B.

<table>
<thead>
<tr>
<th>Company</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Eveready Industries</strong></td>
<td>“<em>Eveready Industries India Limited</em> is one of India’s most reputed FMCG companies” [<a href="http://www.evereadyindustries.com/about.shtm%5D%E2%80%9CThe">www.evereadyindustries.com/about.shtm]“The</a> company has a portfolio comprising dry cell batteries (carbon zinc batteries, rechargeable batteries and alkaline batteries), flashlights (torches) and packet tea.” [<a href="http://www.evereadyindustries.com/about.shtm%5D**Eveready">www.evereadyindustries.com/about.shtm]**Eveready</a>** is India’s largest selling brand of dry cell batteries and flashlights (torches), with dominant market shares of about 46% and 85% respectively” [<a href="http://www.evereadyindustries.com/about.shtm">www.evereadyindustries.com/about.shtm</a>]</td>
</tr>
</tbody>
</table>
| **Garrity Lites**  | “Garrity Industries is known in the flashlight industry for innovation. Blazing the path -- not following -- is the Garrity Way. The creator of the first disposable flashlight, the first rubber flashlight, the first to include batteries, and the first to use clam shell packaging, Garrity Industries has become a leading World-wide manufacturer of a broad range of disposable, refillable, and rechargeable flashlights and lanterns. While others imitate, Garrity innovates!”[www.garritylites.com/]
| **Dorcy**          | “Dorcy International, located in Columbus, Ohio, Rickenbacker foreign trade zone Dorcy is the leading manufacturer and distributor of flashlights and lanterns in the U. S. Dorcy is the fastest growing of the flashlight companies and includes Sears, Kmart, Wal-Mart, and most major retail chains as customers. Dorcy has been in the flashlight business for 35 years and is privately owned”[.www.dorcy.com/]                                                                                                                                                                                                 |
### Table B.8 Competitive product and description

<table>
<thead>
<tr>
<th>Products</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Eveready 1251 Eveready Industrial Flashlight</strong></td>
<td>Heavy-duty industrial flashlight features super-rugged, chemical-, grease- and impact-resistant polypropylene case. Enhanced with nonmoving internal and self-cleaning external switch systems. Large switches are easy to operate, even with gloved hands. Offers shatterproof K-resin lenses; ribbed, nonslip grips; nonroll barrel designs; and nonconductive hanger rings. Uses D batteries. Batteries not included.</td>
</tr>
<tr>
<td><strong>Garrity No. G500GST06H 2 D Cell Flashlight with Batteries</strong></td>
<td>You can always bring a little extra light into the dark house with a bright-shining flashlight. Soft grip handle makes for a comfortable hold. Uses 2 &quot;D&quot; cell batteries (included) Heavy-duty Soft grip handle Carry strap (included)...</td>
</tr>
<tr>
<td><strong>Dorcy 41-2380 2D Ultra Industrial Light with Batteries</strong></td>
<td>Dorcy 41-2380 2D Ultra Industrial Light with Batteries Manufactured from high quality, impact resistant materials, which make the lights virtually indestructible. Each light has a &quot;Blinking LED Light Locator&quot;. Each light will utilize and of our &quot;Snap on accessories; which is a belt clip, heavy duty magnet, and adjustable tripod. Batteries included.</td>
</tr>
</tbody>
</table>

### ii. House of Quality

Based on the information gathered from the preliminary need assessment and an extensive literature research of papers in the area, a Quality Function Deployment (QFD) matrix was developed. The QFD approach used in REPMES calls for the following seven step process: (1) identification of the customer requirements, (2) generation and ranking of a list of desired product attributes, (3) benchmarking of attributes against commercially available products, (4) development of the matrix of product attributes against engineering characteristics, (5) identifying the strength of each attribute to the corresponding engineering characteristic(s), (6) identifying the relationship between each of the engineering characteristics, and, finally, (7) setting target figures for each characteristic. The information generated through the QFD method was mapped into a House of Quality (HOQ), as shown in Table B.9.
Table B.9 - Quality Function Deployment (QFD) / House of Quality Matrix

<table>
<thead>
<tr>
<th>Customer Requirements / Needs</th>
<th>Relative Im</th>
<th>Engineering Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ergonomic</td>
</tr>
<tr>
<td>Portable</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Inexpensive</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Look Nice</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Illumination far distance</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Turn on fast</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Compact</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Easy to change bulb</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Easy to maintain</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Easy to find and operate</td>
<td>7</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measurement Units</th>
<th>Point</th>
<th>Grams</th>
<th>Lumen</th>
<th>N*m</th>
<th>Sec</th>
<th>Point</th>
<th>Candela</th>
<th>Sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Flashlight Metrics</td>
<td>128</td>
<td>290.20</td>
<td>16.50</td>
<td>None</td>
<td>45</td>
<td>122</td>
<td>1.30</td>
<td>1.05</td>
</tr>
<tr>
<td>Raw Score</td>
<td>150</td>
<td>181</td>
<td>224</td>
<td>113</td>
<td>79</td>
<td>362</td>
<td>193</td>
<td>171</td>
</tr>
<tr>
<td>Relative Weight (%)</td>
<td>10.11</td>
<td>12.20</td>
<td>15.10</td>
<td>7.62</td>
<td>6.00</td>
<td>24.41</td>
<td>13.01</td>
<td>11.53</td>
</tr>
<tr>
<td>Rank</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>7</td>
<td>8</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

Engineering Metrics Benchmark

- Eveready 1251
- Dorcy 41-2380
- Garrity No. G500GST06H

<table>
<thead>
<tr>
<th>Engineering Metrics Benchmark</th>
<th>Measurement Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eveready 1251</td>
<td>118</td>
</tr>
<tr>
<td>Dorcy 41-2380</td>
<td>135</td>
</tr>
<tr>
<td>Garrity No. G500GST06H</td>
<td>120</td>
</tr>
</tbody>
</table>

Note: The Flashlight V2D-B has a pre-focused beam; therefore there is no option to adjust.

B.5 Mechanical features analysis

For this case study of the flashlight, no mechanical features were analyzed due to the fact that it was not required by the reverse engineering objectives of the Flashlight V2D-B. The objective of the Flashlight V2D-B was to understand how the flashlight's illumination functions. The mechanical feature of a component constitutes areas of physical features in relation with any other component of the flashlight. As explained previously in Chapter 3, the model process for the mechanical feature is heat treatment, mechanical structure, failure analysis, and quality evaluation reports. The design team
included in the report and TDP of the flashlight in this appendix contains a section of extra information that will include mechanical features of those components that interact with other components, for example the base threads and the light cover attach to one another.

B.6. Electrical Features Analysis

a. Schematic diagrams

The Flashlight V2D-B contains a source of electrical energy (the dry cells Batteries [5]). It also has a bulb that changes the electrical energy into a more functional form of energy (light [2]), and a switch to control the energy delivered to the bulb [2], as shown in the figure below.

![Figure B.12 Schematic diagram of the Flashlight V2D-B](image)

When the switch of the flashlight is turned to the ON position, the bulb lights up. In fact, the lighting of the bulb occurs immediately after the flashlight is turned ON. There are no perceivable time delays between when the last connection is made and when the light bulb is perceived to light up.

The fact that the light bulb lights and remains lit is evidence that the charge is
flowing through the light bulb filament and that an electric circuit has been established. The flashlight circuit is a simple closed loop through which the charges can continuously move.

The electric circuits which are the combination of battery, light bulb and wires consist of two distinct parts: the internal circuit and the external circuit. The part of the circuit containing battery is the internal circuit. The part of the circuit where charge is moving outside the battery through the wires and the light bulb is the external circuit.

b. Circuit simulations

Due to the simplicity of the electrical circuit of the Flashlight V2D-B, no circuit simulations were made but the schematic diagram in sufficiently detailed to understand and replicate a similar flashlight.

c. Component Specification

Table B.10 includes details about the flashlight’s batteries and bulb specification, including how long the Flashlight V2D-B will last when it is in full performance. Note that another bulb feature is its tungsten filament with a resistance of 0.17 Ohms, obtain from Ohm’s Law “R=\(\frac{V}{I}\) = 0.17 OHM.”

<table>
<thead>
<tr>
<th>Table B.10 Electrical feature Flashlight V2D-B at 1 Meter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristic</td>
</tr>
<tr>
<td>---------------------------------</td>
</tr>
<tr>
<td>Ampere</td>
</tr>
<tr>
<td>Voltage</td>
</tr>
<tr>
<td>Power</td>
</tr>
<tr>
<td>Estimated time that Flashlight V2D-B will remain on</td>
</tr>
</tbody>
</table>
B.7 Material properties Features Analysis

For the flashlight case study, no material properties processes were conducted because it was not required by the reverse engineering objectives and sub-objectives. Extra information obtained in the research analysis of the material property of the Flashlight V2D-B is presented in this appendix and also in Chapter 4 in the critical analysis section.

B.8 System Functionality Analysis

As explained previously in Chapter 4, there are many techniques available to establishing system functionality that engineers can use to understand a system more efficiently. After gathering and analyzing the product documentation and selecting the design team, product functionality needs to be set, as explained in Chapter 3. The tools used to understand the functionality of the Flashlight V2D-B were the Set Mode, 5 Whys, FAST method, Function tree and Black box.

a. Set Mode

Based on the information gathered from preliminary research and extensive information investigation, the design team established that the Flashlight V2D-B has 2 modes (ON and OFF) are shown in the schematics below, Table B.11, depending of the users’ need.
In order for the Flashlight V2D-B to change from mode 1 to mode 2, it is necessary to use kinetic energy, usually this energy comes from a person's hands. This will allow the electrons to flow from one pole of the battery (-) to another (+) through an electric circuit which in this case is made of aluminum, copper, steel and tin.

b. Identifying the root cause using the Five Whys

It is already settled that the flashlight has two modes (dynamic and static), but another question that may arise is, for example what makes the flashlight go from one mode to another. The next tool used is called the Five Whys; "It's a great Six Sigma tool that doesn't involve data segmentation, hypothesis testing, regression or other advanced statistical tools, and in many cases can be completed without a data collection plan." [55]

"By repeatedly asking the question "Why" (five is a good rule of thumb), you can peel away the layers of symptoms which can lead to the root cause of a problem. Very often the ostensible reason for a problem will lead you to another question. Although this technique is called "5 Whys," you may find that you will need to ask the question fewer or more times than five before you find the issue related to a problem." [55]
**Problem Statement:** You are on your way to the bathroom from the bedroom and there is no electricity, you then turn on the flashlight to illuminate your way to the bathroom.

1. Why is it that when you turned on the flashlight, it started illuminating?
   - Because the tungsten filament of the bulb glowed

2. Why did the tungsten filament of the bulb glow?
   - Because electricity flows through it and the glow is in the form of visible light

3. Why does electricity flow through the tungsten filament?
   - Because when the switch is in the ON position, the electric circuit is in a closed loop and allows the electrons to flow from one pole of the batteries to another.

4. Why is the switch in the ON position?
   - Because people can get hurt while walking without any illumination

In this case, only four ‘Whys’ were required to figure out that a flashlight is needed when there is no light. The flashlight illuminated because the bulb has a tungsten filament that glows when electrons flow through it, as described in the problem statement.

c. **FAST Diagram Method for the Flashlight V2D-B**

The Function Analysis System Technique (FAST) is used to define, analyze, and understand product functions, how the functions relate to one another, and which functions require attention to increase the product value. It is used to display functions in a logical sequence, prioritize them, and test their dependency. [40]
The first step done by the design team was to brainstorm and identify all of the functions that the Flashlight V2D-B does when its switch is turned ON and turned OFF. Then ask “What does this product do” rather than “What is this product” to define the functions. During this process, it became obvious that some functions have different levels of importance. Out of all of the functions, the one function that was the main reason that the product exists in the eyes of the customer, was to illuminate (emit light) as shown in Figure B.13 and also identified by the Five Whys.

Once the basic function is identified, all the other functions that the flashlight performs are subordinate to the basic function. This is done to target the exact need of what the customer desires, and paying close attention to that basic function and making all other minor functions. The design team classified these secondary functions as essential and categorized them as required to the performance of the basic functions.

The FAST diagram below describes that after a person uses kinetic energy to activate the switch, two main things happen: one being the flow of electrons and the other the emission of light. While the basic functions happen, the sub-function adjacencies to the basic function also occur.
Figure B.13 FAST diagram for the Flashlight V2D-B, inspired by Kevin Otto and Kristin Wood [40]

d. Function Tree for the Flashlight V2D-B "Rayovac"

A method that was used for the flashlight by the design team was the function tree. Within the function tree method, the objectives are targets and the ultimate goal to reach. Hence, the Function Tree is a hierarchic pattern of particular sub-objects to reach the main object which in this case is to illuminate things.

This function tree is created by answering these repeated questions: "What does the Flashlight V2D-B want to accomplish?" followed by "How will it be accomplished?" The next step within the function tree (Figure B.14) includes that the functions mapped out were based from the performance measures. Other functions that were not a concern to the customer were also mapped out in the function tree.
e. **Black Box of the Flashlight V2D-B**

Once again, the design team models a product, conceptually, as a Black Box, but now with three types of inputs and outputs. A Black Box model system, as shown generically in Figure B.15, allows us to focus on the greatest, overall need for a product. It also initiates a technical understanding of a product based on its inputs and outputs, known as material, energy, and signal flow. These flow types are sufficient to describe a technical system or product.
The Flashlight V2D-B illumination system as shown below in Figure B.16, when used in darkness, provides a clear vision where lighting is needed. The Flashlight V2D-B emits light when a finger is applied with force to the switch to position it from OFF to ON. The flashlight deploys a radiate light in a spherical circle of 3 meters that brightens the object. Typically, the flashlight will illuminate depending on the battery life.
Refine function structure for the flashlight V2D-B

---

**Figure B.17 Refined function structure for the Flashlight V2D-B**

---

**B.9 Final Technical Data Package for the Device**

---

**a. 3-D Solid Model of the Device**

The following is the 3-D solid model drawings for the Flashlight V2D-B. The device is displayed in several views to show all details from top, side, and back.
Figure B.18 Back Exploded view of the Flashlight V2D-B “Rayovac”

Figure B.19 Complete Assembly - Default view of the Flashlight V2D-B “Rayovac”

Figure B.20 Complete Assembly - Top View of the Flashlight V2D-B “Rayovac”

Figure B.21 Complete Secondary Assembly - Default view of the Flashlight V2D-B “Rayovac”
Figure B.22 Complete Secondary Assembly - Default side view of the Flashlight V2D-B "Rayovac"

Figure B.23 Disassembled view of the Flashlight V2D-B "Rayovac"

Figure B.24 Complete transparent view of the Flashlight V2D-B "Rayovac"
b. 2-D Drawing Package

Based on the US military specification MIL-DTL-31000C, this 2D TDP will be sufficiently detailed to support production, engineering, and logistics support on 2D engineering drawings. This drawing will be generated in a digital form with a 3D Model.
Figure B.27 Flashlight Water Protector Washer
Figure B.28 Flashlight Bulb Base
Figure B.29 Flashlight Copper Pole
Figure B.30 Flashlight Bulb Base
Figure B.32 Flashlight Bulb “Mag 4 Cell”
Figure B.33 Flashlight Light cover
Figure B.34 Flashlight V2D-B Spring
Figure B.35 Flashlight Convex Lens
Figure B.36 Flashlight Hand Band
B.11. Extra information

There are many ways to represent technical descriptions of a component and its features. The following form is specifically sectioned into areas where specifications of the component are detailed. To better understand the components, the form is designed to provide enough space for additional information. Figure B.37 represents the form with specified numbers that are described below the form. Following the description of the form, the components of the Flashlight V2D-B are described with the form.

![Figure B.37 Component Form for the Flashlight V2D-B](image)

(1) Model number of entire product, in this case the flashlight which is V2D-B
(2) Description of part's capability.
(3) Date of project approval
(4) Person approved by
(5) Detailed description of component
(6) Related parts/features, any part that touches or is needed by given component
(7) Area for type of picture selected, Actual, 3D or 2D
(8) Classification of picture type, Actual, 3D or 2D
(9) Area for type of picture selected, Actual, 3D or 2D
(10) Classification of picture type, Actual, 3D or 2D
(11) Area for any additional information needed for better understanding of the form
(12) Each technical form should have a distribution statement. According to the Department of Defense Directive 5230.24 dated 18 March 1987 states that all documents must be assigned a distribution statement by the contributor, in this case RIT Mechanical Department.
(13) Person who obtained or drew the pictures that would be part of TDP form
(14) If drawing is to be used by third person, contractor number is needed in this area
(15) If drawing is to be used by third person, contractor name is needed in this area
(16) Area for additional technical description (mechanical or design) on how the component interacts with other components
(17) Date drew or obtained
(18) Specific component name
(19) Current design activity
(20) Part number from TDP Bill of Materials
(21) Area for additional information of second drawing
The bulb is the source of light in a flashlight. It contains a tungsten filament that glows when electricity flows through it. This glow is in the form of visible light. Tungsten is a natural element and the filament is nothing more than a very thin wire.

Tungsten (formerly wolfram) is a chemical element that has the symbol W (L. wolframanum) and atomic number 74. A very hard, heavy, steel-gray to white transition metal, tungsten is found in several ores including wolframite and scheelite and is remarkable for its robust physical properties, especially the fact that it has a higher melting point than any other non-alloy in existence.

The bulb KPR102 is a glass enclosure around the filament (Tungsten) that is filled with a low-pressure noble gas to prevent the filament from burning out due to evaporation at the high temperature.

The bulb KPR102 also contains a glass mount on the inside, which supports the filament and allows the electrical contacts to run through the bulb. One of the electrical contacts usually goes through to the bottom of the bulb, while the other goes through to the aluminum base of the bulb.

The weight of the bulb KPR102 is 2.8 g.

Bulb KPR102 Characteristics:

- Design Volts: 2.4
- Design Amps: 1.2
- Design watts: 1.65
- Approx. Mean Spherical candelas: 1.3
- Filament design nation: C-12R
- Lumen: 1.65

Mechanical Features:
- Easy to change bulb: the bulb KPR102 do not have screw threads like other bulb; when get into an appropriate bulb socket (Bulb Base), this allows the electrical current to pass through the filament.

Notes:
- The numbers of the part feature were obtained from the Chapter 3.3 "Know the flashlight V2-D-B".

---

**Figure B.38 Component Form for the Bulb of the Flashlight V2-D-B**

<table>
<thead>
<tr>
<th>Picture Type</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1] Bulb-cover reflector</td>
<td></td>
</tr>
<tr>
<td>[2] Bulb #KPR102</td>
<td></td>
</tr>
<tr>
<td>[3] Bulb Base</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Picture Type</th>
<th>3D</th>
</tr>
</thead>
<tbody>
<tr>
<td>[A] Glass bulb</td>
<td></td>
</tr>
<tr>
<td>[B] low pressure inert gas</td>
<td></td>
</tr>
<tr>
<td>[C] Tungsten filament</td>
<td></td>
</tr>
<tr>
<td>[D] glass support</td>
<td></td>
</tr>
<tr>
<td>[E] Contact wire that goes to base</td>
<td></td>
</tr>
<tr>
<td>[F] Base contact wire</td>
<td></td>
</tr>
<tr>
<td>[G] Electrical foot contact</td>
<td></td>
</tr>
<tr>
<td>[H] Support wire</td>
<td></td>
</tr>
<tr>
<td>[I] Contact wire that goes to foot</td>
<td></td>
</tr>
</tbody>
</table>

This drawing was generated from an actual solid model shown above. Changes shall be done by the design source.

**PART NO.**

<table>
<thead>
<tr>
<th>Contract Number</th>
<th>DESIGN ACTIVITY</th>
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<tr>
<td>RIT MECHANICAL DEPARTMENT. THESIS RESEARCH, &quot;A REVERSE ENGINEERING PROCESS FOR MECHANICAL ENGINEERING SYSTEMS (REPMES)&quot;</td>
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**Contractor:**

<table>
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<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frank B. Tamarez G</td>
<td></td>
</tr>
</tbody>
</table>

**Bulb #KPR102**
Figure B.39 Component Form for the Light reflectors of the Flashlight V2D-B

**Light rays reflector**

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>V2D-B</td>
<td>Light rays reflector</td>
</tr>
</tbody>
</table>

**Materials and Dimensions**

- The material of the Bulb Cover Reflector is divided into 3 components.
- The top is plastic, coated with a shiny aluminum layer and is called the reflector. This component reflects light rays from the bulb to allow a steady light beam, which is what you see coming from a flashlight.
- The cover below is made of iron and carbon (metal alloy), this makes sure that when it comes in contact with the copper pole it does not produce enough arc that they get attached together.
- The black reflector is made of Plastic of 0.3 inches in length which screws the bulb base tightly to hold the bulb firmly.
- The weight of the Bulb KPR.100 is 11.7 g.

**Mechanical features:**

- Thread Pitch = 0.0025
- Hand of the Thread right hand
- Major Diameter 0.27 inches
- Minor Diameter 0.58 inches

**Notes:**

The numbers of the part feature were obtained from the Chapter 3.3 "Know the flashlight V2D-B"

---

**Picture Type**

- Actual

---

**Components:**

1. Bulb-cover reflector
2. Bulb = KPR.100
3. Convex lens
4. Glass bulb
5. Low pressure inert gas
6. Tungsten filament
7. Glass support

---

**Contract Number:**

**Design Activity:**

RIT MECHANICAL DEPARTMENT, THESIS RESEARCH, "A REVERSE ENGINEERING PROCESS FOR MECHANICAL ENGINEERING SYSTEMS (REMEAS)."

---

**Drawing/Obtained by:**

Frank E. Tameez G

**Date:**

Unknown
The bulb base is made of plastic of 0.75 inches in height and 0.25 inches in diameter, which screws the bulb cover to hold the bulb firmly. The inner semi-circle in the bulb base (see actual picture type) holds the bulb and then connects it with the bulb cover.

At the bottom of the bulb base, there is a copper that helps the smooth flow of current to the bulb. As the base of the bulb is aluminum, it again makes sure that the arc is not so high that they get attached together when the switch is turned on.

The bulb base also has 12 slots that allow for the bulb to provide a good grip for the person when connecting it to the bulb cover.

Copper is a chemical element in the periodic table that has the symbol Cu (Latin: Cuprum) and atomic number 29. It is a ductile metal with excellent electrical conductivity and finds extensive use as an electrical conductor, as a building material, and as a component of various alloys.

The weight of the bulb base is 2.15 g.

Mechanical feature:
- Thread Pitch = 0.0625
- Hand of the Thread right hand
- Major Diameter 0.4 inches
- minor Diameter 0.29 inches

Notes:
The numbers of the part feature were obtained from the Chapter 5.1 “Know the flashlight V2D-B”

[[2] Bulb #KR102
[3] Bulb Base
[4] Battery
[5] Copper strip (allows current flow from bulb to batteries)
[6] 12 ridges (makes it easy to grip)
[7] Cover reflector placement area with crew threads
[8] Bulb placement area without crew threads

This drawing was generated from an actual solid model shown above. Changes shall be done by the design authority.
The lens is a convex lens. A convex lens is a lens that is curved outward (convex); the ends are narrow and the middle is wide. Often referred to as a converging lens.

The material used for the lens is plastic and is transparent in nature. To provide focus in the center of the lens, it is molded to bestow focus exactly on the center.

The diameter of the lens is 2.135 inches which fits correctly with the bulb cover.

The lens is molded in a way at the center that allows three lenses and help increase focus at that point as well.

The weight of the Convex lens is 3.95 g.

Notes:
The numbers of the part feature were obtained from the Chapter 3.3 "Know the Flashlight V2D-B"
[B] The Manufactured mold lines were necessary due to manufacturing process.

Images in convex mirrors are always smaller [57]
Component Form for the Flashlight base of the Flashlight V2D-B

**Flashlight Base**

- **[5]** Battery
- **[7]** Flashlight base
- **[8]** Rubber band

**Mechanical feature:**
- **A** 2 plastic shaft (maintain the copper and aluminum poles static)
- **B** Threads for the light cover (tightly seals light cover)
- **C** Pressure washer limit stop (helps create pressure against light cover)
- **D** Upper base slope (bulb cover reflector incline)
- **E** Switch button placement area
- **F** Flashlight base
- **G** Fillet edges (non sharp corner)
- **H** Base-stand (help stop from rolling over and to be static on surface)
- **I** Base notch (rubber band placement)

**Notes:**
- The numbers of the part feature were obtained from the Chapter 2.5 "Known the flashlight V2D-B"

**Table:**

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Date</th>
<th>Approved</th>
</tr>
</thead>
<tbody>
<tr>
<td>V2D-B</td>
<td>Flashlight Base</td>
<td>AGO 07 2006</td>
<td>Frank B. Tamares G</td>
</tr>
</tbody>
</table>

**Picture Type:** Actual

**Picture Type:** 3D

---

**Design Activity:**
- RIT MECHANICAL DEPARTMENT. THESIS RESEARCH "A REVERSE ENGINEERING PROCESS FOR MECHANICAL ENGINEERING SYSTEMS (REMEERS)."

**Contractor:**
- Frank B. Tamares G

**Drawing Obtained by:**
- Frank B. Tamares G

**Date:**
- Unknown
The material is aluminum which has an electrical resistivity of (20°C) 26.59 nΩm. A low resistivity indicates a material that readily allows the movement of electrons.

It has a spring to help keep both batteries together and circulate electricity.

The spring is in the form of six circles in decreasing diameters, so that when the batteries are inserted the spring compresses more in comparison to a spring that has circle of the same diameter.

The length of the aluminum has to be designed in a way that it does not fall short while connecting the top and the bottom of the battery.

The large metal helps to connect the top and the bottom through the switch metal.

The weight of Spiral spring is 4.7 g.

The weight of the Aluminum bottom pole is 3.1 g.

**Mechanical feature:**

— the use of different material like iron and carbon (metal alloy), aluminum and copper to make sure that when in contact does not produce enough arc that they get attached together.

**Notes:**

- The numbers of the part feature were obtained from the Chapter 2.3 "Know the flashlight V2D-B."
- The spring is attached to the aluminum in such a way that it gets stuck in the 10th snap which holds it steady.
- The second snap above helps to hold the bulb switch. The snap might be small but serve a great purpose.
### Light cover

The material of the Light Cover (Table 6.3, chapter 6) is ABS thermoplastic housings. It has the same property of the base.

- The head of the light has 32 holes to help provide very good grip which helps closing the lid to the base easily.
- The head also acts as a support to hold the lens so that the lens does not fall forwards.
- The length of the head is 1.35 inches which is good enough to hold the bulb cover.
- The diameter is 2.2 inches which allows bulb cover to be placed inside the light cover and then connect to the base.
- The weight of the aluminum bottom pole is 10.15 g.

#### Mechanical feature:
- **Thread Pitch:** 0.0700
- **Hand of the Thread:** Right hand
- **Major Diameter:** 8.50 inches
- **Minor Diameter:** 7.95 inches

#### Notes:
- The numbers of the part feature were obtained from the Chapter 5.3: "Know the flashlight V2D-B".

---

**Picture Type**

<table>
<thead>
<tr>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Light cover" /></td>
</tr>
<tr>
<td><img src="image" alt="Bulb" /></td>
</tr>
<tr>
<td><img src="image" alt="Convex lens" /></td>
</tr>
<tr>
<td><img src="image" alt="32 ridges" /></td>
</tr>
<tr>
<td><img src="image" alt="Lens limit stop" /></td>
</tr>
</tbody>
</table>

This drawing was generated from an actual solid model shown above. Changes shall be done by the design activity.

**PART NO.**

| 10 |

---

**Contract Number**

<table>
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**Drawing/Obtained by:**

<table>
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<tr>
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<th>Date:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unknown</td>
<td></td>
</tr>
</tbody>
</table>
The switch provides enough room for the thumb or a finger to be in place on top of it to move it forward and backward to switch on and switch off the light.

The handle provides enough support for the thumb to push the switch back and forth.

The copper attached to the switch helps connect the bottom and the top part in order for the bulb to light. The copper has an electrical resistance of \( 16.58 \, \text{m} \Omega \text{m} \).

The copper pole is designed in a way that it is not flat and a little slant ensures the proper flow of electricity.

The weight of the switch is 1.5 g.

The weight of the copper pole is 2.2 g.

**Mechanical features:**

- the use of different material like iron and carbon (metal alloy), aluminum and copper is to make sure that when get in contact does not produce enough arc that they get attached together.

**Notes:**

The numbers of the part features were obtained from the chapter 3.3 “Know the flashlight V2D-B”

---

**Table:**

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Date</th>
<th>Approved</th>
</tr>
</thead>
<tbody>
<tr>
<td>V2D-B</td>
<td>Copper pole and The switch</td>
<td>AUG 07 2006</td>
<td>Frank B. Tamaze G.</td>
</tr>
</tbody>
</table>

---

**Diagram:**

- [9] Aluminum bottom pole
- [12] Switch
- [11] Copper pole
- [A] Protuberance attachment for copper bulge
- [B] Switch bulge (help move on and off position)
- [C] Copper bulge (attach to switch)
Appendix C  Reverse Engineering Report and Technical Data Package for the Ford Torque Converter

This appendix presents the end results of the REPMES$_2$ case study from Chapter 6. At the conclusion of the REPMES$_2$ process, the reverse engineering team would prepare a comprehensive TDP as their report of results and Multimedia video that explains how the torque converter functions in just 12 minutes. This appendix simulates that report and provides information about the Multimedia TDP.

Appendix C. Table of Contents

C.i  Title Page
C.ii  Executive Summary
C.iii  Reverse Engineering Objectives and Statement of Work
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C.2.  Economic factors
C.3.  Product Dissection and Inspection Report
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  b.  Gathering Basic information
  c.  Mass of the torque converter components
  d.  Photographic Bill of Materials
C.4.  Torque Converter Functionality
  a.  Event process chain diagram
  b.  Identifying the root cause using the Five Whys
  c.  FAST Diagram Method for the Torque Converter
  d.  Function Tree for the Torque Converter
  e.  Black Box analysis for the Torque Converter
C.5.  Design Features Analysis
  a.  Mathematical modeling of the Torque Converter and Fluid Coupling
b. Analyzing the torque converter in terms of fluid and clutch friction
c. Critical analysis design feature
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c. Metallography
d. Research and Comparisons
e. Analysis of volume fraction by image
f. Critical analysis for narrowing down options

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b. Identifying the root cause using the Five Whys
c. FAST Diagram Method for the torque converter
d. Function tree for the torque converter
e. Black Box analysis for the torque converter

C.10. Final Technical Data Package for the Device
a. 3-D Solid Model of the Device
b. 2-D Drawing Package

C.11. Extra information
Title Page

The technical data package and engineering report are typically presented to management in the form of a formal technical report. Normally, the TDP report includes the names of the REPMES engineering team, the product under investigation, date of the review, and other relevant information. An example of a technical report title page is shown in Figure C.2 and an example of a TDP for the multimedia video CD cover is illustrated in Figure C.2.
C.ii Executive Summary

As explain in Appendix B, throughout history, an interest in understanding how products function has increased tremendously. This leads a company or individual groups of people to create and gather technical information of a product where in most instances it is not required to for a specific objective. Therefore all of the efforts of researching technical information translate to a waste of time and money. REPMES in this case study uses one of its objectives, “Knowledge Expansion” to define a sub-objective(s). Knowledge expansion as an objective for the torque converter focuses on the entire product, whereas it contradicts the previous case study which focused on one area of improvement for the product. Though this does not help reduce the technical information of a product immensely, this translates to analyzing the torque converter in it entire dimension based on the sub-objective.
The sub-objective(s) for the torque converter is to understand the torque converter and to provide a technical data package that would be easily understood and could be utilized in the future. As prepared in the Multimedia video TDP on a CD and as explained in the abstract, a thorough understanding of how a torque converter works to expand knowledge was achieved with this case study. The following report, technical data, and Multimedia TDP results use these criteria to conduct a detailed description of the study with the intent to understand the Torque Converter manufactured by Ford, Serial No. Ys7PAA1121 and provide detailed information about the torque converter that will help engineers understand how its components work and other features of the torque converter or a similar developed device.

As mentioned above, the design team documented and created a TDP multimedia CD that fully explains how a torque converter functions in just twelve minutes. This multimedia CD includes a TDP which explains the functionality of the torque converter, along with simulation of how its components interact. Animation was also used to simulate the use of a torque converter in a vehicle from start to finish. The multimedia CD is attached to this thesis.

C.iii Reverse Engineering Objectives and Statement of Work

The purpose of this Technical Data Package (TDP) and Multimedia TDP is to provide a technical description of the Torque Converter that helps engineers understand how it functions and as mentioned before, to provide a technical data package that would be easily understood and could be utilized in the future. The primary focus of the TDP should be to analyze all of the part of the torque converter.
This TDP does not include financial, management, or contract administrative data.
This TDP will use the SI system of units.

C.1.  Introduction
As introduced in Chapter 6, the torque converter was incorporated by Dynaflow transmission in 1948 and later to other automatics. Just like the manual transmission cars use clutches to be able to come to a complete stop without damaging the engine, automatic transmission cars use a torque converter. Throughout this case study more information is going to be gained by learning more about the torque converter’s functionalities and features. This reverse engineering analysis for the torque converter process took 804 hours to be implemented; with the objective of knowledge expansion and to reach a sub-objective of providing a technical data package that would be easily understood and could be utilized in the future.

C.2.  Economic factors
The project cost for the torque converter was calculated upon a percentage of machines used, professors time, design team, etc. There was restricted information on the torque converter; therefore an estimate of $12,500 is being used for the project cost of the torque converter. To avoid inaccuracies, the LCS of the torque converter is defined as not available (N/A) but it is much greater than the RE costs because according to the objective and sub-objective(s), the LCS will provide more benefits through time than the initial cost of the investment. This engineering judgment made, affects the decision to go ahead with the project or not continue with the project and look at other possibilities.
According to the recommendation sheet below, Figure C.3, this Ford Torque Converter did not have a model number available. There was no technical data available except for general information and restrictions on the torque converter. From a scale of 1 to 5, with 5 being the most complex, this product received a 5 for product complexity. The project type is for data development and knowledge expansion. According to the sheet, the design team needs to include in the TDP the mechanical feature, electrical feature, design feature, material properties, engineering drawings, usage data and any other valuable data.

Now it is time to obtain the actual product. After getting in contact with many companies and researching various places, the torque converter was donated by an automotive shop, whose name will remain disclosed. Now that the actual torque converter is obtained, let's continue with REMPES$_2$. 
**REPMES**

**PROJECT SELECTION RECOMMENDATION SHEET**

(Use additional sheet for remarks. Identify item by number)

<table>
<thead>
<tr>
<th>LOCATION (include building and room number)</th>
<th>Date and time of Inspection</th>
</tr>
</thead>
<tbody>
<tr>
<td>RIT, Mechanical Engineering Department Bldg 9</td>
<td>9/4/06 9:00 AM</td>
</tr>
</tbody>
</table>

**EQUIPMENT IDENTIFICATION**

<table>
<thead>
<tr>
<th>COMPONENTS</th>
<th>MANUFACTURER</th>
<th>MODEL (Include type, style, size, etc.)</th>
<th>SERIAL NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque converter</td>
<td>Ford</td>
<td>unknown</td>
<td>Y57PA A1121</td>
</tr>
</tbody>
</table>

**TECHNICAL DATA AVAILABLE**

- DETAILED DRAWINGS (2D, 3D): □Yes ☑No
- COMPONENT SPECIFICATION (technical manuals): □Yes ☑No
- MEDIA DIGITAL TECHNICAL DATA: □Yes ☑No
- RESTRICTIONS: ☑Yes □No Company has restricted information
- MECHANICAL, ELECTRICAL OR DESIGN DATA: □Yes ☑No
- GENERAL INFORMATION (internet or cyclopedia): ☑Yes □No

**ECONOMIC FACTORS**

- Unit Cost: $259.00 US
- Unit Cost obtained: Donated
- Annual Cost: N/A
- Life Cycle Cost: N/A
- Life Cycle Saving (LCS): N/A
- Projected Cost to RE: $12,500
- Project Return on Investment: N/A

**DETERMINATION OF PROJECT TYPE**

- Product verification: 
- Data Development: 
- Knowledge expansion: 

PRODUCT COMPLEXITY (5=COMPLEX: 1=SIMPLE)

- 5

**TECHNICAL DATA PACKAGE PROJECT LIST**

(At the end the TDP will have)

<table>
<thead>
<tr>
<th>Electrical feature:</th>
<th>☑</th>
<th>Manufacturing feature:</th>
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<tbody>
<tr>
<td>Mechanical feature:</td>
<td>☑</td>
<td>Engineering Drawing:</td>
</tr>
<tr>
<td>Design feature:</td>
<td>☑</td>
<td>Usage data:</td>
</tr>
<tr>
<td>Material property:</td>
<td>☑</td>
<td>Other data:</td>
</tr>
</tbody>
</table>

**INSPECTED BY (Type or print name)**

FRANK B. TAMAREZ G.

**SIGNATURE**

Figure C.3 Project Selection Recommendation Sheet
C.3. Product Dissection and Inspection Report

As explained in previous chapters, a visual and dimensional inspection is needed to check the overall conditions in terms of quality and functionality. To inspect the torque converter, a handsaw and an electrical band saw were used to open it and check all of the internal components. When the torque converter was opened, a good amount of ATF leaked out, therefore indicating that the product documentation was in sync with what was found: that the torque converter functioned with fluid. Other facts that were observed when the torque converter was opened were that there were a total of four assemblies within: the impeller, the stator, the turbine, and the torque converter base.

a. Product inspection

The top part of the torque converter had many blades, but after careful inspection, it was realized that those blades were from the impeller. The impeller also has a guide ring inside with the blades. There was a stator between the impeller and turbine; it was observed that there was a bearing between the stator and the impeller to avoid friction between the two. The stator has a one way clutch; hence it will only rotate in one direction which was observed when manually moving it in both directions. It has curved polymer blades and is also smaller than the impeller. The torque converter clutch and the turbine were interconnected, and could be detached. The turbine blades were larger than the impellers, but the inner guide ring was the same size. The clutch has many springs, possibly to avoid contraction shocks. The
material of the entire torque converter seems to be steel. All of the images that were discussed above of the torque converter may be found in bill of material.

The visual inspection form that was completed for the torque converter is shown below in Figure C.4.

<table>
<thead>
<tr>
<th>LOCATION (include building and room number)</th>
<th>Date and time of Inspection</th>
</tr>
</thead>
<tbody>
<tr>
<td>RIT Mechanical Engineering Department</td>
<td>2/10/06 10:16 AM</td>
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</tbody>
</table>

**EQUIPMENT IDENTIFICATION**

<table>
<thead>
<tr>
<th>COMPONENTS</th>
<th>MANUFACTURER</th>
<th>MODEL (Include type, style, size, etc.)</th>
<th>SERIAL NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque converter</td>
<td>Ford</td>
<td>N/A</td>
<td>YS7PAA1124</td>
</tr>
</tbody>
</table>

**VISUAL INSPECTION OF EQUIPMENT**

<table>
<thead>
<tr>
<th>ITEM FOR VISUAL INSPECTION</th>
<th>ANSWER OR DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product have an excellent physical appearance</td>
<td>Yes No</td>
</tr>
<tr>
<td>Is functioning properly</td>
<td>Yes No</td>
</tr>
<tr>
<td>Does it match the product documentation</td>
<td>Yes No</td>
</tr>
<tr>
<td>Is the product corroded</td>
<td>Yes No</td>
</tr>
</tbody>
</table>

**COMPONENTS FOR VISUAL INSPECTION**

(Are the following in good condition?)

<table>
<thead>
<tr>
<th>ITEM FOR VISUAL INSPECTION</th>
<th>ANSWER OR DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>The impeller</td>
<td>Yes No Scratch marks</td>
</tr>
<tr>
<td>The turbine</td>
<td>Yes No</td>
</tr>
<tr>
<td>The stator</td>
<td>Yes No</td>
</tr>
<tr>
<td>Torque converter clutch</td>
<td>Yes No</td>
</tr>
<tr>
<td>Turbine hub</td>
<td>Yes No</td>
</tr>
<tr>
<td>Torque converter base</td>
<td>Yes No Some minor bendings</td>
</tr>
<tr>
<td>Stator one way clutch</td>
<td>Yes No</td>
</tr>
<tr>
<td>Ring bearings</td>
<td>Yes No</td>
</tr>
</tbody>
</table>

Additional Information:

A small metal piece was attached for rotational stability.

INSPECTED BY (Type or print name) SIGNATURE

FRANK B. TOMAREZ 6

Figure C.4 Inspection form for the Torque Converter
b. Gathering Basic information

The torque converter has 87 parts total: 27 impeller blades, 27 turbine blades, 2 guide rings, 1 impeller case, 1 turbine case, 1 torque converter case, 1 torque converter clutch, 8 springs for torque converter clutch, 1 stator case, 1 stator bearing, 1 small guide ring for the stator, 7 sprags, 7 springs for the stator clutch, and 1 outer ring. The metrics International System of Units will be use to measure any element of the torque converter.

c. Mass of torque converter components

The following tables display the various parts of the torque converter and the corresponding weights for each and total weight.

<table>
<thead>
<tr>
<th>Part</th>
<th>Weight (kg)</th>
<th>Part</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impeller</td>
<td>3.104</td>
<td>7 Sprats</td>
<td>0.005 / each</td>
</tr>
<tr>
<td>Turbine</td>
<td>2.692</td>
<td>TC base</td>
<td>2.72</td>
</tr>
<tr>
<td>27 Impeller Blade</td>
<td>0.0142 / each</td>
<td>TC clutch</td>
<td>2.72</td>
</tr>
<tr>
<td>27 Turbine Blade</td>
<td>0.0135 / each</td>
<td>7 Sprats spring</td>
<td>0.001 / each</td>
</tr>
<tr>
<td>Bearing protection</td>
<td>0.136</td>
<td>Shaft inner ring stator-clutch</td>
<td>0.121</td>
</tr>
<tr>
<td>Bearing ring</td>
<td>0.047</td>
<td>Outer ring Stator-clutch</td>
<td>0.285</td>
</tr>
<tr>
<td>Impeller ring</td>
<td>0.143</td>
<td>Turbine ring</td>
<td>0.143</td>
</tr>
</tbody>
</table>

Table C.2 Torque converter total weight

| Total weight of the Torque Converter | 12.86 kg |

249
d. Photographic Bill of Materials

The Bill of Materials shown below in Figure C.5 describes the torque converter in terms of its assemblies, sub-assemblies, and basic parts. This basically consists of a list of parts that composes the torque converter. To represent this information, similar to the last case study, the Ishikawa Diagram was used to show hierarchical information with the principal or top level being the final product. This increasing level of detail continues for all sub-assemblies until it reaches its main part (the torque converter). The Ishikawa Diagram\(^1\) is a cause and effect diagram that can be used to illustrate how all of the parts of the torque converter are in relation to one another.

Following the diagram are pictures of the parts and corresponding part number that are indicated in the Ishikawa Diagram. The pictures are actual photos of the individual parts.

---

\(^1\) More information about how to create this diagram may be found Appendix A.
Figure C.5 Ishikawa Diagram “Assembly Precedence Diagram” for the Torque Converter
Bill of Material “Actual Pictures”

Note: The part numbers are related to the Ishikawa Diagram (Figure C.5)

Table C.3 Bill of Materials for the Torque Converter “Impeller Assembly”

<table>
<thead>
<tr>
<th>Part No.</th>
<th>Image “Impeller assembly”</th>
</tr>
</thead>
<tbody>
<tr>
<td>3, 1 and 2</td>
<td><img src="image" alt="Image of Impeller Assembly" /></td>
</tr>
</tbody>
</table>

Table C.4 Bill of Materials for the Torque Converter “Turbine Assembly”

<table>
<thead>
<tr>
<th>Part No.</th>
<th>Image “Turbine Assembly”</th>
</tr>
</thead>
<tbody>
<tr>
<td>11, 12, 13, and 14</td>
<td><img src="image" alt="Image of Turbine Assembly" /></td>
</tr>
</tbody>
</table>
### Table C.5 Bill of Materials for the Torque Converter “Stator assembly”

<table>
<thead>
<tr>
<th>Part No.</th>
<th>Image “Stator Assemble”</th>
</tr>
</thead>
<tbody>
<tr>
<td>4,5,6,7,8,9 and 10</td>
<td><img src="image" alt="Stator Assembly" /></td>
</tr>
</tbody>
</table>

### Table C.6 Bill of Materials for the Torque Converter “TC Clutch”

<table>
<thead>
<tr>
<th>Part No.</th>
<th>Image “Torque Converter Clutch”</th>
</tr>
</thead>
<tbody>
<tr>
<td>18,19 and 20</td>
<td><img src="image" alt="Torque Converter Clutch" /></td>
</tr>
</tbody>
</table>
C.4. Torque Converter Functionality

As stated in Chapters 6.6, the tools used to understand the functionalities of the torque converter are the same as the ones applied to the first case study with the Flashlight V2D-B and other tools were also used. As stated in the first case study, more information on how to use the various methods will be found in Appendix A. Also, other tools used for this case study were system dynamics equation and event process chain diagram.

a. Event process chain diagram

The event process chain diagram is widely used for analyzing business processes. As stated previously, Kim used this process for analyzing a system of a hospital visit. [16] REMPES$_2$ will use this same tool to explain the different stages of a torque converter. As shown by Figure C.6, there are two stages for the torque converter: Rest and Moving.

The circular shape represents an Event (E), the rectangles represent a Process (P), and the diamond shape represents a Decision (D). The torque converter begins
from rest and then the engine starts running. The torque converter then starts rotating and moves into the “Moving” stage where acceleration is applied. When the torque converter rotates above stall speed, it begins transmitting torque which is applied to the wheel, which indicates that the turbine is rotating. If more acceleration is applied, and one wants to continue with more velocity, the torque converter will reach a point of cruising speed, which indicates that the impeller and the turbine are at approximately the same speed. The process can be continuous if after the vehicle is in cruising speed and then decides to decelerate, it can either continue to decelerate or accelerate and keep it as a repetitive process. If after more acceleration is applied, and then one wants to decelerate, then the torque converter will free wheel, which will rotate at stall speed and eventually the event will end.

![Event process chain diagram for the torque converter](image)

**Figure C.6** Event process chain diagram for the torque converter

b. **Identifying the root cause using the Five Whys**

It is already settled that the torque converter has two modes (rest and moving), but another question that may arise is, for example, what makes the torque converter...
transfer engine torque to the wheels. The next tool that is going to be applied to the understanding of the torque converter is the Five Whys. Again, as explained in Chapter 4.4, the Five Whys is “...a great six Sigma tool that doesn’t involve data segmentation, hypothesis testing, regression or other advanced statistical tools, and in many cases can be completed without a data collection plan.” [55]

**Problem statement:** Suppose you have always driven standard shift vehicles. And now you are driving an automatic vehicle, you wonder what the connection is between the engine and the wheels.

1. Why does the vehicle run, without a manual clutch?
   - Because in automatic vehicles, there is a torque converter that takes the place of the clutch, and is run by automatic transmission fluid (ATF)

2. Why is it that when the vehicle accelerates, the car moves forward?
   - Because the torque converter’s turbine is rotating in a clockwise direction and it is connected to the transmission shaft, and the shaft is connect to the wheels, which makes the car move

3. Why does the turbine rotate clockwise?
   - Because the ATF is thrown by the torque converter’s impeller in a clockwise direction and hits the turbine

4. Why is the impeller moving at a clockwise direction?
   - Because it is connected to the engine, and the engine is rotating in a clockwise direction

In this case, only four “Whys” were needed to answer the problem statement of how is there a connection between the wheels and the engine on the automatic
vehicle. The connection exist because when the engine rotates, it makes the torque converter’s impeller rotate and throw off ATF to the torque converter’s turbine which is connected to the transmission shaft, and the shaft is connected to the wheel. Therefore as the turbine rotates, the wheels rotate as well.

c. FAST Diagram Method for the Torque Converter

The Function Analysis System Technique (FAST) method, as mentioned in Chapter 4.4, is used to define, analyze, and understand product functions, how the functions relate to one another, and which functions require attention to increase the product value. It is used to display functions in a logical sequence, prioritize them, and test their dependency.

Now that the event process chain diagram and the five whys are complete, the FAST method is going to be applied to the torque converter. This diagram can be seen below in Figure C.7. The torque converter has nine primary steps and outside of the boundaries there are four basic functions. The basic function or main purpose of this product is to transmit engine torque to the wheels. All the functions located to the right of the basic function depict the conceptual approach selected to satisfy that main purpose.

The FAST diagram could be looked at from left to right or from right to left. The question ‘How’ is expressed on the left side and if read from left to right then ‘How’ is applied to every step until a conceptual understanding of the torque converter is achieved. On the right side of the diagram the question ‘Why’ is posed and should be applied if read from right to left. ‘Why’ is posed throughout the diagram from right to left until a conceptual understanding of the functions of the
torque converter is achieved. Both sides are separated by dotted lines that indicate boundaries.

The FAST diagram was created under the following conditions: the torque converter is running above stall speed, the car is moving forward, it is not expected to expand due to heat produced by friction, and that the car is at cruising speed. The primary steps are the main steps that are needed in order for the torque converter to efficiently transfer engine torque to the wheels. The other steps are all secondary steps for this process. The blocks that are not connected to the entire flow are simply comments about that chain of steps. The red line indicates fluid leaving the torque converter.

Now, let's explain the primary functions going from left to right. In order for the clutch to engage, the turbine must rotate. For the turbine to rotate, the impeller must throw off ATF to the turbine. Also, in order for the impeller to rotate, the engine must also be rotating. Looking at the diagram from right to left, it is concluded that there are three primary steps that lie on the outside boundary: engine torque, transmission oil pump and the oil cooler. As stated before, the engine rotating causes the impeller to rotate. The transmission oil pump provides fluid through the impeller vanes causing the turbine to rotate. At the same time, the turbine throws off ATF to the oil cooler and resends it through the transmission oil pump safely.
When the clutch engages, it is caused by centrifugal force making the entire clutch to contract. The clutch has springs that cause the contractions to repel, all of these interactions cause heat by friction. Frictional heat translates to a lost of energy. When the turbine rotates, since it's attached to the transmission shaft, the shaft will rotate as well. Simultaneously, the turbine redirects fluid to the stator and throws off fluid to the cooler to be cooled. When a load is incremented, caused by road friction and the car's weight, the turbine is the one affected. As fluid flows from the turbine and the impeller, there is a heat caused by friction that will as stated before, translates.
into a lost of energy. The impeller is the drive member of the system, and it redirects the fluid from the stator and the transmission oil pump to the turbine. The stator redirects the fluid received from the turbine, in one direction due to the one way clutch attached to it, which makes the entire stator a torque multiplicator. The torque multiplication prevents a torque loss and eliminates rotation of flow.

d. Function tree for the Torque Converter

Based on other tools used to understand the functionalities of the torque converter, a function tree was created. Figure C.8 displays the function tree created for the torque converter in hierarchic fashion, with the main objective at the top which is to transfer engine torque to the wheels. Following the main purpose is what steps lead up to it. The following steps are that the clutch engages, the turbine starts rotating, and fluid friction is thrown off by the impeller. As shown in the function tree, the engine torque causes centrifugal force and the oil cooler sends fluid back to the transmission oil pump, and both lead up to automatic transmission fluid frictions thrown off by the impeller. The function tree starts from the bottom and follows the steps up to the main purpose, which is as stated before to transfer engine torque to the wheels.
Transfer engine torque to wheels

- Clutch engaged
  - Turbine rotating
    - ATF frictions thrown off by impeller
      - Centrifugal force
        - Engine torque
      - Transmission oil pump
        - Oil cooler

Figure C.8 Function Tree for the torque converter

**e. Black Box analysis for the Torque Converter**

With the information gained from the various techniques of the torque converter’s functionalities, it was much easier to create a Black Box of the torque converter. The Black Box is displayed by Figure C.9, and as shown there are three main elements to the Black Box: material, energy, and information. The same conditions that were described in the FAST method will also be applied to this method. The energy that enters the system is engine torque, the material is Automatic Transmission Fluid (ATF), followed by the information that the torque converter will rotate will rotate above stall speed.
The elements that exit the system in terms of energy, material, and information are sound, kinetic energy and heat as energy, ATF as material, and the information is the wheels rotating. Basically, the Black Box is composed of the same events that were explained in the FAST method diagram and all of the tools used above. In terms of energy, the system begins with applying engine torque to make the impeller rotate. This motion then translates to a centrifugal force that throws off the material received (ATF) to the turbine, causing it to rotate. As shown above, both the energy and material cause the clutch to engage. Then the engine torque is transferred to the wheel. The stator multiples torque and redirects fluid to the impeller. More torque is then transferred to the turbine by the impeller, and finally the system ends when the engine motion comes to a stop.
C.5. Design Features Analysis

a. Mathematical modeling of the Torque Converter and Fluid Coupling

In this section, mathematical models of the torque converter (TC) will be obtained. With mathematical models, the design team will understand the torque converter’s dynamic models that extends to its functionality and help investigate the TC in the following aspects: (1) the dynamic of the TC in cruising speed, (2) the influence of torque from the engine and the transmission shaft connected to the wheel, (3) repeatedly conduct test to obtain information about TC reactions under certain conditions, (4) possible TC re-design. The model of the system, as shown in Figure C.10, “Torque Converter” has some operation restrictions that were defined. These restrictions are as follows: (i) the TC is moving in one direction, (ii) the TC is running above stall speed, (iii) the TC is operating in normal conditions, (iv) frictional heat does not expand the TC, (v) stiffness of the transmission shaft is infinite - there is neither backlash nor elastic deformation, (vi) the number of blades of each member is proportional to the radius of the member.
The graphic shown below (Figure C.11) demonstrates the torque converter in a dynamic system with its three principle components. The driving element (impeller) which is connected to the engine, the driven element (turbine) which is connected to the propeller shaft, and the reaction member (stator) which allows change in torque between the input and output members are what make up the torque converter. More information may be obtained above in Section 6.6 Critical Analysis of the Torque Converter.
Figure C.12 shows a quick display of Newton’s Second Law applied to the torque converter system. The equations demonstrate the relationship between members mathematically. For this system, the following three equations were obtained:

**Impeller**

\[ I_i \dot{w}_1 + B_1(w_1 - w_2) + B_3(w_1 - w_3) - T_{Eng} = 0 \]

Solving for \( \dot{w}_1 \)

\[ \dot{w}_1 = \frac{1}{I_1} \left[ B_1(w_2 - w_1) + B_3(w_3 - w_1) + T_{Eng} \right] \]

**Turbine**

\[ I_j \dot{w}_2 + B_2(w_2 - w_3) + B_1(w_3 - w_1) - T_{Load} = 0 \]

Solving for \( \dot{w}_2 \)

\[ \dot{w}_2 = \frac{1}{I_2} \left[ B_1(w_1 - w_2) + B_2(w_3 - w_2) + T_{Load} \right] \]

**Stator**

\[ I_k \dot{w}_3 + B_3(w_3 - w_1) + B_2(w_3 - w_2) - T_{Stator} = 0 \]

Solving for \( \dot{w}_3 \)

\[ \dot{w}_3 = \frac{1}{I_3} \left[ B_3(w_1 - w_3) + B_2(w_2 - w_3) + T_{Stator} \right] \]

Figure C.12 Three components equation for the torque converter

where

\[ I_i = \text{Mechanical polar moment of inertia} \text{* (kg} \cdot \text{m}^2) \]
\[ w_k = \text{Angular Velocity} \text{* (rad} \cdot \text{s}^{-1}) \]
\[ B_j = \text{Viscous friction} \text{* (kg} \cdot \text{m}^2/\text{s}) \]
\[ B_i = \text{Viscous and clutch friction shown in Figure C.13 (below)} \text{* (kg} \cdot \text{m}^2/\text{s}) \]
\[ T_{Eng} = \text{Torque developed by the engine} (\text{N} \cdot \text{m}) \]
\[ T_{Load} = \text{Torque transmitted to the wheel} (\text{N} \cdot \text{m}) \]
\[ T_{Stator} = \text{Torque transmitted to transmission shaft} (\text{N} \cdot \text{m}) \]

* where \( i = 1 = \text{Impeller} \rightarrow \text{Turbine} \)
  \( j = 2 = \text{Turbine} \rightarrow \text{Stator} \)
  \( 3 = \text{Stator} \rightarrow \text{Impeller} \)
  \( k = 1 = \text{Impeller} \)
  \( 2 = \text{Turbine} \)
  \( 3 = \text{Stator} \)
The diagram above represents the frictions that are affecting the turbine, viscosity ($B_v$) and clutch friction ($B_s$). When the fluid pushes the turbine against the torque converter clutch, the turbine begins to rotate at the same rate as the impeller, helping the ratio get closer to one rapidly. Due to the fact that the clutch has slippage, $B_s$ will never be infinite. The friction from the clutch is also larger than the viscosity friction.

To help protect the system, and for the equation to work in a situation when the load is greater than the engine torque, additional conditions should be defined, as shown below in Figure C.14.

Condition

\[
\text{if } T_{\text{Load}} > B_1 (w_1 - w_2) + B_2 (w_3 - w_2) \\
\text{then } \left[ B_1 (w_1 - w_2) + B_2 (w_3 - w_2) + T_{\text{Load}} \right] = 0
\]

\[ \dot{w}_2 = 0 \sim w_2 = \text{Const} \]

Figure C.14 – Additional conditions for the system
This information is referred to as a simulation, because the design team can use them to verify the accuracy of the torque converter model and also to perform experiments with the performance of the TC system.

As stated in the critical analysis of the torque converter, there is a point when the TC moves into cruising speed or steady state speed. The equation below simulates what is happening dynamically in the system. More information and a graphic representation of the steady speed state could be found in the critical analysis, Section 6.6.

At steady state speed

\[ \dot{w}_1 = \dot{w}_2 = \dot{w}_3 = 0 \sim w_1 = w_2 = w_3 = \text{Const} \]

(2)-(1)

\[ B_1(w_1 - w_2) + B_3(w_1 - w_3) - T_{\text{Eng}} = B_2(w_2 - w_3) + B_4(w_2 - w_4) - T_{\text{Lead}} \]

\[ 2B_1(w_1 - w_2) + B_3(w_1 - w_3) - B_2(w_2 - w_3) - T_{\text{Eng}} + T_{\text{Lead}} = 0 \]

\[ B_1 = \frac{T_{\text{Eng}} \left( \frac{T_{\text{Rate}} - 1}{2} \right)}{2 (w_1 - w_2) + K_1 K_2 (w_1 - w_3) - K_2 (w_2 - w_3)} \]

\[ B_2 = \frac{T_{\text{Eng}} \left( \frac{T_{\text{Rate}} - 1}{2} \right)}{2 K_2 (w_1 - w_2) + K_1 (w_1 - w_3) - (w_2 - w_3)} \]

\[ B_3 = \frac{T_{\text{Eng}} \left( \frac{T_{\text{Rate}} - 1}{2} \right)}{2 K_2 K_1 (w_1 - w_2) + (w_1 - w_3) - \frac{1}{K_2} (w_2 - w_3)} \]

Figure C.15 – Equations when system is at steady state speed

Many of the fundamental laws of the sciences and mathematicals can be formulated as differential equations. The torque converter differential equation represents the relation between the rates of change of continuously changing amounts modeled by functions. This differential equation takes into account all components of the torque converter and will also help simulate the dynamic model of the system.
To obtain a final differential equation for the torque converter, several steps need to be completed. First, convert the torque converter equations into a Laplace domain.

**Laplace**

\[ S I_1 w_1(s) + B_1 (w_1 - w_2) + B_3 (w_1 - w_3) - T_{Eng} = 0 \]  
\[ (1) \]

\[ S I_2 w_2(s) + B_2 (w_2 - w_3) + B_4 (w_2 - w_1) - T_{Load} = 0 \]  
\[ (2) \]

\[ S I_3 w_3(s) + B_3 (w_3 - w_1) + B_2 (w_3 - w_2) - T_{Stator} = 0 \]  
\[ (3) \]

\( (3) \Rightarrow (4) \) Solving for \( w_3 \)

\[ w_3(s) = \frac{B_2 w_2 + T_{Stator} + B_3 w_1}{SI_3 + B_2 + B_3} \]  
\[ (4) \]

\( (4) \Rightarrow (2) \Rightarrow (5) \) Solving for \( w_2 \)

\[ S I_2 w_2(s) + B_2 w_2 - B_2 \left[ \frac{B_2 w_2 + T_{Stator} + B_3 w_1}{SI_3 + B_2 + B_3} \right] + B_1 w_2 - B_1 w_1 - T_{Load} = 0 \]

\[ w_2(s) = \frac{B_1 w_1 + T_{Load} \left[ SI_3 + B_2 + B_3 \right] + B_2 T_{Stator} + B_2 B_3 w_1}{\left[ SI_2 + B_2 + B_1 \right] \left[ SI_3 + B_2 + B_3 \right] - B_2^2} \]  
\[ (5) \]

*Figure C.16 Laplace transform equation for the system*
(3) \rightarrow (1) = (6) Solving for \( w_2 \)

\[
SI_1w_1(s) + B_1w_1 - B_2w_2 + B_3w_1 - B_3 \left[ \frac{B_2w_2 + T_{\text{Stator}} + B_3w_1}{SI_3 + B_2 + B_3} \right] - T_{\text{Eng}} = 0
\]

\[
w_1 = \frac{w_1}{SI_1 + B_3 + B_1} \left[ \frac{SI_3 + B_2 + B_3}{SI_3 + B_2 + B_3} - B_3w_1 - B_3T_{\text{Stator}} - T_{\text{Eng}} \left[ \frac{SI_3 + B_2 + B_3}{SI_3 + B_2 + B_3} \right] \right] + B_2B_3
\]

\[
w_2(s) = \frac{B_1 \left[ SI_3 + B_2 + B_3 \right] + B_2B_3}{\left[ SI_1 + B_3 + B_1 \right] \left[ SI_3 + B_2 + B_3 \right]}
\]

Figure C.17 – Solving for angular velocity 2

After the Laplace domain has been set, solve equation (3) in terms of \( w_3 \). Then, plug \( w_3 \) into equations (2) and then equation (1). Equation (2) and (1) became equations (5) and (6), respectively. Both are to be solved for \( w_2 \). With assistance from the computer software, Maple 10.0, equation (5) and (6) are set equal to each other. Below, ‘\( p \)' represents equation (5) and ‘\( p_2 \)' represents equation (6).

\[
p = \frac{(B_1w_1 + T)}{(SI_2 + B_2 + B_1)} \cdot \frac{(SI_3 + B_2 + B_3) + B_2B_3w_1 + B_2T_s}{(SI_3 + B_2 + B_3) - B_2^2}
\]

\[
p^2 = \frac{w_1 \cdot (SI_1 + B_1 + B_3) \cdot (SI_3 + B_2 + B_3) - B_2^3w_1 - B_3T_s - T_{\text{Eng}}(SI_3 + B_2 + B_3)}{B_1(SI_3 + B_2 + B_3) + B_2B_3}
\]

Figure C.18 – Equations using Maple 10.0

Now that ‘\( p \)' and ‘\( p_2 \)' are set equal to each other, they can be rearranged to set them both equal to zero, as shown below:

\[
p - p^2 = 0
\]

\[
\frac{(B_1w_1 + T)}{(SI_2 + B_2 + B_1)} \cdot \frac{(SI_3 + B_2 + B_3) + B_2B_3w_1 + B_2T_s}{(SI_3 + B_2 + B_3) - B_2^2} - \frac{w_1 \cdot (SI_1 + B_1 + B_3) \cdot (SI_3 + B_2 + B_3) - B_2^3w_1 - B_3T_s - T_{\text{Eng}}(SI_3 + B_2 + B_3)}{B_1(SI_3 + B_2 + B_3) + B_2B_3} = 0
\]

Figure C.19 – Equations using Maple 10.0
Multiple the two

the

equations with

corresponding denominator and obtain the

follow:

,-p2-0

((B1y,1 + 71)(S13 + B2 + B3)+B2B31 +
+ B2 +

((S12 + B2 +

B3))

B2Ts)

(BI (SI3 + B2 +

Figure C.20

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-

(WJ

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(SI3 + B2 + B3)

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Equations using Maple 10.0

-

function of Maple

terms. Figure C.21

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B1) (S13 + B2 + B3)-B2*)=0

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to

work out

the

equation and

below, displays the expanded equation.

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B3)

+ 3 BI

+


S13S12B3
B31

<;

+

B3)

S132

+

B3)

B22

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B2 + 77

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(Sll + BI +

*!

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\tl
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B3)

B31

S132


B32
B1 + TI
B2 +

(Sll + Bl + B3)B2iS13->tl
(SII + Bl + B3)BpBl-\tl

+ 2Bl7lSl3B3+B32lBim+TlSl?Bl +

B27 B31

1

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BIi*lSlP+VB2*Bl+Bl1Y>lB27

S13B1 B3-2l

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T,*gB22Sn+T,ngB2-SI3 + T,ngB2iB3+T.ngB22Bl

Figure C.21

-

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-

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TmgSIS1

-(Sll+Bl

B2 + TtngSlf BI

Expanded

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(l

equation

below (Figure C.22).

equation

w1(I1I^I^)+wl(-2BJI1I,Is-2B3IiI^I3-ajIil|-B1T^i*-B4I4I^

?ft

-2M1

iA-V. ii V*A W

+

^-^h*Ai^^i3MhM^Ah^M

-6^1,-83^1,-6^,1^

^^V^I*^I+2^I)+I^(^^?^?'^+23^^)+^(i^')+*^(^,lVa,I^
+1

B^Balj )+tu- (B^+B^^B^+B^e^B^^+Ts^CBjIjI^+t^^CBjIj+B^alj+B^ + B^Ij

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Figure C.22

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Final Differential Equations

the differences between the differential

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+ B3TsS12Sl3 + B3TsSI2B2 + B3TsB2S13 + B3TsBlS13

2J

TsB2 +

-

2i

-

Tt*gB32S12+T,rig37B2+T.ngB3:'Bl + 2T.ngB2Sl2B3+2T.*gB2BlB3

+

Equations using Maple 10.0

The final differential
Differential

-

+

Ts B3 + 2 TIB2B1B3 + 2 B2TsBl B3 + B2TsBl SI3

+ 2TmgSI3 SO B2 + 2TmgSI3 B2 B3 + 2TmgSI3 SO B3 + 2TtngS13 BI B2 + 2TtngSI3 BI B3
+

(Sll

B3 + T1SI3B2B3 + 2 TI SIS BI B3 + 2 TISI3B1 B2

equations of the

torque

fluid coupling refer to Extra Information located below.

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b. Analyzing the torque converter in terms of fluid and clutch friction

"Newton's second law, often called the momentum equation, states that the resultant force acting on a system equals the rate of change of momentum of the system when measured in an inertial reference frame; that is,

\[ \sum \mathbf{F} = \frac{d}{dt} \int_{c.v.} p \mathbf{V} \, d\mathbf{V} + \int_{c.s.} p \mathbf{V} \cdot (\mathbf{V} \cdot \mathbf{n}) \, dA \]

Figure C.23 – Equation obtained from [58]

where the quantity in parentheses is simply a scalar for each differential area dA." [58]

"When applying Newton's second law the quantity \( \sum \mathbf{F} \) represents all forces acting on the control volume. The forces include the surface forces resulting from the surroundings acting on the control surface and body forces that result from gravity and magnetic fields. The momentum equation is often used to determine the forces induced by the flow." [58]

All of this explains that if a triple integral for control volume and control system purpose was applied to the equation above, and also making the valid assumptions, the result will be the three equations for the torque converter.

For further analysis, a technical paper written by Katsuya Suzuki and Kazuhiro Tanaka called "Torque Converter with Lock-up Clutch by Bond Graphs" [59] displays how the torque converter characteristics were analyzed through differential equations and bond graphs as shown in the graphic below. Assumptions for the equations are indicated in the red box below.
For pump:
\[ T_1 = I_1 \omega_1 - \rho S_1 \dot{Q} + \rho \dot{Q} \left( (r_2 \omega_2 - c_2 \tan \alpha_{2j}) \right) - (r_2 \omega_2 - c_2 \tan \alpha_{2j}) \]
(1)

For turbine:
\[ T_2 = I_2 \omega_2 - \rho S_2 \dot{Q} - \rho \dot{Q} \left( (r_2 \omega_2 - c_2 \tan \alpha_{2j}) \right) - (r_2 \omega_2 - c_2 \tan \alpha_{2j}) \]
(2)

For stator:
\[ T_3 = I_3 \omega_3 - \rho S_3 \dot{Q} - \rho \dot{Q} \left( (r_2 \omega_2 - c_2 \tan \alpha_{2j}) \right) - (r_2 \omega_2 - c_2 \tan \alpha_{2j}) \]
(3)

where \( \rho S_\dot{Q} \) represents change in momentum of fluid existing in impeller: the dot indicates differential by time: \( S_i \) is a constant determined by the blade configuration as follows
\[ S_1 = \int_{12} r \tan \alpha_{dl} \]
(4)
\[ S_2 = \int_{12} r \tan \alpha_{dl} \]
(5)
\[ S_3 = \int_{12} r \tan \alpha_{dl} \]
(6)

Basic equations are introduced on the basis of the theory of Ishihara [1] and by referring to the expansions by Hrovat et al.[11]. The basic equations use the following assumptions:
(1) Free passage between the adjacent outlet and inlet of impellers is extremely small.
(2) Cross sectional area of flow passage is constant.
(3) Flow concentrates along a mean streamline, conforming to the blade angle. In other words, one-dimensional flow approximation is used.
(4) Influence of blade thickness is ignored.
(5) Fluid is incompressible. The basic equations are obtained as described below, on the basis of the law of angular momentum, and the law of conservation of kinetic energy.

Nomenclature (See Fig. 1.)
\begin{itemize}
  \item \( A \): Cross sectional area of flow passage at an arbitrary point (m²)
  \item \( c \): Meridian plane component of flow velocity (m/s)
  \item \( E_k \): Energy loss of fluid (J)
  \item \( E_k \): Kinetic energy of fluid (J)
  \item \( I \): Sum of the moments of inertia of impellers and mechanical parts rotating together with each impeller and the moment of inertia of fluid in the impellers (kgm²)
  \item \( L \): Sum of the coefficients of frictional loss in the flow passage in impellers
  \item \( l \): Flow path length in meridian plane (m)
  \item \( P_L \): Pressure loss (Pa)
  \item \( Q \): Flow rate (m³/s)
  \item \( r_1 \): Pump inlet (stator outlet) radius (m)
  \item \( r_2 \): Turbine inlet (pump outlet) radius (m)
  \item \( r_3 \): Stator inlet (turbine outlet) radius (m)
  \item \( S \): Constant determined by blade configuration (m²)
  \item \( T_1 \): Pump brake torque (Nm)
  \item \( T_2 \): Turbine brake torque (Nm)
  \item \( T_3 \): Stator brake torque (Nm)
  \item \( t \): Time (s)
  \item \( a \): Blade angle (Meridian plane as reference) (rad)
  \item \( \alpha_{d} \): Blade angle (Meridian plane as reference) (rad)
  \item \( \alpha_{j} \): Blade angle (Meridian plane as reference) (rad)
  \item \( \dot{c} \): Fluid density (kg/ m³)
  \item \( \dot{c} \): Rotational angular velocity (rad/s)
\end{itemize}

For example, \( a_{12} \) represents pump impeller outlet angle.

Figure C.24 – Torque Converter equation analysis for the bond Graphic by Katsuya Suzuki and Kazuhiro Tanaka [59]

Comparing the technical papers results with the results displayed in Figure C.24 above, the only difference is that they did not include friction caused by the clutch (B₃).
c. Critical analysis design features

One of the most important design features of the torque converter is that for an automatic transmission it takes the place of the clutch found in any manual shift vehicles. It allows the engine to continue running when the vehicle comes to a stop. As Figure C.25 shows that the torque converter is located between the engine and transmission and is filled with Automatic Transmission Fluid. "A torque converter uses fluid to smoothly transfer engine torque to the transmission." [51] The torque converter is a type of fluid coupling that connects the engines crankshaft to the transmissions input shaft. [52] The torque converter allows some slippage between the engine and the transmission, "so that the engine will remain running when the vehicle is stopped while it is in gear. The torque converter also multiplies torque when the vehicle is under load to improve performance." [53]
The impeller is the drive member of the unit and its fins are attached directly to the converter cover. Therefore, the impeller is the input device for the converter and always rotates at engine speed.

The impeller has 31 fins adequately positioned to allow the fluid to impel. The fins are positioned on the impeller hub, and it is stabilized with the help of the guide
ring. The fins have a total of five membranes: two are attached to the guide ring and the other three are attached to the impeller. The guide ring serves two main purposes, one is to stabilize the fins and the second is to help the fluid flow smoothly. The guide ring and fins are displayed in Figure C.27 above.

![Image of guide ring and fins](image)

**Figure C.28 Impeller cover**

The impeller cover has ridges on the outer side because there is where the fins are positioned on the inside. The circular shape that it is, allows for the torque converter to move fluid around more easily that a square or rectangular shape. Some torque converters are equipped with a stabilizer to help maintain its position and rotation movement. As shown in Figure C.28.
The above drawing (Figure C.29) is of the Impeller Case and shows all dimensional specifications. The torque converter's complete drawing package is shown below. Some parts of the torque converter have two or three drawings due to its complexity; therefore it is shown at different views.
The turbine is the converter’s output member and is coupled to the transmission’s input shaft. The turbine is driven by the fluid flow from the impeller and always turns at its own speed. The fins of the turbine face toward the fins of the impeller. The impeller and the turbine have internal fins, but the fins point in the opposite direction.” [51]

Similar to the impeller, the turbine has 32 fins attached that are stabilized by a guide ring. The center of the turbine has 32 input shaft ridges for the transmission input shaft. The turbine also has 16 clutch attachers which were welded and that connect and engage the clutch and the turbine, so that they can both move simultaneously. This can all be seen in Figure C.30 above.
The stator is the redirecting device of the converter. The stator assembly is about one half the diameter of the impeller or turbine and is positioned between the impeller and turbine. The stator is not perfunctorily connected to either the impeller or turbine; instead, it fits between the turbine and the impeller. All of the fluid in the torque converter must pass through the stator. The stator redirects the fluid leaving the turbine back to the impeller. By redirecting the fluid so that it is flowing in the same direction as engine rotation, it allows the impeller to rotate better.
The stator is supported by a one-way clutch that is stabilized to the stator support shaft. The one-way clutch allows the stator to rotate only in the same direction as the impeller. "The clutch allows the stator to freewheel when the impeller and turbine reach their coupling stage. The outer edge of the stator fins normally forms the inner edge of a three-piece fluid guide ring," as shown in Figure C.32. [51]

Figure C.32 above shows the clutch also has a friction eliminating plate to prevent friction between the impeller and the stator and a clutch protecting plate. The clutch protector is used to maintain all components within for example the bearings and springs. The clutch protector plate is located under the friction eliminating plate.

The one way clutch, shown in Figure C.33 below, is composed of seven springs, seven cylindrical bearings, four clutch guides to direct the correct orientation when placed within the stator, and the inner ring with 32 ridges which is where the shaft will attach. When the one way clutch rotates clockwise, the cylindrical bearings rotate and allow the rotation. When the one way clutch attempts to rotate counterclockwise, the bearings compress the springs and do not allow it to rotate therefore not allowing the stator to rotate.

![Figure C.33 Stator's one way clutch shown in a 3D model using Pro-E wildfire 2.0](image-url)
C.6. Mechanical Features Analysis

a. Operations

Figure C.34 Torque Converter's interaction

When the engine starts, the impeller rotates at engine speed at any time the engine is running. Acting as a passage for the fluid, the impeller is made up of many curved vanes that radiate out of an inner ring. The inner ring is shown below in Figure C.35. When the converter starts to rotate, the vanes of the impeller start to circulate fluid.

Figure C.35 Impeller's inner ring
"The fluid in the torque converter is supplied by the transmission’s oil pump. It enters though the converter’s hub, then flows into the passages between the vanes. As the impeller rotates, the fluid is moved outward and upward through the vanes by centrifugal force because of the curved shape of the impeller. The faster the impeller rotates, the greater the centrifugal force becomes." [51]

![Diagram of Fluid Flow](image)

**Figure C.36 Fluid flow from Impeller**

The fluid flows from the outer perimeter of the vanes into the turbine. It tries to force the turbine into a rotation, when the fluid strikes the curved vanes of the turbine. The fluid rotates in a clockwise direction as it leaves the vanes of the impeller, because the impeller is turning in that direction. Nonetheless, the fluid turns the turbine in the same direction as the impeller due to that the turbine vanes are curved in the opposite direction of the impeller.

The above figure (Figure C.36) illustrates oil entering through the impeller and passing it through to the turbine. The engine is connected to the torque converter base through several bolts that are welded on the base itself. The transmission shaft is connected to the stator and the turbine. The shaft also aids the fluid to enter and leave
the torque converter. When the gears are shifted, there is a state of hydraulic pressure. The pressure of the oil created by the impeller helps the shifting of gears.

![Fluid flow from and to the oil pump]

Figure C.37 Fluid flow from and to the oil pump

More force transferred from the impeller to the turbine by the fluid, is due to higher engine speed and the rapidness that the impeller turns. This is the reason why the torque converter allows the engine to be at rest when in gear. On the other hand, when the engine speed is low, there is not enough fluid force to move the turbine against the load on the drive train. If the fluid movement in the torque converter is not very strong and just circulates from the impeller to the turbine and back to the impeller (shown in Figure C.37): for that reason, there is little or no power through the fluid coupling to the transmission.

As implied before, when engine speed increases, the fluid thrown at the turbine is with greater force and causes the turbine to rotate. Engine power is transmitted to the transmission, once the turbine begins to rotate. However, “the force from the fluid must be great enough to overcome the load of the vehicle before the
turbine can rotate. Some of the energy in the moving fluid returns to the impeller as the torque converter responds to the torque requirements of the vehicle and to vortex flow. At low speeds, most of the energy in the fluids is lost as the fluid bounces back away from the turbine vanes.” [53]

“Vortex flow is a continuous circulation of the fluid, outward in the impeller and inward in the turbine, around the split guide rings attached to the turbine and the impeller. The guide rings direct the vortex flow to provide for a smooth and turbulence-free fluid flow.” [51]

“As the vortex flow continues, the fluid leaving the turbine to return to the impeller is moving in the opposite direction as crankshaft rotation. If the fluid were allowed to continue in this direction, it would enter the impeller as an opposing force and some of the engine’s power would be used to redirect the flow of fluid to prevent this loss of power, torque converters are fitted with stator.” [51]

b. Multiplication

According to Dictionary.com, multiplication is to make many or manifold: increase the number quantity, etc. In this case, multiplication is done on torque, or the twisting force within the torque converter. The difference of a fluid coupling and a torque converter is that the torque converter has a stator. The stator eliminates the rotating flow and creates a vortex flow. The stator receives the fluid thrown off by the turbine and redirects the fluid so that it reenters the impeller in the same direction as crankshaft rotation. “The redirection of the fluid by the stator not only prevents a torque loss, but also provides for a multiplication of torque.” [53]
The stator is the part of the torque converter that multiplies, and as stated before is attached to a circular hub, which is mounted on a one-way clutch. The clutch assembly has an inner and outer components separated by spring-loaded cylindrical bearings. When the stator is turned in the same direction as turbine rotation, the bearings are able to rotate and the stator is able to turn. But if the stator turns in the opposite direction of the turbine rotation, the stator will lock.

The stator plays an important part in the fluid flow process. Fluid has to pass through the stator from the turbine to the impeller, and in passing the direction of fluid flow is reversed by the curvature of the stator blade. The fluid moves in the direction that aids to the rotation of the impeller. The impeller speeds up at the speed of the fluid movement and leaves with nearly twice the energy and exerts a greater force on the turbine, this is called torque or twisting force multiplication.

"It is vortex flow that allows for torque multiplication. Torque multiplication occurs when there is high impeller speed and low turbine speed. Low turbine speed and the stator cause the returning fluid to have a high-velocity vortex flow. This allows the impeller to rotate more efficiently and increase the force of the fluid pushing the turbine in rotation. When the vehicle’s torque requirements become greater than the output of the engine, the turbine slows down and causes an increase in vortex flow velocity. This causes an increase in torque multiplication. As the vortex flow slows down, torque multiplication is reduced." [51]

An example of how the torque converter works could be explained through an example of a fan. Refer to the “REPMES: How a torque converter works” DVD which is attached to this thesis.
C.7. Electrical Features Analysis

Unfortunately, no electrical feature for the torque converter was conducted due to the fact that the torque converter is a fully mechanical device that does not possess any electrical characteristics. Design and mechanical features of the torque converter can be found in the following sections.

C.8. Materials Properties Features Analysis

The material composition of the torque converter varies with the different parts the torque converter is composed of. Various experiments were conducted to test what type of material the torque converter is, since material specifications were not given at the time when the inspection form was completed. The model number was not specified but the manufacturer, which is Ford, was given.

The Rockwell hardness test, Brinell hardness test, the Metallography test and analysis of volume fraction by image were the various material testing experiments that were performed. The experiments were performed on the turbine and the impeller. Specifically, the tests were done to one of the turbine blades and to the case of the impeller. Other tests that could be conducted is the density test and magnetic properties.

a. Rockwell Hardness

The Rockwell Hardness test is probably one of the most used methods for determining the strength of steel. The hardness of a material is often equated to its wear resistance and its durability. The Rockwell Hardness is categorized by different types of scales depending on the material. For the torque converter, the ‘C’ scale was
used for the case of the impeller and the ‘B’ scale was used for the turbine blade. The ‘C’ scale or ‘HRC’ is used for harder metals and a load of 150 kg is applied to the material with this scale. The ‘B’ scale or ‘HRB’ is used for softer metals and a load of 100 kg is applied to the material with this scale. The ‘B’ scale was used on the turbine blade originally, but due to the load applied, the turbine blade will either break or bend, as a result the data on Table C.8, had many variability. The HRB scale data is considered poor data for the turbine blades, because of sample breakage. A suggestion could be to test the turbine blade with superficial Rockwell test (T or N scale) as a next step. The following material property test will be performed on the impeller case, in exception to the two Hardness tests (Rockwell and Brinell).

Figure C.38 Rockwell Hardness Machine - RIT Materials Lab Bldg 70

The Rockwell machine shown in Figure C.38 is automatic and test results were automatically put on a spreadsheet on the computer. To measure the Rockwell hardness of a specimen, first all of the prior test results need to be cleared and the specimen needs to be placed on the platen followed by the indenter being lowered until it is near the specimen. Eight samples of hardness test were taken for accuracy
and repeatability. The tables below (Table C.8) show the results taken from the experiment.

Table C.8 Rockwell Hardness values for the impeller and the turbine

<table>
<thead>
<tr>
<th>Impeller Case</th>
<th>Test No.</th>
<th>Hardness</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>12.30</td>
<td>HRC</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>12.74</td>
<td>HRC</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>12.63</td>
<td>HRC</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>10.66</td>
<td>HRC</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>11.37</td>
<td>HRC</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>12.00</td>
<td>HRC</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>13.42</td>
<td>HRC</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>13.74</td>
<td>HRC</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td>12.36</td>
<td>HRC</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Turbine Blade</th>
<th>Test No.</th>
<th>Hardness</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>8.48</td>
<td>HRB</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8.64</td>
<td>HRB</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>17.62</td>
<td>HRB</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>16.78</td>
<td>HRB</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>26.29</td>
<td>HRB</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>17.72</td>
<td>HRB</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>5.85</td>
<td>HRB</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>19.33</td>
<td>HRB</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td>15.09</td>
<td>HRB</td>
</tr>
</tbody>
</table>

The Rockwell hardness of the impeller was about 12.36C and for the turbine blade was 15.09B. A second hardness test is going to be conducted for consistency and accuracy on the material type. The second test is going to be the Brinell Hardness test.

b. Brinell Hardness

Similar to the Rockwell Hardness test, the Brinell Hardness test also measures materials hardness for thicker materials. Depending on the hardness number of the material and the load applied, a range of material types can be determined. The Brinell Hardness was one of the first testing for hardness of material and was widely used in the early to mid 1900s. In order to continue with the consistency of experiments, the same specimens that were used for the Rockwell will also be used for the Brinell.
The Brinell hardness machine (Figure C.39) applies a force with an indenter to the specimen that is being tested. The indenter can be a hard steel or diamond ball and can range from 1 mm to 10 mm in diameter, for this case a 10 mm diameter hard steel ball was used. The various loads that were used in this experiment were 3000 kilogram-force (kgf), 1500 kgf, and 1000 kgf. The loads can range from as small as 500 kgf to 3000 kgf. The highest load was applied to the impeller case, and the 1000 kgf and 1500 kgf was applied to the turbine blade. The smaller force was applied to the turbine blade because it is thinner than the impeller case.

Force F

Figure C.40 Schematic of Brinell indenter
The load, which as stated above can be anywhere from 500 kgf to 3000 kgf, is applied anywhere from 10 – 15 seconds or at least 30 seconds. For the torque converter specimens, 15 seconds was used for each of the respective parts because of the load applied.

The load is applied to the specimens with a hard steel ball which creates an indentation on the material. After the load was applied for 15 seconds, the indenter rises away from the material. Figure C.40 shows the measurements and forces that need to be determined and with a measurement device, the diameter of the indentation is to be taken and plugged into the formula below (Figure C.41).

\[
BHN = \frac{F}{\frac{\pi}{2} D_2 \left( D_2 - \sqrt{D_2^2 - D_1^2} \right)}
\]

*Figure C.41 Brinell Hardness number equation [60]*

BHN = Brinell Hardness Number
F = Force applied
D2 = Diameter of the Brinell Ball
D1 = Indentation diameter on material

Since the Brinell ball makes the deepest and widest indentation compared to other hardness tests, the test averages are determined for a wider quantity of material, and therefore is more accurate. Using the formula above and applying conversion factors, the table below was created with the results from the Brinell experiment.
According to the results on the table above, the Brinell hardness number of the impeller is about 145 and the turbine blade was about 89. But due to the load applied, the turbine blade will either break or bend, as a result the data on Table C.9, had many variability. Now that the Rockwell and Brinell hardness testing is complete, and results are organized, the type of material the turbine blade and the impeller case are can be narrowed down. With the hardness results from both experiments along with the color, texture, density, and size of the material, and after completing some research, it is known that the materials are some type of steel. There are many types of steel and therefore additional experiments needs to be conducted to learn more information about the type of steel. The metallographic sample testing was conducted to compare the microstructure of the steels with published data. This will provide more information on the type of steel that it is composed of. With the hardness and the microstructure photos, a type of steel can be determined.

c. Metallography

Metallography is the study of the structure of metals and alloys by means of microscopy, which are photographs of the microstructure of the specimen. One must
keep in mind, that all elements in their solid form have a specific arrangement of atoms.

Figure C.42 – Polishing equipment in Materials Lab RIT Bldg 70

The first step for this experiment was to cut off a piece of the impeller and a piece of the turbine. Both parts were then polished through successively smaller grits, from 5 µm to 1 µm, for a total time of two hours, making sure to wash the two specimens between grits, as shown in Figure C.42. The specimens were polished until a mirror-like shine was accomplished. The specimens were then etched with a 3% Nitric Acid in Ethyl Alcohol to expose the grain structures, which are to be viewed through a microscope.

The next step is to examine the specimens through a microscope and capture the pictures on a computer. The microscope’s magnification varies from 100x to 500x. It is critical to examine and analyze every detail of the photos captured through the microscope. The last step is to compare the captured pictures with published pictures to identify the microstructure of the part and determine the type of material the specimens are.
The two microstructure photos above (Figure C.43) are of the impeller case and a microscope magnification of 500x was used. The photo on the right was heat treated. The light and dark areas indicate the carbon content of the material. The light areas in the grain structure are called ferrite and the dark areas of the grain structure are called pearlite. “Fully ferrite steels are obtained only when the carbon content is low. The most obvious microstructural features are the ferrite grain boundaries . . . Ferrite is a soft low-strength phase. If the ferrite grain size is fine, good ductility and formability are obtained. Because ferrite has a body-centered cubic (bcc) crystal structure, ferrite steels exhibit a transition from ductile to brittle behavior as temperature decreases or as strain rate increases.” [61] “Pearlite is mixture of ferrite and cementite in which the two phases are formed from austenite in an alternating lamellar pattern. Formation of pearlite requires relatively slow cooling from the austenite region and depends on the steel composition. Pearlite forms at temperature below the lower critical temperatures of the steel in question and many are formed isothermally or by continuous cooling.” [61]
From the observation of Figure C.43 - (1) the size of ferrite grain structure is larger than the pearlite grain structures. Though, the content of ferrite and pearlite seems to be the same amount, it is evident that there is slightly more pearlite than ferrite in the structure experimented, it appears to be about 40% ferrite and 60% pearlite.

d. Research and Comparisons

The design team recommended comparing the results from the different experiments with published data, references, and photographs. Resources include the Material Science Lab, Library References for example the Knovel database, and internet research. The following is going to be an analysis of the published information found with the experiment results.

To narrow down the type of material the specimens were, the different experiments provided characteristics about the specimen that could be compared with other data. Before research was conducted, the design team suggested various assumptions on what the material was: some of the assumptions include that it was low or medium carbon steel due to its physical appearance, microstructures, and hardness. The design teams' assumption was the basis of the research. Higher priority research will be on carbon steels that range from 0.04% to 0.60% carbon content and microscope magnification of 100x to 500x because it could easily be compared with published data with this range of magnification.
Figure C.44 shows a microscopic picture of low carbon steel, a 0.25% carbon content. The “structure is proeutectoid ferrite (white) at prior austenite grain boundaries, and a mixture of ferrite and pearlite within grains.” [61] Though the magnification of the picture was 100x, it is clear that ferrite is the dominant factor, whereas in the impeller case, shown in Figure C.43, shows an almost equal amount of ferrite as pearlite. After analyzing and comparing this microscopic picture, it is evident that more research needs to be conducted with higher carbon content.
The figure above, Figure C.45, displays a carbon steel microstructure with 0.30% to 0.40% carbon content. The specimen on this photo was taken, “... after being normalized by austenitizing by 900 degrees Celsius (1650 degrees Fahrenheit) for 3 h and air cooling. The structure consists of pearlite (dark constituent) and ferrite (light constituent).” [61] This photo shows the comparisons from a 0.25% carbon content as shown in the microstructure above and one with a 0.30% to 0.40% carbon content. Comparing the two microscopic pictures, this one displays less ferrite in the microscopic picture than the 0.25% carbon content one, which indicates that the design team is on the right track with researching microscopic pictures with a higher carbon content.
The figures above display carbon content of a .40% carbon steel. The photos above were taken with magnification of 200x and is “... 25mm (1 in.) in diameter, austenitized 30 min at 915 degrees Celsius (1625 degrees Fahrenheit) and cooled slowly in the furnace. White areas are ferrite; dark areas, pearlite.” [61] The photo on the right was taken with a magnification of 500x and is the same content carbon steel as the photo of Figure C.46. In this case, though pearlite seems more dominant, it looks like there is an equal amount of both ferrite and pearlite present. The shapes of both grain structures are similar to the one taken from the impeller; they are round and formatted together. Other grain structures found during the research were pictures of microstructures that had many small lines or equivalent therefore they were immediately removed because the impeller microstructures are more round and ferrites and pearlites seems to be grouped together.
Now the design team is closer to identifying the material composition of the impeller case. From the microstructures, the material seems to be at or higher than a carbon content of 0.40% carbon steel.

The figure above is of 1045 carbon steel at a magnification of 500x. This carbon steel was “normalized by austenitizing at 1095 degrees Celsius (2000 degrees Fahrenheit) and cooling in air. Structure consists of pearlite (dark gray), and ferrite (light).” [61] This photo resembles the closest to the microstructure picture taken of the impeller case. There seems to be an exact match in the amount of ferrite and pearlite content. This 1045 carbon steel contains 0.45% carbon in its composition. There is not a vast difference between 1040 and 1045, since the carbon content will be between 0.40 % and 0.45%. The magnifications are the same in both microscopic pictures, and the grain structures are round and grouped together. After researching and comparing the microstructures and noticing the similarities, a continuation of the hardness testing was then explored. Brinell Hardness number and Rockwell was
research for the 1045 carbon steel and according to Metal Suppliers Inc. [62], the
Brinell number was 167 and the Rockwell was C16. According to Table C.8, the
Brinell hardness number for the impeller was 157 and a Rockwell of about C13.
Rockwell and Brinell Hardness depends on heat treatment and carbon content. Due to
this information, further analysis will be accomplished.

e. Analysis of volume fraction by image

To avoid extensive trail and error with respect to research of grain structure
comparisons, other resources can be used. Another method that can be used to
analyze microstructures is using computer software programs. ImageJ [63] is an
image analysis computer program and will be used to measure the area fraction (and
inferring the volume fraction) of pearlite versus ferrite in the microstructures of the
impeller case. ImageJ can show, measure, edit, and analyze images that include 8-bit,
16-bit, 32-bit, 8-bit Color, and RGB (Red Green Blue) Color. It is also capable of
reading a number of image formats, which include TIFF, PNG, GIF, JPEG, BMP, and
many others. ImageJ smoothes and sharpens images to obtain better results and can
indicate edges of images to distinguish different areas or shades of areas more easily.

ImageJ was used for the microstructure picture of the impeller case (Region of
Interest –ROI). After the image is uploaded into the ImageJ program, it is sharpened
for precision and is converted to a white and black image using the “threshold”
function. The image type was changed to 8-bit grayscale image due to its simplicity
since the microstructure of the impeller case only has about three colors. The Voxel
counter function within the program counts the number of black and white pixels of
the image, and proceeds to resulting the total number of pixels and the fraction of
pixels that are black. The black areas are indicative of the pearlite content of the microstructure. Sometimes, it is best to invert the colors for better results. It was assumed that the volume fraction should be equal to the area function due to the fact that the program is working with one image (2D).

The results for the impeller case show that for a total ROI volume of 231,678 pixel$^3$ which equals an area of 231,678 pixel$^2$, the volume fraction of the pearlite is 54.23%, making the ferrite a 45.77%. Stated above in the Metallography section, it was assumed that 40% was ferrite and 60% was pearlite, these assumptions were very close in value to the experimental results obtained from ImageJ. Figure C.48 shows the microstructure of the impeller case in black and white from ImageJ.

![ImageJ black and white photo of impeller](image)

Figure C.48 – ImageJ black and white photo of impeller

Now that the weight percent of the pearlite and ferrite is known, the carbon content of the impeller case could be mathematically solved through the equation below:
Figure C.49 Composition of %Carbon vs. Temp. Equation of % weight Carbon, taken from [64]

For the above diagram, “A portion of the Fe – Fe₃C phase diagram used in computations for relative amounts of proeutectoid and pearlite microconstituents for hypoeutectoid (C’0) and hypereutectoid (C’1) compositions.” [64] In other words, the equation to the right of the phase diagram can be used to calculate the carbon content of a material if the fraction of pearlite content is known. When substituting the fraction of pearlite content obtained from ImageJ in the equation above, the carbon content of the impeller case is 0.42 wt% carbon.

f. Critical analysis for narrowing down options

Two steel rods, one 4340 alloy steel and one 1045 carbon steel will be tested to narrow down the option of whether the impeller is carbon steel or alloy steel, therefore a Jominy Hardenability will be used. The goal of this experiment is to determine the hardenability curve for the two steels that are going to be used. The steel 4340 and 1045 will need to be heated above the austenizing temperature. After
an hour being heated, the two specimens were removed and quenched to provide a cooling gradient. The specimens were then dried and the Rockwell hardness test was performed along the cooled specimens. The next step is to compare the hardenability curve obtained from the experiment results with published hardenability curves. After that is accomplished, pictures of microstructure were taken and examined of the Jominy end quench.

The graph below displays the Rockwell Hardness versus the distance starting from the quenched end moving upward.

![Distance vs. Hardness Graph](image)

The graph below is a published hardenability curve for alloy steel and carbon steel.
Comparing the two graphs, it shows that the impeller’s hardenability is closer to that of the carbon steel specimen. The table below (Table C.9) is the chemical composition of plain carbon steel and an alloy steel.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>Si</th>
<th>Mo</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain Carbon Steel</td>
<td>0.3</td>
<td>0.7</td>
<td>0.1</td>
<td>0.14</td>
<td>0.26</td>
<td>0.03</td>
<td>0.003</td>
<td>0.02</td>
</tr>
<tr>
<td>Alloy Steel</td>
<td>0.3</td>
<td>0.6</td>
<td>0.7</td>
<td>3.5</td>
<td>0.26</td>
<td>0.35</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>
The grain structures of the specimens of the steel bars categorize the characteristics of that material, for example in relation with the hardness also. Photomicrographs of the grain structure were taken to determine what type of structure the segment has in various parts of the specimens. Table C.10 above shows the microstructure picture of the 1045 carbon steel that was tested and the impeller case that was tested. The ferrite and pearlite content grain structures are very similar and the corresponding hardness as well.

The critical analysis shows that the 1045 carbon steel is the most similar in characteristics and properties to that of the impeller. Through extensive research and various experiments, the 1045 carbon steel was the most evident to the impeller. The very minimal difference between the 1045 carbon steel and the impeller might be due to that the torque converter undergoes much different physical environmental conditions and treatment. Nonetheless, this would not change the percent of carbon content of the material. Also variability of natural materials, differences in polishing technique and etching time could affect results very minimally. A recommendation for further analysis could be to use X-ray analysis to determine the chemical
composition within that material. The X-Ray analysis is more accurate, but more costly.


a. 3-D Solid Model of the device created using Pro-E Wildfire 2.0

Figure C.52 Torque converter front and back view

Figure C.53 Exploded view of the torque converter with corresponding main component names
Figure C.54 Torque converter’s turbine front and back view without blades

Figure C.55 Transparent 3D model of the Torque Converter with animation of the vortex flow rotation
b. 2-D Drawing Package

Figure C.56 Impeller Case 1/3
Figure C.60 TC Turbine 1/2
Figure C.61 TC Turbine 2/2
Figure C.63 Bearing Frame of Stator
Figure C.64 Shaft support Stator Ring
Figure C.65 Impeller Blade
Figure C.66 Turbine Blade
Figure C.71 Torque Converter Clutch 2/2
Figure C.72 Torque Converter Base 1/2
Figure C.73 Torque Converter Base 2/2
C.10. Extra information

a. Graph of Cruising speed

In this section, an explanation of the torque converter when it is at cruising speed will be accomplished as well as the system modeling of a fluid coupling in comparison with the torque converter.

As mentioned previously, the torque converter is a doughnut-shaped component that has three main parts: the impeller, the turbine, and the stator. Each of these has blades that are curved to increase torque converter efficiency.

![Graph of Cruising speed](image)

**Figure C.74 Graph of Cruising speed**

The torque converter's impeller needs to be a certain speed in order to move the turbine. Once the turbine and the impeller are at about the same pace, it is considered to be cruising speed, as shown in Figure C.74 above. When the vehicle is operating at cruising speeds, the torque converter operates as a fluid coupling and transfers engine torque to the transmission.

The torque converters relationship between the output torque and input torque exist in a ratio as described below in Figure C.75. The numerator is the output torque
and the dominator is the input torque. When the vehicle is at cruising speed, the ratio is approximately one.

\[
\text{Output Torque Ratio} = \frac{\text{Output Torque}}{\text{Input Torque}} \approx 1
\]

Figure C.75 Ratio at Cruising speed

b. Fluid Coupling

Let's now analyze a system without a stator. The fluid coupling is similar to the torque converter but the only difference is that the torque converter has a stator bestowed between the impeller and the turbine. The following diagrams and equations are a display of Newton's Second Law applied to the torque converter.

![Turbine and Impeller Diagrams](image)

\[
\begin{align*}
\mathbf{I}_2 \omega_2 + & \mathbf{B}(\omega_1 - \omega_2) \omega_2 + \mathbf{T}_{\text{Load}} = 0 \\
\omega_2 &= \frac{1}{\mathbf{I}_2} \left[ \mathbf{B}(\omega_1 - \omega_2) + \mathbf{T}_{\text{Load}} \right] \\
\end{align*}
\]

\[
\begin{align*}
\mathbf{I}_1 \omega_1 + & \mathbf{B}(\omega_2 - \omega_1) \omega_1 + \mathbf{T}_{\text{Eng}} = 0 \\
\omega_1 &= \frac{1}{\mathbf{I}_1} \left[ \mathbf{B}(\omega_2 - \omega_1) + \mathbf{T}_{\text{Eng}} \right] \\
\end{align*}
\]

Figure C.76 Turbine and Impeller Equations
where

\[ I_i = \text{Mechanical polar moment of inertia} \ (\text{kg} \cdot \text{m}^2) \]
\[ \omega_i = \text{Angular Velocity} \ (\text{rad} \cdot \text{s}^{-1}) \]
\[ B_i = \text{Viscous and clutch friction} \ (\text{kg} \cdot \text{m}^2 / \text{s}) \]
\[ T_{\text{Eng}} = \text{Torque developed by the engine} \ (\text{N} \cdot \text{m}) \]
\[ T_{\text{Load}} = \text{Torque transmitted to the wheel} \ (\text{N} \cdot \text{m}) \]

\[
\begin{align*}
B &= B_v + B_s \\
\text{Where} \\
B_s &> B_v
\end{align*}
\]

Figure C.77 Viscosity and clutch Friction

Similar to the torque converter, the fluid coupling also has additional conditions that should be defined to help protect the system and for the equation to work in a situation when the load is greater than the engine torque. The condition system dynamic equation is illustrated below.

\[
\begin{align*}
\text{Condition} \\
\text{If } T_{\text{Load}} &> B(\omega_1 - \omega_2) \\
\text{then } &\left[ B(\omega_1 - \omega_2) + T_{\text{Load}} \right] = 0 \\
\dot{\omega}_2 &= 0 \sim \omega_2 = \text{Const}
\end{align*}
\]

Figure C.78 Viscosity and clutch Friction under condition
Below is the steady state speed equation for the fluid coupling. Unlike the torque converter’s steady state speed, the fluid coupling only has one variable as a final solution.

At steady state speed

\[ \dot{w}_1 = \dot{w}_2 = 0 \sim w_1 = w_2 = \text{Const} \]

\[ 0 = B(w_2 - w_1) + T_{\text{Eng}} \]

\[ 0 = B(w_4 - w_2) + T_{\text{Load}} \]

\[ B(w_4 - w_2) + T_{\text{Load}} = B(w_2 - w_1) + T_{\text{Eng}} \]

\[ T_{\text{Eng}} - T_{\text{Load}} = 2B(w_4 - w_2) \quad (D) \]

\[ T_{\text{out}} = T_{\text{Rate}} \cdot T_{\text{Eng}} \quad (E) \]

\[ B = \frac{T_{\text{Eng}} (T_{\text{Rate}} - 1)}{2(w_4 - w_2)} \quad (F) \]

Figure C.79 Equation for steady speed

Below are the differential equations along with transfer function of the fluid coupling.

Differential equation

\[ I_1I_2 \ddot{w}_1 + B(I_1 + I_2) \dot{w}_1 \cdot I_2 \dot{I}_{\text{Eng}} + B(T_{\text{Eng}} + T_{\text{Load}}) \]

Transfers function

\[ w_4(s) = \frac{(SI_2 + B)T_{\text{Eng}} + B T_{\text{Load}}}{I_1I_2 S^3 + B (I_1 + I_2)S + I_1I_2 S^3 + B (I_1 + I_2)S} \]

Figure C.80 Differential Equation and transfers function for Fluid Coupling
This appendix includes the final process for REPMES with a breakdown of each section. Each section has a series of steps that need to be taken to continue with the entire process.
Figure D.1a REPMES$_2$ – Revised Process
Figure D.1b REPMES2 – Revised process continued
Complete Technical Data Package (CTDP)

Define TDP contents

Multimedia (video and audio)  Computer documented  Scripted manual

Writing general information

Bill of material

Complete labeled diagram (exploded view)

Manual instructions

Engineering drawing and associated information, with distribution statements

Component specification

Performance characteristics

Are Manufacturing requirements needed?

End of CTDP

TDP purpose, specification and standards

Manufacturing information

Important safeguards

Preservation, packaging and packing information

Quality information

Special tooling

Inspection information

Figure D.2 REPMES$_2$ – Complete Technical Data Package
Figure D.3 Need assessment, Kevin Otto and Kristin Wood [40]

Figure D.4 Engineering Specifications, Kevin Otto and Kristin Wood [40]
Figure D.5 Select n Product to reverse
Figure D.6 Steps toward product selection
Start of RE sub-objectives

Knowledge Expansion
  Identify reasons for knowledge expansion
  Select sub-objective based on reasons

Replace Lost TDP
  Identify reasons for Replace Lost TDP
  Select sub-objective based on reasons

Benchmarking
  Critical assessment analysis
  Rank user potential sub-objective
  Identify and select potential sub-objective based on engineering specification

End of RE sub-objective

Figure D.7 RE sub-objective(s)
Obtain product(s) for RE

Similar Product(s) for RE available

Create a prototype (s)

End of obtain product for RE

Figure D.8 Getting the Product (s) for RE

Start of Getting product documentation

Careful analysis of technical data

Others usage data

End of Getting product documentation

Examples of design questions:
What was difficult for them?
What design problem did they solve that they are proud of?
What related technologies were they interested in?

Figure D.9 Getting Product Documentation
Start of design team selection

Identify product features & characteristic

Select area of product analysis

Estimate number of personnel for RE project

Assign personnel engineering functions

Document personnel and functions

End of design team selection

Figure D.10 Design Team Selection
Start of RE plan

Design Team defines a deadline for each part of the RE project

Create in detail a RE plan

Create RE schedule for entire project

Document and distribute to design team

End of design team selection

Figure D.11 Design Team Selection
Figure D.12 Product Functionality, Kevin Otto and Kristin Wood [40]
Figure D.13 Visual inspections, Kevin Otto and Kristin Wood [40]
Figure D.14 Design Features
Start of design feature

Model process for electrical feature

Mathematical model

Electrical drawing

Electrical description

End of design feature

Yes

System modeling

A

A

Figure D.15 Electrical Feature

Start of Mechanical feature

Model process for Mechanical feature

Heat treatment

Mechanical structure

Failure analysis

Fluid analysis

Quality evaluation reports

End of Mechanical feature

Figure D.16 Mechanical Feature
Start of technical implementation

Define field set operation

Destructive procedure

Subtract and operate procedure (SOP) → A

Not Destructive procedure

Destructive procedure → B

Post-teardown reporting

End of technical implementation

Figure D.17 Technical Implementation
Start of critical analysis

Isolate problem to components

List of components to Re-examine

Set component functionality

Collect existing data of components

Answer and create new questions

Functional and economic analysis

Engineering judgment

Go / No go decisions

End of critical analysis

Figure D.18 Critical Analysis
Start of validation

Develop component validation capability

- Generate a large number of test scenarios
- Execute the test Scenarios using a similar unit if possible

Validate validation capability

- Observe any differences in the expected functional performance of the similar unit
- Postulate cause for the differences and make changes

End of validation

Figure D.19 Validation, inspired by Riffle [32]
Start of design verification

Verify that documentation and product prototype matches

Answer prototype questions

Creating the technical data

Quality control

End of design verification

Examples of questions:
Are prototype required?

Figure D.10 Design verification

Start of RE plan

1) Estimation of the current state of the process
2) Monitoring control
3) Error detection and comparison of data
4) Corrective procedure

Process state estimation

End of RE plan

Figure D.21 Process State Estimation
Depending on physical property:
- Weight, color, texture, size, and density

Figure D.22 Material Property Process