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Testing Guidelines for New Product Development

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ABSTRACT

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While many literary sources outline the product development process, few make mention of the prototyping and testing stage. This thesis suggests that because of its importance in the product development process, “Testing” should be documented as a major step and not just listed as a side note. As part of the testing step, it is suggested that standardized, in-use, and market tests be used to properly evaluate a product. While many rely solely on standardized tests to validate their products, effective in-use tests can be another vital tool that can prove the performance of the product in more specific and relevant applications. In-use tests are a major focus in this thesis and the process of developing and using these in-use tests is explored.

A case study is used to prove that effective product development will follow the outlined testing procedure. Also, it shows that in-use testing, combined with other types of testing, can be a vital tool to ensuring the successful launch of a newly developed product. As a result of the case study, the traditional new product development process is amended and a set of guidelines are proposed for use in constructing a successful testing methodology for the new product development process.

Keywords: Product Development, standardized testing, in-use testing, prototyping

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1 INTRODUCTION

1.1 Background

Countless people throughout the world have risen from rags to riches because of their ability to turn an idea of a product into something very real, useful, and marketable. The United States is filled with many entrepreneurs using revolutionary product ideas to fuel their pursuit of the American dream. Whether or not these inventors have been instructed in the traditional steps of product development, their paths generally follow the same logical process of creating an idea for a new product, building and testing that product, and setting up manufacturing and releasing the product to the public. Much of the success of these entrepreneurs lies in their ability to effectively evaluate whether or not the most recent incarnation of their product idea is suitable for use by their intended customers. Inventors often have wonderful ideas of a product that can definitely fill a gap in the lives of their targeted customers, but when they forgo testing to validate their final production design, they usually meet the swift hand of failure because their product does not hold up to the rigors of its intended use. Effective testing of products in their anticipated environment is vital to ensure the product's successful launch and sustainability.

There are a few different types of testing that happen throughout the development process. Concept testing is a type of testing that is done early on in the design phase and is important to ensure that the basic design of the product will actually work and that it fulfills the outlined customer needs. In this type of testing, it is not critical to have a product in a final or even a near-final state. For example, when designers explore options for dramatically changing the shape of a new mobile phone, they may just want to test how it feels when holding it up to their head; in such a test, they would most likely make a non-working model in order to simply show the concept and allow designers to feel what the final product might be like. It would not be essential to have all working components of a phone installed at this point in the process because the focus would be on the shape rather than electronic functions. While concept testing is an important part of the product development process, there is another very important developmental process called prototype or product testing that can be done either to assist the development process or to help validate the product after launch. This thesis will address some challenges inherent in the prototype or product testing process.

Product testing or full-prototype testing is where a final-stage prototype or actual product is tested to ensure that it functions and performs as desired by the person or company selling the product. In this type of testing it is crucial to use the same exact design or materials to be used in the actual product that will ultimately end up in the hands of the customers or, at a minimum, use a design and materials that are so similar to the final product that they could be comparable. For many products, customers like to see proof that the product will perform exceptionally under similar conditions in which they intend to use them. It would be foolish to try to sell a product without, first, verifying that it will actually work and perform in a variety of environments as intended by the designers. This kind of validation or verification is often done by using pre-established standardized tests.

Standardized tests are created or maintained by a governing body or oversight group that provides information and instructions on the exact procedures for different tests. The purpose of standardized tests is to have a base from which to compare different products throughout different locations and time periods. Examples of standardized tests surround us every single day and affect nearly all of the products we purchase and use. A good example of a common standardized test is the Environmental Protection Agency (EPA) fuel estimates that are displayed on all new cars (see Figure 1-1). These fuel economy (also known as gas mileage) numbers are determined through rigorous standard tests that are performed consistently with every vehicle as to give a solid base for comparison when people are shopping for cars. All cars are driven on a track at the same speeds in the same conditions and fuel intake is monitored. Fuel economy results are then calculated and posted on the windows of all new cars. People that commute or otherwise spend a lot of time driving are usually concerned about spending too much on fuel; these customers can compare the fuel economy estimates between different cars and have confidence that the posted results were attained through a consistent and repeatable process. Having confidence in these tests is important, which is why the EPA dedicates great resources to maintain a high quality and consistent testing process. Without a set standard for testing fuel economy, customers would be at an extreme disadvantage because they would have no solid base from which to compare the performance of various vehicles.

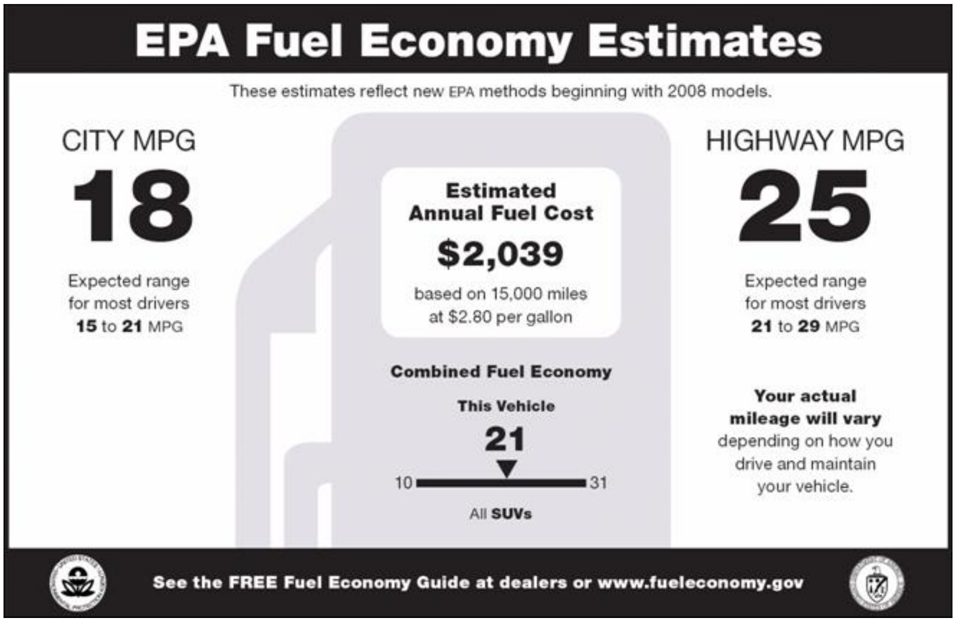

Figure 1-1—EPA Fuel Economy Window Sticker (EPA, 2010)

While EPA fuel estimates are very useful to many car buyers, there are some limitations to the tests. City economy and highway economy are the two metrics reported from the tests performed, but there may be some areas where a more specific test would be appropriate. For example, the testing procedures used by the EPA would probably not reflect the performance of an automobile in a high-altitude area where there are many steep and windy mountain roads. Automobiles that perform well on highway economy tests may use a greater amount of fuel in windy and hilly conditions, making the EPA estimates irrelevant to some buyers. Customers in such areas may desire to have a more suitable comparison of fuel economy under conditions similar to their specific environment. Dealerships in that area could benefit from doing their own specified testing to bring more useful information to their specific customers. This kind of testing can include driving a pre-determined mountainous route and then measuring fuel consumption from that route in order to get a mountain-driving mileage estimate. While this would not be a standardized test, it could provide important and useful information to local customers. Although standardized tests are very important and have many wide uses, it is sometimes necessary in certain situations to develop specific tests that better fit the intended use and environment of the product.

While standardized tests, in general, are appropriate for a majority of applications, it is often beneficial to make modifications to already established standard tests, or even develop completely new tests in order to properly evaluate a product for its intended uses and environment. If a very specific aspect or function of a product needs to be tested, there is a limited set of standardized tests from which to choose for testing. If no pre-established standardized test comes close to addressing the desired performance characteristics of a specific product, it can be advantageous to develop an in-use test to appropriately evaluate the product or materials for the specified environment or use. An in-use test is usually a very specific test that is set up to precisely measure the desired attributes of the product in a way that will give confidence to the developer that the product will perform as desired. Customers also like to have proof that the things they might purchase will perform well throughout the intended product life, so it is important to develop pertinent and reliable tests in order to maintain significant sales of a new product.

Sometimes, it can be very useful to combine standardized and in-use testing in evaluating a product. Following is an example of an application where both standard tests and in-use tests can be used together. In the motorcycle industry, there are stringent DOT and SNELL standardized tests that a helmet must pass to be considered safe. While safety standards are the most important consideration when buying a helmet, often motorcycle riders want to make sure other advertised features of the helmet really work. In areas where the climate is very hot, it can be very uncomfortable wearing a helmet if the vents on the helmet are not well designed. Since there are no current standardized tests available to show the venting and cooling effectiveness of helmets, how can a rider make sure that a helmet will be vented properly without actually buying and trying it out? If this is a major concern for enough customers, a helmet manufacturer or distributor can take the initiative and develop an in-use test to provide information on the effectiveness of its helmets by developing a cooling test to measure temperatures inside a helmet under certain wind speeds and temperatures. These tests can then be used to compare the effectiveness of one helmet model versus another as to provide an apples-to-apples comparison. In-use tests such as this can be a critical factor in the successful rollout and lifelong success of many different products and can be combined with the results of standardized tests to give the customer enough information for them to make informed purchasing decisions.

After a product has gone through standard and in-use tests to validate its performance in a laboratory setting, it is critical to perform limited market tests. By running market tests, a developer can see how the product will actually fare in a real-world situation with the real customers. Even if a product performs perfectly in lab and other controlled tests, the customers may not use the product with complete adherence to the recommended instructions and sometimes the results can be catastrophic. Organizations that do limited market tests before a full launch of their product often receive valuable information they could not have otherwise gathered.

In summary, as a product developer moves from a characterization of general materials to the verification of an actual material and design, it is necessary to move from standard tests to in-use tests because in-use tests use concepts of standardized tests but modify them so they have direct and immediate application to the actual product. The process of developing an effective testing methodology for a new product is investigated throughout this thesis.

1.2 Case Study

To demonstrate that an effective testing methodology can be created for evaluating a new product, this thesis provides a case study that highlights a company that was in the early stages of development of a new product and their collaboration with the author in developing and executing a proper testing methodology for its product. By connecting with a company that was trying to validate its design and material choice for a new product, the process of developing some specialized tests for the product in order to fully explore the nature of in-use testing and whether or not it can be used as an effective tool in the new product development process could be developed and evaluated. Hazard Protection Systems was going through the new product development process at the time of this thesis and had connections to professors at BYU. This provided an excellent case study for the general investigation of in-use testing.

1.2.1 Hazard Protection Systems, Inc. & NCASE

Hazard Protection Systems, Inc. (HPS) is a company that, over the last few years, has gone through the development process for a new product by creating a new ballistic fire protection product (NCASE™). As of May 6, 2010, over 5,000 soldiers have died and over 20,000 have been wounded in action in Operation Iraqi Freedom and Operation Enduring Freedom, otherwise known as the wars in Iraq and Afghanistan (Defense, 2010). Many of these fatalities and horrific injuries have come when transport vehicles drive over or next to improvised explosive devices (IED's) that are detonated. These hidden explosive devices come in so many shapes and forms that it is extremely difficult to identify and disarm all of them. Since many military vehicles have external fuel tanks on the under-carriage, they are vulnerable to a flare-up during an IED detonation because the tank can be pierced from shrapnel or gunfire.

In these instances, the fuel is expelled (often up to 100 gallons in a tank) and can ignite; thus adding to the awful damage of the blast. The reduction or elimination of this fuel flare up can save lives and major injury on the battlefield and has been addressed by HPS with the invention of the NCASE product.

NCASE is a passive fire mitigation system that releases fire-extinguishing agent (in powder form) when impacted. These agents absorb heat in a direct application method that suppresses the fire in less than a second. The current version of the NCASE product contains sealed plastic pouches of fire extinguishing powders that are sown into a Kevlar® blanket that is then strapped around a fuel tank. Kevlar was chosen as the material for this product because of its general strength and versatility; it is used in many military applications where strength and durability are important product characteristics. Although Kevlar is used in many military applications, HPS wanted to validate their product design and ensure that the Kevlar material used on their product would stand up to the rigors of its intended environment.

In order to determine the properties of the NCASE materials in the proposed environments, HPS connected with Brigham Young University to conduct this testing. This product was chosen as a case study not only to determine if the materials they selected are suitable for use in the intended harsh environments, but also to determine whether or not modified or in-use tests can be effectively developed and utilized in the new product development process.

1.3 Problem Statement

Testing should always play an important role in the development of new products and can be done in various ways. In standardized testing, all of the tests are outlined with very specific details with no question as to how the test is to be performed. However, some tests need to be modified in order to gauge performance in specific environments that are different from those allowed for standard tests. The question then arises, "How can performance in specific conditions be reliably measured without standardized tests?"

In-use testing can be much more applicable in determining performance characteristics of a product or its components but it is often more difficult to perform in a repeatable and meaningful way that can be trusted by customers. Difficulties arise with in-use testing because there are so many unknowns that must be carefully considered and addressed in the course of the testing process. Many product developers have a hard time deciding what tests to use in order to prove to themselves and to their customers that the products are suitable for use. Once specific product characteristics are identified and selected for further testing, it is challenging to go through the process of designing a testing methodology that would yield consistent and quality results. Because in-use tests cannot generally be picked out of a book or looked up on the internet, they require a greater deal of creativity than standardized testing alone. Developing in-use testing can be incredibly challenging because all developed tests *need* to be repeatable, accurate, realistic, doable, believable, and understandable.

1.4 Objective

The objective of this thesis is to develop a set of guidelines that can be used by entrepreneurs and product developers to develop an effective testing methodology within the new product development process. This thesis will also define procedures by which products can be tested in circumstances when existing standardized tests are not suitable or applicable for the intended product uses and/or environments. Through a case study, this thesis will document the process by which the NCASE product and materials were tested and evaluated, including the modification of existing standard tests and the development of completely new in-use tests for the purpose of evaluating whether or not the product is suitable for use in the intended environments. In addition to exploring the testing methodology, the integration of in-use tests is greatly explored throughout the thesis.

1.5 Thesis Statement

Through the analysis of the product testing used in the case study, a set of guidelines can be developed to assist in a generalized method for new product testing.

1.6 Case Study Null Hypothesis

Through the analysis of the product testing used in the case study, a set of guidelines *cannot* be developed to assist in a generalized method for new product testing.

1.7 Methodology

After a thorough review of literature discussing the key points of product development, testing methodologies, and some applications and guidelines for in-use testing, a special case study was performed with Hazard Protection Systems' NCASE product. HPS needed to test their NCASE product to prove to themselves and to their customers that the product materials would hold up to the extreme conditions experienced in Iraq and Afghanistan. After these product uses and environments were discussed, tests were developed (either modified from standard tests or they were developed from basic principles) for the specific purpose of analyzing the properties of the NCASE materials. After considerable effort in creating scientific in-use tests, the materials were then evaluated using these new procedures and the data was evaluated and proclaimed suitable or unsuitable for use based on the acceptance criteria designed into the tests. After testing and evaluation of the NCASE product and its materials, a list of suggestions or guidelines was created in hopes to guide future product development efforts where standardized tests do not adequately demonstrate performance characteristics of the intended products. These guidelines were developed based on literary research, interviews with others who have developed in-use tests, and personal experience with the development of the in-use tests for the NCASE product.

1.8 Scope and Delimitations

Explosive field-testing will not be completed on the NCASE product. Testing of the effectiveness of the internal powders will not be addressed. This application of standard and modified tests will only be directly applied to the NCASE product.

1.9 Glossary of Terms

acceptance criteria—Conditions agreed upon by an organization and its customer to which the product must meet in order for the purchase to ensue.

functional testing—Tests that are performed to evaluate the actual performance of a new product or component of a product. These tests can be done with standard tests (if available) or in-use tests.

in-use test—A laboratory test designed to simulate real world conditions in a controlled environment. In-use tests are not regulated by a sanctioning body and are commonly designed for a specific product application.

standardized test—A laboratory test of a product or material that has been documented and accepted by a sanctioning body as a standard test. These tests have a wide appeal and are fairly broad in their application.

2 REVIEW OF LITERATURE

2.1 Review of Product Development Process

Whether or not an inventor or product development firm has a specified product development process, there is a common set of steps that are generally taken to bring an idea from conception to a successful new product. Some outlined processes are very complex while others are very simple. To maintain consistency in referring to the product development cycle, this thesis will follow the steps in the order that Crawford and Di Benedetto have outlined in "New Products Management" (Crawford 2008). These steps are not, necessarily, the complete or the simplest, but they serve as a good starting point from which to consider the development process.

2.1.1 Step 1: Opportunity Selection

The first step of the product development process is "strategic in nature and is the most difficult to describe or define" (Crawford 2008). If an individual or firm decides to move forward with development of a product that will have no value to the end customer, they will ultimately fail no matter how unique their product may be. Identifying a currently unmet customer need and then proceeding with developing a product to fill that need will yield the greatest possibility for success. Some may simply come up with an idea on-the-fly for a new product while others might have a structured approach to identify and then select customer needs to drive their product development. While there are many different approaches to opportunity selection, the important thing to understand is that no matter the approach, making sure there is a legitimate need for a new product is the most important part of the development process. All following steps would subsequently be in vain unless the product fits a real and marketable customer need.

2.1.2 Step 2: Concept Generation

After a legitimate need has been identified, the next step in the process is to create ideas of how to fulfill this need. Again, this is another process that can be done in many different ways. IDEO, a California-based design company, was featured by ABC's Nightline for a segment that showcased their design process; their concept generation methodology shown in that special has proven effective over time. After IDEO designers agree on customer needs, they split up and have a limited amount of time to come up with as many designs as possible that are aimed at satisfying those needs. One of the interesting aspects of IDEO's process is that the designers are highly encouraged to come up with pie-in-the-sky ideas; although such ideas may not always be feasible for production or development, others may be able to take aspects of those aggressive ideas and turn them into a very feasible and effective product designs (ABC, 1999). This process of idea creation allows the designers to develop product ideas that would then be shared and selected in the concept evaluation step described in the next section. By developing as many product ideas as possible within a reasonable time period, there will be a greater selection of ideas to pull from when all of the design ideas are on the table together.

In this stage of concept generation, there are many different ways to approach this process of creating new ideas. If this process is done with the help of many different designers and engineers (as compared to a lone-ranger type approach), it is important to appoint a leader that can facilitate this idea creation process. The leader must “actuate this brainpower to generate relevant options…he must provide a ‘safe place’; he must help the participants perceive the elements of the problem, perhaps in a new light….The leader must also infuse electricity into the meeting…and manage the group dynamics along the way” (Buggie, 1981).

2.1.3 Step 3: Concept Evaluation/Selection

The New Products Management textbook (Crawford, 2008) outlines a handful of different evaluation tools that can be used in narrowing down ideas. These tools are typically focused on quantifying how well the proposed design will fit customer needs. IDEO started its evaluation process for the next-generation shopping cart (as seen in the abc documentary) by bringing all of the designers together in a big room and having them place their idea sketches on the walls around the room. Each person was given a set number of Post-it notes that they used to identify their favorite designs. At the end of this process, the top designs with the most votes were selected for concept testing by breaking the group into small teams to build working prototypes in order to demonstrate the various designs.

Generally, after some designs have been selected in the design process, it is common to build some basic functional prototypes (or concept models) in hopes of proving or disproving their effectiveness. In IDEO’s example, the designers split up into groups on a few different designs for a next-generation shopping cart. The groups built a mock-up of their designs and they all brought them back together to evaluate whether the ideas would actually work in real life. This step was highly important because it allowed everybody to physically experience the ideas of their peers and allowed them to more effectively evaluate whether the ideas presented were solid or not. As a result of this process, the whole group was able to come up with a final design that incorporated individual aspects from each different prototype (ABC, 1999).

While IDEO's prototypes were built to simply provide a physical incarnation of the selected designs so everybody could see, touch, and use the product, it is possible for groups to put their designs through a series of standardized or modified tests depending on customer demands. For example, if a new product must withstand a specified force before breaking, it would be important to build a prototype early in the development process that would have the same strength characteristics as the final product so that the tests performed will be completely applicable to the end product. The prototyping process can be used as an aesthetic tool to help designers better visualize the product and it can also be used by engineers to make sure the product will perform well in the intended uses and environments.

2.1.4 Development

It may be difficult to proceed with the development step because so many great ideas have arisen in the concept evaluation and selection phase and the requirements of the product are so varied. Crawford and Di Benedetto summed up the challenge: "Designers undergo rigorous training to learn how to design products that function well mechanically, that are durable, that are easy and safe to use, that can be made from easily available materials, and that look appealing. Clearly, many of these requirements will be in conflict, and it is up to the skillful designer to achieve all of them simultaneously" (Crawford, 2008). In the design process, it is important to develop specific design goals or objectives, which include:

- Design for Speed to Market
- Design for Ease of Manufacture
- Design for Differentiation
- Design to Meet Customer Needs
- Design to Build or Support Corporate Identity

- Design for the Environment (Crawford 2008)

The development process is the step where a design is chosen based upon the previous steps of concept generation and selection plus a synthesis and modification so that they all fit into a single concept model. Product design is a tricky process because it must be done within the "triangle of constraints: the end use of a product, the materials of which it is made, and the tools and processes by which it is made" (Parsons, 1989).

2.1.4.1 Prototype Development

"Prototypes are a form of experiment in that the organization is generally testing some aspect of the new product or of the process by which the product will be built" (Bean, 2000). Although prototypes can be created and used in the concept phase of product development, this later, formal prototype stage of development is highly focused on the end product rather than concepts or ideas. After IDEO took all of their ideas and merged them together for a final design, everybody got together to create a high quality prototype to demonstrate their finalized product (ABC 1999). A high quality prototype at this level allows the designer to perform critical evaluations of the final design. These prototypes can be taken to the end user to see how actual customers would use the product and how it would perform under such conditions; this testing is commonly referred to as product use testing, in-use testing, or market testing. "Testing should continue until the team is satisfied that the new product does indeed solve the problem or fill the need that was expressed in the original protocol" (Crawford, 2008). If the design proves faulty, it is time to go back to the drawing board and make some minor or major adjustments to the current design and then prove the design through the development and testing of another prototype.

An important aspect of prototyping is to make sure the design can be economically manufactured. "The process design must be compatible with the part design for the prototype to have any real meaning. If the part design does not satisfy all of the criteria or design rules for the manufacturing process that is envisioned, neither the part-design dimensions nor the performance characteristics can be verified" (Strong, 2006). Once a designer feels like the product design and the prototype have passed the necessary tests, it is time to move to product launch.

Bean and Radford emphasize the importance of having a prototyping plan in their book *Powerful Products: Strategic Management of Successful New Product Development*. "This plan will include tests appropriate to the product at that stage of development but will also include tests to assure the product team that the prototype, in critical aspects, sufficiently represents the product that production will build and customers will receive to make the tests both technically useful and effective in communicating information to the manufacturing plants and to critical customers" (Bean, 2000). This prototyping plan is a great activity to integrate into the development process and it is something that many literary sources fail to address or properly emphasize.

2.1.4.2 Benefits of Prototypes

While there are many benefits to prototyping, David S. Bent created a simple list of benefits that show why the prototyping process is so crucial to the new product development process:

1. **Knowledge**—Prototyping can help the design team overcome lack of knowledge of how the product will perform in a real-world situation.
2. **Risk Reduction**—By creating and evaluating a prototype, much of the guess work can be overcome and there can be greater confidence in the final product.

3. **Reduced Time to Market**—Effective prototyping and testing can allow the design team to proceed with certainty instead of ambiguity.
4. **Marketing to Client**—An effective prototype can be touted as real physical evidence of a successful design which may influence a client, vendor, etc. to make investment or purchase decisions.
5. **Psychological Benefit**—If the prototyping process proves successful, it can boost the confidence of the design team, which can translate into added enthusiasm for the remaining work. (Bent, 1999)

2.1.5 Launch

There is no such thing as a perfect design, so even though a designer or engineer might want a significant amount of time to further develop a product before launch, it is sometimes beneficial to simply move forward with the best design because customers cannot and will not wait forever before moving on to another product that can fulfill their needs. While there are many details about product launch that can be covered (such as marketing, manufacturing, distribution, etc.), the most important concept for product launch in the context of this thesis is that once a product is launched, the design process is never over. Because a design is never perfect, and also because customer needs change over time, it is vital to constantly re-evaluate and improve the product after it is launched. By going through the design steps over and over, some would argue it is a cyclical process, but if done properly, it is should be more of a helical process because every cycle should bring an upward improvement, preventing you from going in the same circle over and over again.

2.1.6 Testing—Crawford & Di Benedetto's Oversight

The steps in the new product development process as outlined in this thesis and by Crawford & Di Benedetto are very effective in illustrating the major steps in the process with one exception. The prototyping process is mentioned, but there was a lack of emphasis on the actual testing of product prototypes. Without a proper and detailed testing plan, the prototyping process is essentially done in vain. Only by constructing a stringent and scientific testing process, can one most effectively capitalize on the prototypes that are created. Therefore, "Testing" should stand alone as an outlined step in the product development process because it is very different from "Prototype Development" and also a very critical step in ensuring that newly developed products are successful.

2.2 Testing

After prototypes are built, they must be evaluated by constructing a series of appropriate tests to either validate the design, or identify areas for design improvements. Prototype testing at the basic level should evaluate whether or not the product will perform as intended and also hold up to the rigors of frequent and heavy use.

Testing of prototypes can be done with already defined standardized tests, or with in-use tests. To determine which kinds of tests are necessary, the product development team should group together to identify key metrics that, if measured, can prove or disprove the efficacy of the new product. Standardized tests are great because they are pre-set procedures that can be performed easily and the results can be trusted and compared by almost anybody. Limitations to standardized testing exist and are covered in the following sections, along with a discussion about in-use testing and why it can be an effective complement to standardized tests.

2.2.1 Purposes of Testing

Before discussing the specifics of standardized and in-use testing, it is important to review why testing is important in the product development process. Even though the Crawford & Di Benedetto text did not list Testing as a major step in the process, they did emphasize the importance of product testing in an earlier edition of the *New Products Management* book. The book outlined four benefits of product testing and are listed below (Crawford, 1991):

1. **Fulfill Protocol**—This purpose is far more important than the following three. The aim here is to see whether or not the designers and engineers have produced a product that fulfills the desired customer needs.
2. **Obtain Ideas for Improvements**—Even if there are some flaws inherent in the design before building a prototype, it is often helpful to actually build the prototype because it can make it easier to visualize solutions to the problem.
3. **Learn Modes of Use**—As most products can be used in various ways, it is important to perform testing in order to explore other possible uses for the product.
4. **Verify Claims**—While customers and competitors can often be very critical of product claims, it is vital to ensure that the product absolutely fulfills all claims made by the company that will produce the end product. Marketing people need this validation before they can feel solid about the product they will promote. "Testing enables the manufacturer to justify certain types of claim about his product which may be made in advertisements and are likely to be challenged by the media—or by the public. The existence of supporting technical evidence can save valuable time" (White, 1973).

2.2.2 The Testing Process

While many authors value the importance of testing, there seems to be no consensus when it comes to the sequence of steps for effective product testing. In an article titled *Learning by Experimentation: Prototyping and Testing*, Stefan Thomke gives a solid approach to the testing process as part of the product development process. The process, shown in Figure 2-1, shows how an organization should integrate their design, prototypes, testing, and analysis. These steps are very simple but effective in showing that the process of testing should be an iterative process. Every time the development team goes through the process of testing as outlined above, they must evaluate whether or not to perform another sequence of testing or move on to the next step in the product development process.

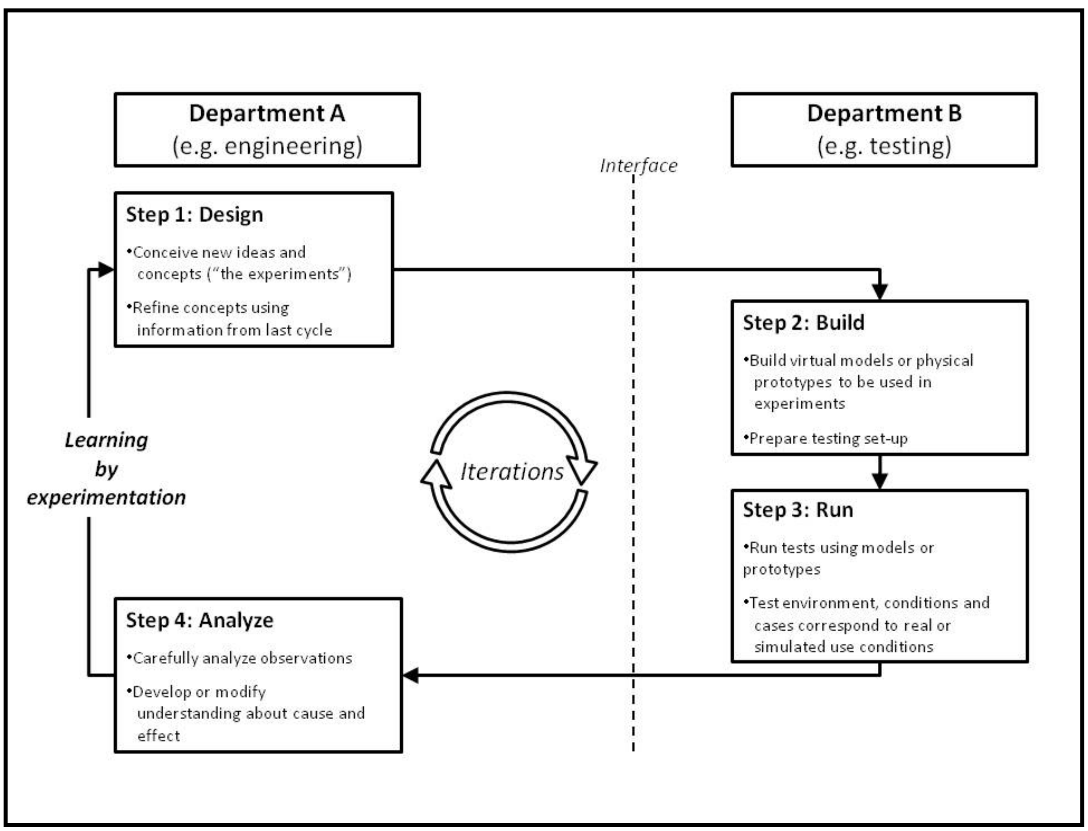

Figure 2-1—Testing Process as Outlined by Thompke (Thompke, 2008)

While the chart in Figure 2-1 is very descriptive about the testing process as a whole, it does not provide much detail about the types of tests that should be run. This thesis proposes a sequence to help in selecting what kinds of tests to perform and when they should be used in the testing process.

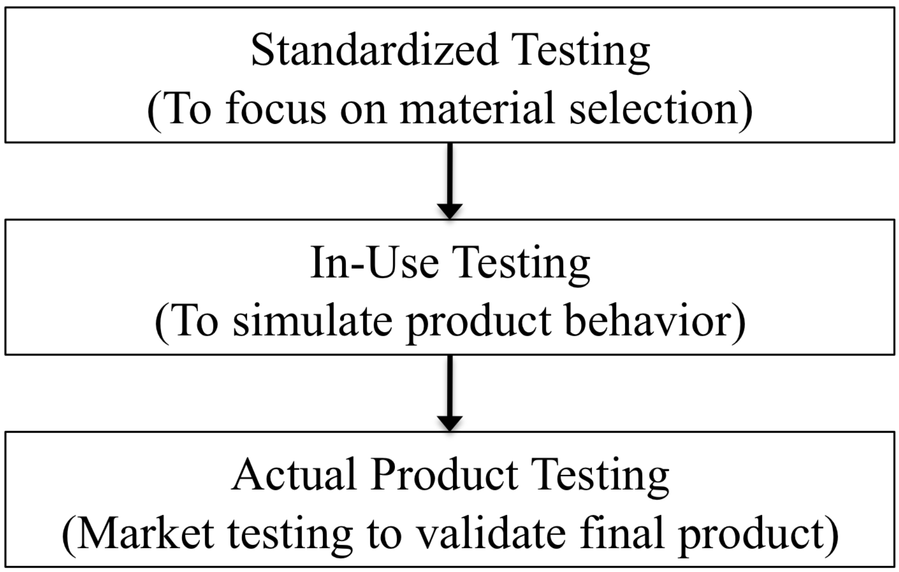

Figure 2-2—Progression of Tests in the New Product Development Process

Figure 2-2 shows the progression that tests should take in the product development cycle. First, standardized tests should be used (as needed) to analyze the performance of specific materials that will become a part of the product. If certain product components need to be able to withstand a specified force or have specific performance properties, standardized tests are generally the best fit for this situation. After the material selection is complete, various components of the new product can be tested with customized tests aimed at evaluating various performance factors in a controlled environment. These types of tests are commonly referred to as "in-use" tests. Lastly, actual product testing (sometimes referred to as market tests) can be used to ensure that the product can be properly and easily used by the end user with high satisfaction.

2.3 Developing Acceptance Criteria for Testing

Before running any tests, it is critical to construct a list of acceptance criteria as to properly evaluate the testing results. Testing should always be conducted with the purpose in mind of accepting or rejecting the current product design based on the results of the test. When the tests are designed, they should include the minimum criteria for accepting the product for further development or for product launch. There are two major categories for developing specifications or acceptance criteria for a product: customer-preference driven, and specification driven. The general process for each method is shown in Figure 2-3 and each process is discussed in following sections.

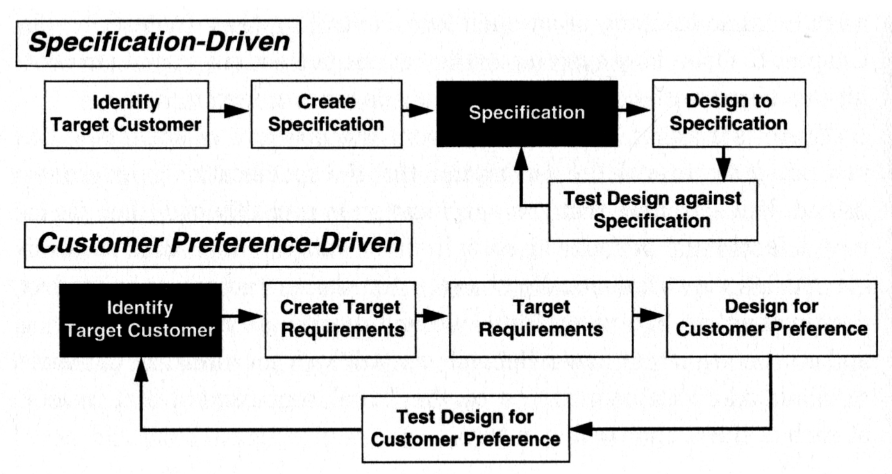

Figure 2-3—Specification vs. Customer-Driven Process (Reintertsen, 1997)

2.3.1 Acceptance Criteria for a Specific Customer (Customer-Preference Driven)

If a product is developed for a specific customer, there is often a clause in the purchasing contract that states specific criteria that must be met in order for the purchase to be made. Many times, the customer's quality control department will do the actual testing on a delivered product to ensure that it passes all of the stated requirements. If this is the case, the manufacturer should be doing the same types of testing to ensure that all of their products will be accepted. These criteria should be agreed upon as early as possible as to ensure that the development process is focused around the proper performance metrics of the new product.

2.3.2 Acceptance Criteria for a General Market (Specification-Driven)

Sometimes products are released into broad markets where it would be almost impossible to have specific acceptance criteria in place for each specific customer. The acceptance criterion for a product that will be released in a general market can be developed in two different ways: through perceived customer needs, or by testing against a direct competitor's product.

2.3.2.1 Criteria Based on Perceived Customer Needs

In cases where there no specific customer contracts for a new product, it is necessary to make a number of assumptions as to what the most important product specifications should be. These product traits must be carefully assessed through interviews with customers in the target market, market research, or even personal experience in the market to which the product will be released. Listed below are two important functions of a good specification:

1. “First, a specification is critical input for the design process. It tells the design team which functions the customer is likely to value in the product. As such, the specification is the echo of the customer’s voice that is heard in the design lab.
2. The second key purpose of a specification document is as a control device for the project. By setting a goal for the performance of the product we create a reference point from which to measure it” (Reinertsen, 1997).

2.3.2.2 Criteria Based on Competitor’s Products

Sometimes, instead of investing in considerable resources to gather the voice of the customer as to their needs and wants for a specific product, it may be cheaper to use an existing product as the base for all testing criteria. If a newly developed product can out-perform an existing market leader, there is a high probability of success in the marketplace. “Where competition exists, it is usually right to test against the market leader. If, however, you are aiming at a particular group in a segmented market, you should test against the brand most likely to be used by that group, which may not be the overall market leader” (White, 1973).

2.3.2.3 Case Study: Hewlett-Packard

In Hewlett-Packard’s (HP) early years, the development team had a unique approach to using perceived customer needs in the design and testing stages of product development. Before development was started on a new product, the development team would get together to write the catalog page for the product they were going to develop. This catalog page would reflect exactly what the customer would want to see when considering purchasing a new product. By doing this exercise, the development could directly focus on the most important product attributes that a customer would desire. If a product attribute was not important or critical enough to make it into the preliminary catalog page, it was subsequently not a major focus in the development process. These aspects that were significant enough to make it on the catalog page were a primary focus throughout the development and testing stages of product development for HP (Reinertsen, 1997).

2.3.2.4 Case Study: The Chemical Industry

In the chemical industry, testing is a very important piece in the development process even after the development process is complete. Before a chemical company (e.g. Dow) releases a new product, they test a number of batches in order to construct a range of product characteristics that will be advertized to the customers. When a customer orders a product such as a specific plastic, they know that the product properties be within a set range as previously identified by the chemical company. After the chemical company actually produces each batch, the specific tests are performed to measure the exact product characteristics to ensure they are within the range of the overall specifications. These detailed results are given to the customer to provide them with a more accurate report of the product upon delivery. General testing procedures and methodologies can vary between industries but it is important to understand the importance of testing in the product development process, no matter the industry.

2.3.3 Acceptance Criteria for a Specific Customer (Customer Preference-Driven)

Products developed under a contract to a specific customer generally outline specific criteria that must be fulfilled before the customer will make the purchase. These types of transactions are more common in business-to-business transactions, but can also be found in the consumer market. Often, these contracts are binding which solidify the purchase as long as the product meets the minimum acceptance criteria. In such instances, it is important to decide with the customer as to what the minimum standards should be. The acceptance criteria should be the primary focus during the development of the product in order to ensure the customer is getting exactly what is desired.

2.3.4 House of Quality

One of the most common tools used in developing product specifications and product acceptance criteria is the House of Quality (HOQ), which is one of the primary design tools of the Quality Function Deployment (QFD) technique. This tool can be used in both the specification-driven and the customer preference-driven methods discussed previously. HOQ's key function is "to translate the requirements of the upstream stage of the NPD process to the input parameters of the downstream stage, and enable the downstream stage to understand the trade-offs required by often conflicting requirements of the upstream stage" (Bhattacharya, 2008). In other words, the process helps take customer preferences and transform them into ranked product specifications. Figure 2-4 shows the basic layout of the matrix that is completed and evaluated in the HOQ process.

Although the House of Quality is typically used in the design process of product development, it can be a great tool in the testing process. Since the HOQ matrix reveals the most important product attributes and characteristics desired by the customer, it should be referred to before testing. When designing the testing plan, the highest ranked product characteristics should be on the top of the list when considering what tests to run and what test metrics and results would be the most important to the end user.

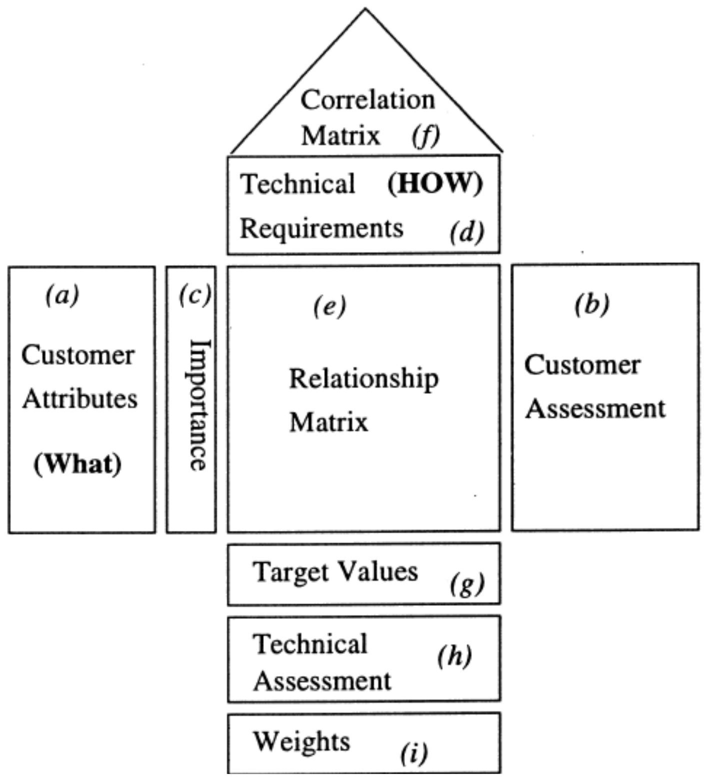

Figure 2-4—House of Quality Matrix (Temponi, 1999)

2.4 Review of Standardized Testing

There are a number of procedures that are highly trusted and already established for the purpose of measuring performance of products and materials. These pre-established testing procedures are referred to as standardized tests and can be incredible tools in the world of product development; they are explained in detail below.

2.4.1 History of Standards

Various engineering standards have been around for ages dating back to around 3000 B.C. with evidence of standard measurements found among the people of Egypt, Mesopotamia, and the Indus Valley. The Indus Valley Civilization, for example, developed a standardized system of weights and measures, which allowed for more precise measurement for construction activities (Baber 1996). This standard set of measurements allowed the people to accurately and precisely measure and build according to those measurements, resulting in much higher quality buildings and formations. Even early Bible accounts indicate that measurements were initially taken using the forearm, hands, and fingers; even though the length of everybody's forearms were not consistent, it allowed for at least some type of measurement. The biblical measurement of the cubit (forearm length) ranged from 17.5" to 21.5" around 800 B.C.; while this measurement was adequate for many purposes, our world we know today would not exist without a stronger system of measurements.

The technical needs of our day have shifted dramatically from the days of old where the only metrics used were lengths and weights. Because of these new and more intricate needs, it has been crucial to expand the use of standards as to provide our society with the proper tools to effectively and consistently deliver high quality goods to its citizens. In a constantly changing world where certainty can hardly be guaranteed, solid standards can help consumers and businesses make wise decisions by ensuring confidence in the products they both purchase and sell. Without standards, it would be difficult to trust any claims made by companies trying to sell their products. Standards allow consumers to make apples-to-apples comparisons between different products in a way that establishes confidence and power in their purchasing decisions.

2.4.2 How Standards are Developed

Standards are usually developed after a special need arises. It would be foolish to spend significant amounts of money to develop a test that is of no use to any party or individual, thus, many tests are developed after a need is identified. If a private organization develops a test for a specific application, it may wish to share the details of this test with a governing body in order to legitimize and regulate the testing parameters. Standards agencies are very eager to work with such labs and private parties in an effort to provide a documented standard for the rest of the world to use.

The International Organization for Standardization (ISO) is a governing body that regulates and controls various standards for many different industries and is explained further in the following section. They have documented their process by which their standards are created which is similar to the other major standards agencies. The first step in their process of creating a standardized test is to wait for an industry or organization to propose a test for a clearly established need. Next, "to be accepted for development, a proposed work item must receive the majority support of the participating members of the ISO technical committee which, amongst other criteria, verifies the global relevance of the proposed item…" (ISO, n.d.). After the standardized test goes through this process, it can be approved as an ISO certified standard. Another way a test may be identified is through an ISO policy development committee that analyzes the needs of developing countries and other consumers for possible needs of standards. Once needs are identified, it is sent to a development group that, in turn, goes through the aforementioned development and approval process to solidify the test as an ISO standard (ISO, n.d.).

2.4.3 Recipe for a Standardized Test

Generally, an outlined standardized test provides clear instructions on how to perform a test so that anybody in any location can perform the test and trust the results as long as procedures are properly followed. Standardized tests can be broken down into four parts:

1. **Material or sample preparation is described in detail**—Samples must be prepared with no deviation to the instructions because any change will cloud the

final results and will prevent a true apples-to-apples comparison of other materials or products that are tested in the same manner.

2. **Testing procedures are carefully outlined**—Included in this step, machinery and equipment needed to perform these tests are identified in great detail. All equipment must be calibrated and approved for use in the standardized test.
3. **Proper data collection methods are outlined**—These procedures must be followed precisely so that the analysis can be trusted.
4. **Testing report format must be created**—All aspects of testing report must be outlined within the text of the testing procedure. This report outline describes exactly how the data analysis is to be conducted and how results are to be displayed.

While some tests may vary from the above outline, this should provide a good impression of what is contained within the text of a standardized test.

2.4.4 Standardized Testing Agencies

There are many different groups and agencies that have become respected authorities on various types of standardized testing. This section will cover some of the major agencies and describe their history, focus, and importance.

2.4.4.1 American Society for Testing and Materials (ASTM)

ASTM is one of the biggest standards agencies and its influence stretches into a host of industries. Even though the name indicates it is an "American Society", it has expanded its reputation to be one of the most trusted standards organizations in the world. The standards within this organization are focused primarily on "technical standards for materials, products, systems, and services" (ASTM International, n.d.). ASTM has a rich history that started over 100 years ago when a group of engineers and scientists decided to create some standards in the railroad system. Their efforts resulted in creating solid standards for rail construction which drastically improved the safety of railroad systems (ASTM, 2010). As there were more needs throughout the country for consistent standards, ASTM offered its expertise and expanded their scope to include various industries. It continues to work with various groups, organizations, and governments to create standards that ultimately establish higher quality and safer products throughout the world.

2.4.4.2 America National Standards Institute (ANSI)

ANSI started in 1916 when the American Institute of Electrical Engineers invited four other major engineering organizations to join together "in establishing an impartial national body to coordinate standards development, approve national consensus standards, and halt user confusion on acceptability" (ANSI, 2010). It's first standard was on pipe threads and then they started developing major safety codes to promote safety in the workplace throughout the United States. Over the years, ANSI has joined other standards and safety organizations to create a large and respected standards organization. Their stated corporate goal is "to lead and foster the work of the broad-based U.S. standardization system, to protect the integrity of this system, to promote global competitiveness of business, and to enhance the quality of life of U.S. citizens" (ANSI, 2010).

2.4.4.3 International Standards Organization (ISO)

The ISO is the largest standards organization in the world, controlling over 18,000 international standards in its portfolio ranging from agriculture and construction standards to medical devices and even management of services (ISO, 2010). The focus on international standards has facilitated trade of goods and services between different countries because with the standard in place, both parties can be confident that their purchased products are of consistent and high quality. The ISO 9001 family of standards is essentially the gold standard of quality control for almost all sectors within manufacturing and is highly regarded and well known in that field.

2.4.4.4 German Institute for Standardization (DIN)

The German Institute for Standardization, or DIN (Deutches Institut fur Normung), has been based in Berlin since 1917 and has primarily focused on creating national standards for Germany, but many of these standards have carried over their borders and now over 90% of their standards have become internationally accepted (DIN, 2010).

2.4.4.5 Japanese Standards Association (JAS)

In 1945, Japan's Minister of Trade and Industry allowed JAS to form as a major standards organization for the country. Their stated objective is "to educate the public regarding the standardization and unification of industrial standards, and thereby to contribute to the improvement of technology and the enhancement of production efficiency" (JSA, 2010). They currently focus heavily on maintaining standards and documenting practices that can be used to strengthen the quality control functions of Japanese based companies.

2.4.4.6 Consumer's Union (CU)

The Consumer's Union is much like the previously mentioned standards organizations except the focus of the Consumer's Union is geared heavily towards end-user or consumer products. CU's mission "is to work for a fair, just, and safe marketplace for all consumers and to empower consumers to protect themselves" (Consumers, 2010). Reports are created based on product research, customer surveys, and laboratory research. The combinations of all aspects of their reports have helped Consumer's Union become one of the most trusted sources in regards to consumer products.

2.5 Review of In-Use Testing

With so many different standards agencies controlling thousands of different standards each, it is tempting to suppose that any aspect of product or prototype testing that needs to be done will have a related standardized test somewhere in the world. Although many procedures are carefully defined and maintained by oversight organizations, there will *always* be needs for customized testing that does not fit any pre-defined procedure because products and consumers are constantly changing.

An in-use test is much like a standardized test, except it generally is a more specific test to measure the performance of a material or product in a way that is not currently standardized and documented by a governing body. If an in-use test is created in the proper manner, it can actually be more useful than a standardized test, except it will not have the big-name organization to validate the strength of the test. While there are multitudes of standardized tests to choose from when conducting product testing, sometimes the available tests do not adequately measure performance in a way that is valuable.

As in the example in Chapter 1, if a fuel mileage estimate for very mountainous driving is desired, there are no available tests for this specific application. If a dealership in the area took the initiative to develop a specific test consisting of mountainous driving to provide his customers with better information for purchasing his automobiles, he may sell more cars or at least take pride in providing his customers with more pertinent data. Even though this newly developed test may not necessarily be immediately adopted as an EPA standard, if the test is documented and executed well, it could provide far better information than any readily available standardized test.

2.5.1 In-Use Testing and Design of Experiments

A product test is essentially an experiment that is set up to determine specific characteristics of the product. In-use tests are very similar to experiments but they are typically less known and usually appeal to a much smaller audience than standardized tests. During the course of this literature review, surprisingly few sources were encountered that specifically addressed the topic of in-use testing as it pertains to product development. In order to provide a clearer approach to the process of constructing and administering an in-use test, the classic scientific process is a great tool and is clearly defined in texts specifically addressing "design of experiments" or DOE. Following is a description of major steps that should be taken throughout in-use testing. Many of the DOE steps have been integrated into the following process.

2.5.1.1 Step 1: Identify Critical Customer Needs

Virgil L. Anderson outlines "Formulation of the Problem" as one of the major experimentation steps in his book *Design of Experiments: A Realistic Approach*. This can relate to identifying critical customer needs for the product. Even though customer needs are assessed when designing the product, the most critical customer needs must be identified as to provide a basis for testing. Once all of the major needs are identified, then the organization doing the testing can proceed to the next step of the process.

For example, if a marketing claim says that a specific product can be used for 1000 hours without needing service, this would obviously be something that should be substantiated through rigorous testing before being advertized. Tests should not be arbitrarily devised simply for the sake of testing, rather, all those involved with the development and launch of the product should have the chance to suggest product characteristics that, if proven through testing, would make the product more marketable because customers can better trust the claims.

2.5.1.2 Step 2: Formulate Testing Procedures

After the critical needs are identified, engineers can proceed with designing a test that will effectively measure the performance of the outlined product characteristics. It is important to identify which variables should be measured and analyzed when constructing various tests. "It is usually quite obvious what the variable should be; however, the means of measurement is sometimes quite difficult" (Anderson, 1974). For example, if endurance testing of a spring is desired, it is not possible to develop "endurance factor" as the final reported metric because it is not something that is easily measured and communicated. Rather, it would be much more applicable to measure the "number of compressions to failure" as it is something that can be attained easily in a lab and it will be a result that anybody can understand. Although this was a simple example, all factors in testing should be easily measureable and understood by a wide audience.

A crucial point to consider in devising a test is to ensure that the results can be adequately analyzed through proven statistical practices. Even if tests are performed perfectly, if the design of the test does not allow for a solid statistical analysis, the test would be done in vain. It is necessary to ensure that the results can be easily analyzed *before* proceeding with the test.

Another important step in this process is that of documentation. If a testing procedure is not properly documented, three major problems can arise:

- **Difficulty in Performing Test**—If the procedures are not carefully outlined, it may be difficult for the person performing the tests to maintain consistency throughout the tests, resulting in skewed, biased, or unreliable results.
- **Lack of Consistency**—If there is not a solid written procedure in place, there is a risk that the next person or group who conducts similar tests will not have the information they need to perform the test exactly as it was performed previously.
- **Lack of Trust**—If procedures are not carefully outlined, there is a risk that people outside of the organization may not trust the results of the tests because they cannot analyze and see exactly what was done to produce those results.

Because of the above factors, it is critical to have a keen focus on clear documentation of all testing procedures, no matter how simple they may be.

2.5.1.3 Step 3: Perform Testing

As the tests are being performed, it is critical that they are executed precisely as they are documented. Paul Berger, in his book *Experimental Design with Applications in Management, Engineering, and the Sciences,* addressed this point in the running of experiments, "It is vital that the experiment that was designed is the experiment that is run" (Berger, 2002). Throughout testing, it is also important to ensure that the data is recorded in a consistent manner and stored properly as to eliminate the risk of digital file corruption or data loss.

2.5.1.4 Step 4: Analyze Data

As stated in the second step, it is necessary to devise a test that produces analyzable results. After results are gathered, they should be analyzed precisely in the way that was outlined in the design of the test. Solid and trusted statistical analysis procedures and tools should be used so customers and peers have no question as to how the results are calculated. Results should be formatted with clear explanations and charts so as to make them easy to understand and trust.

2.5.1.5 Step 5: Evaluate Results and Draw Conclusions

A solid data analysis should provide a good basis for drawing conclusions and devising future action plans. If there are any questions or doubts about the validity of the results, the tests should be adjusted, or performed again under a more watchful eye. Once an organization is comfortable with the results from the testing, it must carefully evaluate the results. This evaluation can sometimes prompt a product modification or redesign, or the organization can proceed forward with further in-use testing, limited market testing, or it can jump ahead to product launch.

2.6 Market Tests

While the focus of this thesis is on the combined effects of standardized and in-use testing, it would be a mistake to overlook the potential importance of a solid market testing practice within the product development process. Product testing can take the shape of a market test where products are given to the actual customers in order to see the response of the end users. At this point, the products used for the market tests should either be a production run, or very similar to it because it is valuable to see how potential customers will interact with the final product. Measurement of results in market testing will often be very different than in previous testing stages. Surveys with results on the Likert scale will provide a measureable base from which results can be analyzed.

2.6.1 Market Testing Case Study—The Gainesburger Dog Food Failure

A classic example of a product that was not properly market tested was that of a new dog food product named Gainesburger. General Foods was the developer of the new dog food that contained more nutrition in less volume, so pet owners would not have to feed their dogs as much food (volume-wise) as they normally do. An extensive amount of testing was done in laboratory settings where doctors and scientists carefully measured out proper amounts of food for dogs in the lab. The lab results turned out great and General Foods decided to roll forward with the sales of its new product. Many customers bought the little packets of food and began to feed their dogs. To the surprise of General Foods and all of the dog owners, many pets eating the Gainsburger pet food were getting sick! After an investigation, researchers found that many of the pet owners were feeding their dogs much more than one packet of food simply because they just didn't think that one little packet was enough for their cherished pet. Even though the product would perform perfectly in lab conditions, General Foods should have done limited market tests to ensure that the end users would properly use the product as intended (Crawford, 1991).

This example proves that even though the final product was proven completely effective in laboratory environments, things can still go wrong! Customers do not always use products exactly as directed, so market tests can be a valuable tool to analyze potential customer behavior and to also see how severe the effects of product misuse can be.

2.6.2 Market Testing Case Study—The Hubble Space Telescope Blunder

Testing of prototypes of the final product in its intended use is critical to success of the product. NASA got to learn this lesson the hard way when they launched their Hubble Space Telescope. While the telescope was being built, the head of NASA, James Beggs, proposed that the fully assembled telescope be further tested on the ground before being launched into space, but his idea of more testing was quickly dismissed. The rest of the Hubble team thought that a fully assembled test would not reveal any more information than the separate component tests had already revealed. NASA launched the telescope without heeding the counsel of Beggs, which turned out to be a major error because the first images sent back to Earth were blurry and distorted which rendered the telescope in its current form as useless. This was an extremely costly mistake that could have easily been corrected had the team decided to heed Beggs' direction and perform further fully assembled tests before launching the flawed telescope into the sky (Slade, 1993).

2.7 In-Use Testing Case Study—Digital Photography Review

In the world of digital photography, the Digital Photography Review website has been one of the most trusted sources for objective and professional equipment reviews for many years. The site was created in 1998 by Phil Askey and was focused on not only providing a database of general camera information and news, but it focused heavily on providing intense high-quality structured camera reviews which has been a cornerstone in its ability to bring viewers to the site. Authors of the site believe in providing "unbiased content with as much detail as [they] can provide…" (Digital Photography Review, n.d.). At the time Digital Photography Review was created, there was a lack of solid equipment testing standards for digital equipment in the photography industry and Askey took this opportunity to develop a scientific approach in creating detailed, reliable, and useful reviews of new photography equipment. These reviews are now a solid resource for millions of photography enthusiasts and consumers who want to make informed decisions before spending their hard-earned money on new equipment. This unbiased content can be provided because of the extensive series of highly objective tests they have created. In regards to his employment history with Digital Photography Review and relationship with Phil Askey, Simon Joinson wrote, "As the cameras got more sophisticated and image quality started to improve the value of Phil's approach became more and more apparent, and it's no accident that by the time I met Phil, he was considered the *only* authority on digital camera image quality by every Japanese manufacturer I ever spoke to" (Joinson 2008). By being a first mover in developing testing procedures, Askey was able to have a major influence on the entire digital photography industry.

2.7.1 DPReview Lens Review Procedure

While there are many different types of equipment that Digital Photography Review has developed tests for, the following is a walk-through of the testing procedures for the camera lens reviews. This camera lens test that DPReview designed is a great example of a test that started out as an in-use test that has transformed into an industry standard. The first step in DPR's lens review is to take a series of pictures of the brand new lens in predetermined angles; these pictures are taken before any other testing procedures because the lens is free from smudges and blemishes that are commonly found after the intensive testing begins. Mulitple pictures of the lens are taken from each angle to ensure the picture used in the review will be perfect; while only 10-15 views are used per review, the total number of pictures taken of the lens can be close to 50. Figure 2-5 shows images from two different lens reviews where you can see that the angles, sizes, lighting, etc., are all exactly the same between the two images, allowing the viewer to perfectly compare the size and appearance of the two lenses. This image is important because it showcases the consistency with which DPReview performs its lens reviews (the lenses are from two different lens reviews from different times). This attention to detail is consistent throughout all of its tests.

Tamron Lens Canon Lens

Figure 2-5—Comparison shots of different lenses (Westlake, 2008)

Step two in the lens testing process is a studio shooting process where test charts are placed at a pre-determined distance under controlled lighting and the lens being reviewed is used to take many pictures of each chart. “Test charts have to be very precisely aligned and focused, and the data shot at least twice to assure reproducibility” (Westlake, 2008). These studio tests measure things such as resolution, distortion, falloff, bokah (background blur), macro performance, and image stabilization. These metrics are chosen for testing because poor performance in any of these areas will likely affect the ability of the user to capture excellent and clear photos in the field. Figure 2-6 shows a test chart that is used for evaluating macro (close-up shooting) performance of the lens. By taking a high resolution shot of this chart from a set distance and lighting, certain performance factors can be exposed and compared. This controlled studio shooting process is vital to the equipment reviews because it allows a quantifiable comparison of performance on factors that are nearly impossible to quantify by field testing alone. Results from this process are often used to narrow the focus on different perfomance characteristics in the third step of the lens testing process.

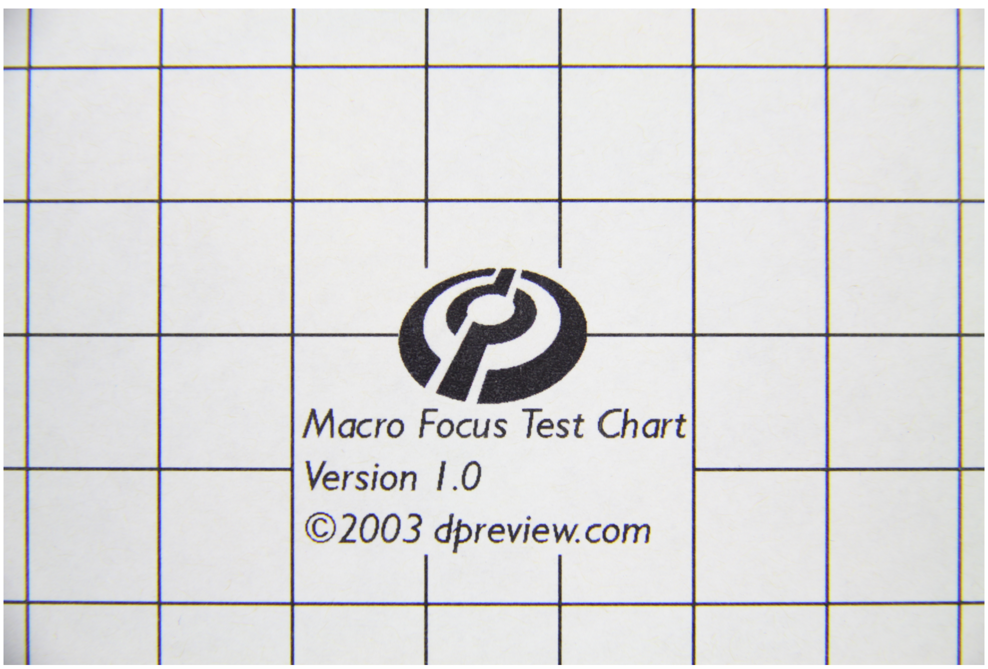

Figure 2-6—Macro Focus Test Chart for Lens Reviews (Westlake, 2008)

The final step in the review process is real-world shooting where the tester takes the camera and lens outside and starts shooting pictures in the same manner that many of the end users of the product would do. An example of this real-world testing is shown in Figure 2-7 where a camera with the tested lens was placed on a tripod and two pictures were taken. One picture was a full wide-angle (zoomed all the way out) and the next picture was taken at full telephoto (zoomed all the way it). These images are very useful in helping a custoemr understand the zoom power of a lens.

Wide Angle (fully zoomed out) Full Telephoto (fully zoomed in)

Figure 2-7—Shots Depicting Zoom Power of Lens (Westlake, 2008)

In talking about this process, one of the regular lens reviewers, Andy Westlake, stated "I actually prefer to shoot with the lens fairly extensively before processing all of the studio data, to get an initial impression of how it performs which isn't colored by those results" (Westlake 2008). This insightful statement shows that the process is highly planned and many factors are taken into consideration before the testing even begins. This reviewer realizes that if he processed all of the lab-testing results first, he would probably try to compensate for some of the weaknesses of the lens which is something many of the end users would not do, so he decided to do some shooting before reviewing the lab results to better simulate using the camera as the average user would. After doing a fair amount of non-biased real-world shooting (before seeing lab results), and once the lab data is processed, the reviewer then goes out for more real-world shooting with the purpose of illustrating any weaknesses identified in the lab tests. If the lab-based weaknesses are not replicated in the real-world shooting session, the reviewer goes back out and does more shooting to validate his findings. In relation to the real-world tests, Westlake says, “It’s also important to realize that a full lens review simply can’t be done purely in a studio environment: the technical data is hugely valuable but it says nothing about autofucus speed under various lighting conditions, or flare, or bokeh; for these we need to go out and take ‘real’ pictures. (Westlake 2008)” In an effort to maintain the integrity of the testing results, real-world pictures are taken with the same lens on multiple camera bases in order to identify and eliminate any deficiencies that may have been caused by the camera base rather than the lens itself.

This lens testing process shows that it is vital to be as scientific as possible but also provide real information that is exactly what the customer wants to see. DPReview’s camera and lens reviews provide incredible detail that only the most intense photography enthusiast would understand, but they also have very clear summaries of their testing that almost anybody can use and understand. From this example, we learn about not only attention to detail, but also the importance of clarity and understanding the audience as to provide them with the most understandable and valuable information possible. This process utilizes a great mix of subjective tests and objective tests and combines them to create a lens review that can be held up as a strong standard in the photography industry.

2.8 In-Use Testing Case Study—Garbage Can Testing

Dr. A. Brent Strong has been a leader in the waste-container industry when it comes to setting standards for rolling waste carts. Years ago, the city of Provo, UT commissioned Dr. Strong to devise a series of tests to be used in analyzing the waste-containers before making a hefty purchase. The containers were to be compatible with the automatic gripping arm dump trucks where a mechanical arm grips the can and hoists it to the top of the truck before spilling its contents into the back of the truck. The city was very interested to see if the carts would be able to withstand 10 years of use.

In devising tests, Dr. Strong had to consider all of the concerns of the city such as tipping force, ability to withstand high winds when empty, strength of lid, and more. One of the major tests that was devised was a grip and lift test that would put the cart through an endurance test of sorts to see if it could handle ten years worth of gripping, lifting, and dropping. If the carts were dumped 52 times a year (once a week) for ten years, then the life of the cart would experience the automatic loading process 520 times! Instead of using a dump truck for this testing, a gripper arm was obtained and used on a special rig for this testing. Each garbage can to be tested was filled with the maximum specified load which was over 300 pounds for the large carts, and then the carts were gripped, lifted, and set down 520 times or until failure.

This test really puts the same stresses on the cart that it would see in normal use, yet it had the advantage of being done in a controlled environment. Another advantage of this test was that it could simulate ten years of use in the matter of a few hours of testing; this benefit alone is so valuable that many garbage can manufacturers consult with Dr. Strong to perform such work so the companies can speed up their development process. The tests that were devised long ago for the city of Provo are now industry-wide standards because the tests were designed with practicality, repeatability, and efficiency in mind.

2.9 NCASE Case Study

To illustrate the application of in-use tests in the real world, this thesis will look at the process by which a new military product was developed and evaluated. In this situation, standardized tests could not adequately test the desired performance characteristics of the product because the product uses and requirements did not relate to any currently available standardized test. Because of this, new tests were carefully created and documented in an effort to effectively evaluate the product design and its materials. This section will describe the development process and some of the major characteristics that the creators of the NCASE wanted to have tested.

2.9.1 Development of NCASE

Development of the NCASE product started when one of the owners of Hazard Protection Systems, Inc. approached Dr. Brent Strong with a product idea because of his solid background and experience with new product development. HPS's product idea consisted of covering that could be filled with a flame-extinguishing powder that could be wrapped around an external fuel tank. This product was conceived in the hopes that it would reduce injuries and fatalities associated with incidents of rocket propelled grenades (RPGs) and roadside bombs, commonly called improvised explosive devices (IEDs), which often strike military vehicles.

After the development of the NCASE had started, HPS and Dr. Strong decided to develop a different design that used a fabric blanket with plastic bags of the flame-retardant powder sown into the middle layers of the fabric, much like a quilt. Candace Jesclard, CEO of HPS, had a lot of experience with sewing and figured out a way to cut and sew fabric so it would fit like a snug jacket over the fuel tank. HPS also realized at this point that a zipper could be sewn into the product so the powder baggies filled with the flame retardant powder could be installed after the jacket was sewn, thus avoiding accidental punctures of plastic bags during manufacturing. The new blanket design is shown in Figure 2-8 as a finished product.

Figure 2-8—NCASE Product Installed on Fuel Tank

Although both the original and the blanket designs would effectively dispel flare-ups on the fuel tanks, preliminary conversations with the military led HPS to shift their focus solely on the blanket design because it would be possible to use materials like Kevlar that are very familiar and trusted by the military in applications where the operating and environmental conditions can be quite rugged. Since using standard and trusted materials like Kevlar was important to the military, HPS and Dr. Strong decided to use a Kevlar fabric that was coated with a urethane polymer coating so as to reduce any possible ultra-violet radiation damage that would come from prolonged sun exposure, something that would be very common for the intended trucks in Iraq and Afghanistan.

After a few months of developing both ideas, HPS performed a live explosive test in Alaska to determine whether or not this concept would prove itself in real-world conditions. For the testing, a bare metal tank filled with fuel was shot with a large caliber rifle on a range and the result was a massive fireball that shot out of one side of the tank (see Figure 2-9). Next, another fuel tank was wrapped with the NCASE product and also shot with a large caliber rifle. There was a cloud of smoke/steam that came out of the can, no flame (see Figure 2-10)! The flame was dispelled because the bullet broke the powder bags and the fuel was infused with the flame extinguishing powder, preventing a dangerous flare up.

Figure 2-9—Sequence of Fire Testing a Bare Fuel Tank

Figure 2-10—Sequence of Fire Testing a Fuel Tank with NCASE Installed

The successful field tests of the NCASE product gave HPS the confidence they needed to present their product to the military (Strong, private conversation). HPS produced some full-size products to send to the military for testing at the official military testing center. After meeting with the military, HPS provided a full-scale prototype to be tested by the military's Aberdeen Test Center near Baltimore, Maryland. This full-size product testing was deemed successful and the Army decided to order NCASE wraps for one type of transport truck that is used heavily in Iraq and Afghanistan. Even though the military had indicated they would order many NCASE products for their trucks, they requested that extensive environmental tests be performed on the product to prove that the product will be suitable for use in the intended harsh environments. From this point on, the focus went from the product design to a validation process to ensure that the materials chosen for the final product would be adequate for the intended conditions. This validation process consisted of a variety of tests that were either newly developed or adapted from existing tests and are the focus of the case study of this thesis.

2.9.2 Environmental and Operating Conditions

Following are descriptions of the environmental and operating conditions that were considered when constructing the testing procedures for the NCASE materials.

2.9.2.1 Sunlight exposure

As the NCASE product will be used in desert environments, it is critical that the product be resistant to decay resulting from exposure to ultra-violet rays. As the product is to be used on an external fuel tank, it will be subject to sunlight exposure as long as it is outside. According to the World Weather Information Service, there are 4 months out of the year in Iraq where the daily high averages over 100 degrees Fahrenheit (WMO, 2010). Figure 2-11 shows the average yearly weather patterns in Iraq. These high temperatures come from intense sunlight exposure, which contains harmful ultra-violet rays that can cause decay in a multitude of materials, especially plastic materials. Unless vehicles are stored in a covered parking area, there is little by way of trees and vegetation to shield the vehicles from damaging UV rays.

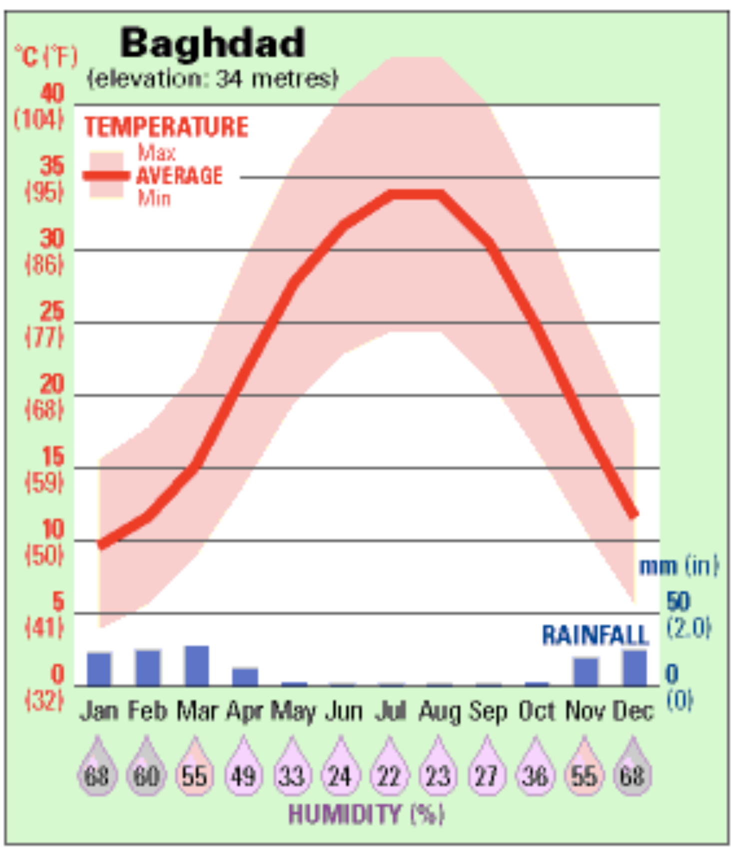

Figure 2-11—Average Weather Patterns in Iraq (iexplore, 2010)

2.9.2.2 Fuel Exposure

The army indicated to HPS that during the filling operation of the tactical vehicles, fuel is commonly spilled around the fill cap region. JP-8, commonly known as jet fuel, is the most commonly used fuel in the military because of the US Army Single Fuel Forward Policy that has been enacted in hopes of simplifying the fuel storage and distribution practices of the military (Fernandez, 2005). Military mechanics stated this occurs on numerous tactical vehicles as a result of improper filling procedures, rush of refueling under combat conditions, or as the result of a design limitation. On many tanks stain marks were observed where fuel had leaked out of the fill cap or was spilled during refueling. HPS immediately recognized this potential endurance threat to NCASE and commissioned a study to determine the long-term exposure threat to the materials used to form NCASE. Within the labs at BYU, specific tests have been developed to adequately measure the performance of the Kevlar material after similar fuel exposures. These tests are explained in the "Test Protocol" section.

2.9.2.3 Cold Weather and Crinkle Exposure

As the product will be used in cold environments like the mountains of Afghanistan, the HPS product needs to be able to perform well after exposure to freezing temperatures. Even though Afghanistan is at the same latitude as the South-Central USA, the high mountains and elevation make it a much colder climate (iexplore.com, 2010). Not only are there harsh winters, but the southern lowlands of the country produce very hot summers as well (iexplore.com, 2010). Figure 2-12 shows the average weather patterns in Kabul, Afghanistan

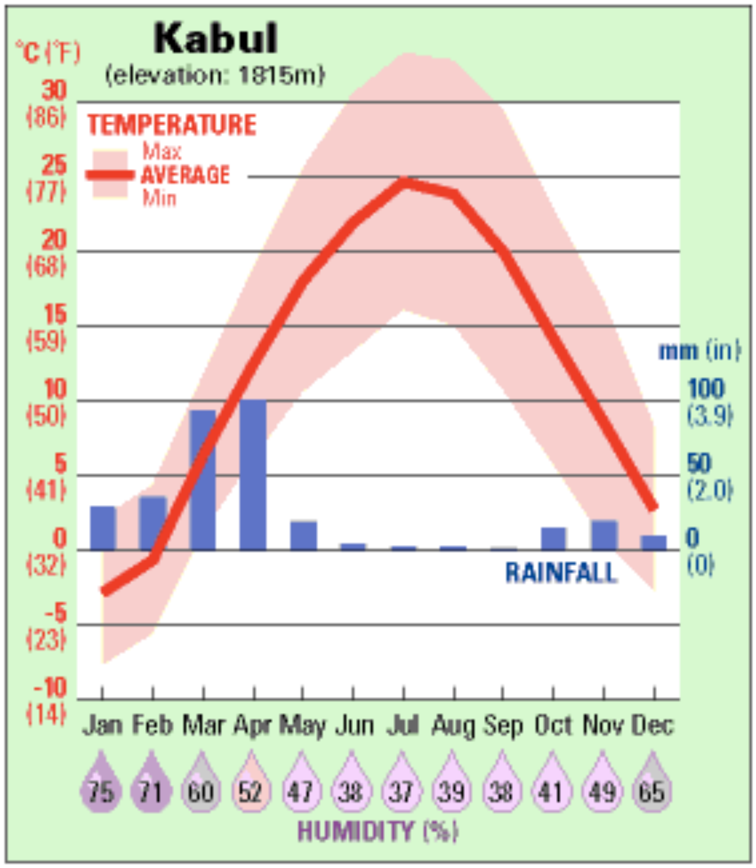

Figure 2-12—Average Weather Patterns in Afghanistan (iexplore, 2010)

There is also the possibility of the product getting pinched or crinkled during normal operating conditions or when the product is being removed or installed for inspection and maintenance. Some tests have been developed to determine whether or not the strength of the material is compromised through freezing, crinkling, or a combination of the two.

2.9.2.4 High-Speed Impacts

Lastly, as this product is designed to be an external safety component on various military vehicles, it will be prone to high-speed flying rocks and pebbles. Fuel tanks on larger transport vehicles are usually mounted underneath the cabin of the vehicle and are very close to the ground, making it more exposed to rocks that are kicked up by tires on both paved and unpaved roads. These rocks can travel over 100 miles per hour and have enough force to break the cars of windshields up to 100 feet away. The product is close to the tires and must be able to withstand multiple severe high-speed impacts without compromising the integrity of the materials.

2.9.3 Review of NCASE Materials

2.9.3.1 Kevlar Fabric

Kevlar fabric is the material used as the outer component on the NCASE product. Kevlar (commercialized by Du Pont Company in 1972), is an aramid fiber that possesses a "high tenacity and modulus, thermal stability and low elongation, stress decay and creep associated with inorganic fibers while retaining the low density, fatigue resistance and wear resistance…characteristic of organic fibers" (Schaefgen, 1983). Kevlar is a highly versatile material that is used in a variety of applications from car tires to bullet-proof vests where strength and toughness are desired product characteristics. "Aramid is a generic term for a 'manufactured fiber in which the fiber-forming substance is a long chain synthetic polyamide in which at least 85% of the amide linkages are attached directly to two aromatic rings', as defined by the US Federal Trade Commission" (Yang, 1993). Kevlar can be produced in a variety of forms such as yarns, short fibers, pulp, felt, woven fabric, cord, etc. The molecular composition of Kevlar can be seen in Figure 2-13.

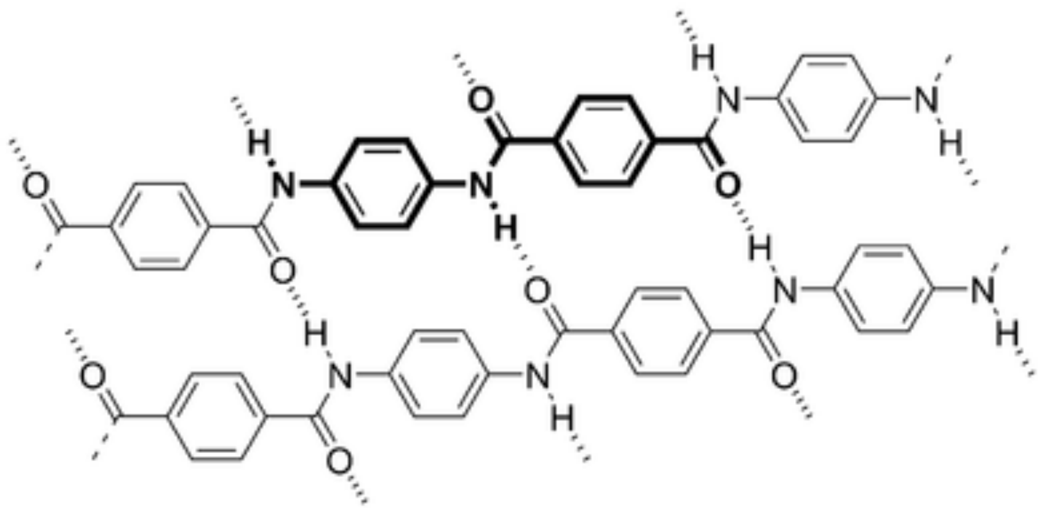

Figure 2-13—Molecular Structure of Kevlar (absoluteastronomy.com, 2010)

The Kevlar used for the NCASE product is a woven fabric that is actually coated with a UV-resistant urethane material. Kevlar fabric is considered a high performance fabric because of its high strength and modulus at low to high temperatures (Yang, 1993). One of the reasons a coated Kevlar was chosen was because it is sensitive to radiation from ultraviolet light, which comes from direct sunlight exposure; however, this deteriorization is not enhanced by moisture or other atmospheric contaminants (Yang, 1993). UV exposure can lead to a loss of mechanical properties and should be considered when selecting Kevlar as a material for a new product.

2.9.3.2 Flame Retardant Powder

The flame retardant powder is branded as Purple K. This well-known flame retardant powder is supplied in bulk to the flame retardant industry (for use in portable flame suppression devices and other applications). Purple K is a slightly modified potassium bicarbonate.

3 METHODOLOGY

3.1 NCASE Testing

To demonstrate whether or not in-use testing can effectively be applied to a newly developed product, a case study was needed for this thesis. Dr. Brent Strong had connections to Hazard Protection Systems, Inc. (HPS) and a relationship was established for this thesis after HPS indicated their need for some customized testing. The NCASE product was in early development stages at the start of this thesis and was, therefore, used as the subject for this research.

Testing of the NCASE materials was done in two separate phases at different time periods. The first phase was conducted in 2008 and two materials were tested: a Kevlar fabric (referred to as Old Kevlar) with a urethane coating and an uncoated nylon fabric. The Kevlar was intended for use in exposed conditions on outer fuel tanks and the nylon was intended for use on fuel tanks that were fully contained in an external box and would not be exposed to sunlight. These materials were to be tested to evaluate performance under (separately) extended sunlight exposures, hydrocarbon (fuel exposure), and impact resistance (for Kevlar).

The second phase of testing was performed in 2010 on different Kevlar fabric (referred to as New Kevlar). This new Kevlar material required an evaluation similar to the previous tests. Separate tests were done to evaluate exposure to hydrocarbons, water, cold weather, impact, and crinkling. Due to time constraints and the long-term nature of sunlight or UV testing, the UV testing was not performed in this run of tests during the 2nd phase of testing.

3.1.1 Environmental & Operating Conditions

Chapter 2 contains a detailed description of various critical operating conditions that were considered in the design of the product and in the selection of materials used to manufacture the product. To effectively evaluate the NCASE product in regards to its performance in the intended environments, a number of tests were designed to effectively simulate specific operating or environmental conditions in a controlled environment. These tests were either developed by slightly adjusting standardized procedures or by creating an entirely new procedure.

3.1.2 Sample Preparation

Test samples for fuel exposure, water exposure, cold weather, and crinkling were cut from the same Kevlar material that was used to construct the NCASE product. The samples were cut in 7/8" x 8" strips because this size allowed for accurate testing in the clamps on the Instron tensile-testing machine at BYU. While dog-bone samples are usually used for tensile testing of solid materials (ASTM D 638-00, 2001), rectangular samples were used in this test because only the fibers in the long direction would receive any load (see Figure 3-1). Careful consideration was placed in cutting the fabric as straight as possible because an off-axis cut would reduce the amount of fibers effectively bearing a load during testing, which could possibly skew test results. It is quite possible that some of the variance in the testing results can be attributed to the angle at which the samples were cut as it is extremely difficult to precisely line up the thin fibers; however, every effort was made to ensure that the samples were cut at the right angle. The specimens were cut using a fresh razor blade to avoid any stress to the material. The specimens were labeled and divided into groups for testing. Control groups were isolated apart from any exposure contamination. Five specimens were exposed in each type of test then subsequently tested on the Instron machine to determine the maximum strength of the material.

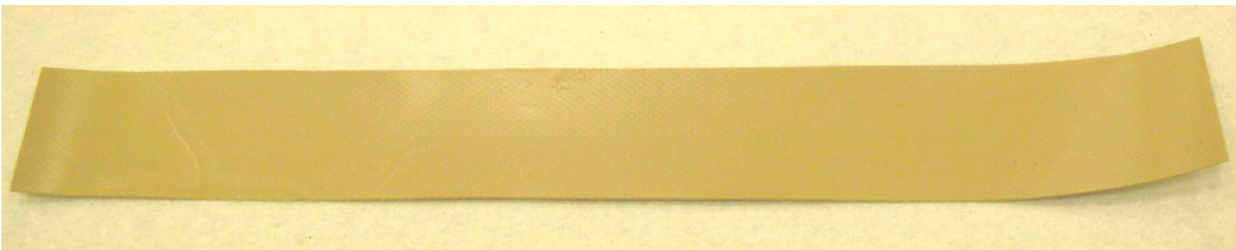

Figure 3-1—Kevlar sample

3.1.2.1 Weathering

As the NCASE product will be exposed to great amounts of heat and ultra-violet radiation in the desert areas of Iraq and Afghanistan, it is crucial to know whether or not the product will survive the test of time. One of the most important reasons organizations perform weathering testing is to determine the service life of their product (Atlas, 2002). The ASTM G7 standardized test outlines conditions for testing the "Atmospheric Environmental Exposure Testing for Nonmetallic Materials." The results of this test would show how the NCASE would perform throughout time in exposed conditions, but it would take months or years to obtain usable results. While it would be ideal to outfit a military vehicle with the NCASE product and place it in service for a few years to see how the product will perform, it would not make business sense to take so much time to only evaluate one aspect of the product's performance. After the product is sold, it would certainly be beneficial to track performance through time, but in the product development process, time comes at a high premium and all efforts to reduce the development cycle should be made. There are ways to accelerate the results from natural weathering tests by placing mirrors near the product and angling them properly as to increase the amount of sunlight exposure, but the testing time would still be very significant.

"The three primary factors of weather are light, moisture and temperature" (Atlas, 2002). Since Kevlar can only be degraded by light exposure and not moisture and normal testing temperatures (Yang, 1993), UV degradation was the only focus for testing of the Kevlar samples. Kevlar and nylon samples were prepared for artificial weathering and were placed in the weatherometer machine at BYU on April 7, 2008 (see Figure 3-2). The samples were held on racks with the appropriate fixtures as outlined in the ASTM "Standard Practice for Fluorescent UV Exposure of Plastics" (ASTM D 4329-99, 2001). The fluorescent UV bulbs can accelerate the natural UV exposure by a factor of about three, thereby reducing testing time considerably compared to non-artificial testing. The first set of specimens was labeled and removed from the machine on May 7, 2008 then placed in a plastic bag which was then stored in a dark desk drawer for the next month. On June 7, 2008, the remaining samples were labeled and removed. All of the weathered samples were then tested on June 20, 2008.

Figure 3-2—Weatherometer in BYU Lab

Maximum tensile strength was used as the metric in comparing exposed samples with control samples. The fabric samples did not have a consistent mode of failure as some would break all at once while others would break one strand at a time. While it may be appropriate in determining the properties of some materials, measuring the pull strength at failure would not be a good metric in giving consistent results because the failure modes were so inconsistent. Instead of measuring failure strength, it was determined that maximum tensile strength of the material would be the most consistent and pertinent metric for this testing because of the consistency the results would provide.

3.1.2.2 Fuel Exposure

The materials used in the NCASE system were exposed to certain hydrocarbon-based liquids (kerosene and diesel) for various time intervals to simulate the exposure that the NCASE product might encounter during fueling operations on a tactical vehicle. In a worst case scenario during product use, fuel spills might flow into the recess between the tank and the NCASE panel and be retained there until evaporated. It is possible that the presence of this fuel would weaken the NCASE product.

JP-8 fuel is currently used in the military for the transport vehicles. As JP-8 fuel was not accessible for the solvent testing, diesel and kerosene were used because they closely resemble the JP-8 fuel and share similar chemical properties. If there is concern regarding the actual effect of JP-8 fuel, further testing may include solvent testing with the actual JP-8 fuel.

The purpose of this test was to establish the effects of several common fuels used in military and commercial vehicles on the material used to produce NCASE. In conformance with standard ASTM testing (ASTM D 543), the material was immersed in the solvent (fuel). As the exposure time of the fuel to the NCASE material can be limited by the spill being cleaned or evaporation, the times for exposure were adjusted accordingly. Furthermore, because the danger in actual use is the loss of physical properties, the test used to evaluate the effect of the solvent was tensile properties (ASTM D 638) rather than the weight gain measurement used in the immersion test (ASTM D 543).

The specimens were dipped into fuels for various exposure times; see Figure 3-3 for an example of how the materials were exposed to the hydrocarbons. The exposure times were chosen to simulate reasonable, worst case exposures that might be encountered in actual use. The exposure times chosen were: 3 seconds, 1 minute, 30 minutes, 1 hour, and 2 hours. After exposure, the specimens were dried and then tensile tested. The hydrocarbon tests were actually conducted at different times to ensure that the diesel and kerosene samples would not be inadvertently interchanged. All Phase 1 and Phase 2 tests were conducted in an identical manner.

Figure 3-3—Sample Being Soaked in Diesel Fuel for Solvent Test

3.1.2.3 Water Exposure

Samples were exposed to water in the same manner as the hydrocarbon exposure as described in the section above. Again, the samples were dried before testing the tensile strength on the Instron machine.

3.1.2.4 Freezer and Crinkle Testing

Although the NCASE product will likely not experience freezing climates on products in Iraq, there are many fuel tank wraps on vehicles in Afghanistan, which has a climate much like Salt Lake City, UT. Because of the likely exposure to cold-weather climates, a freeze test was devised to determine if cold weather will compromise the strength of the Kevlar material. Regular Kevlar samples were cut and then placed into a 0 degree Fahrenheit freezer for various amounts of time. These samples were then removed from the freezer, allowed to come to room temperature, and then subsequently tensile tested on the Instron machine.

Another concern expressed regarding the Kevlar material is its performance after being exposed to forces that fold and bend the material. A test was devised that puts consistent forces on samples that have been folded in a standardized manner. The samples were prepared by folding them like an accordion, folding 1-inch over at a time, creating eight 1-inch sections (see Figure 3-4). After this, the entire folded sample was folded in half and then wrapped with clear tape to maintain the folds for testing (see Figure 3-5). The samples were then exposed to a weight by sandwiching five samples between two metal plates that measured 2-feet x 2-feet each. The samples were placed as follows: one sample in each corner and one in the middle (see Figure 3-6).

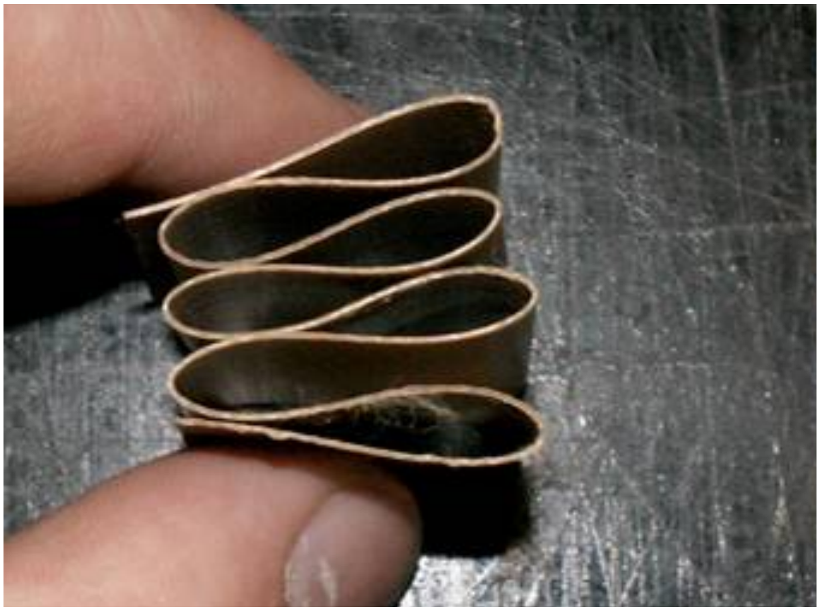

Figure 3-4—Preparation of Crinkle Sample

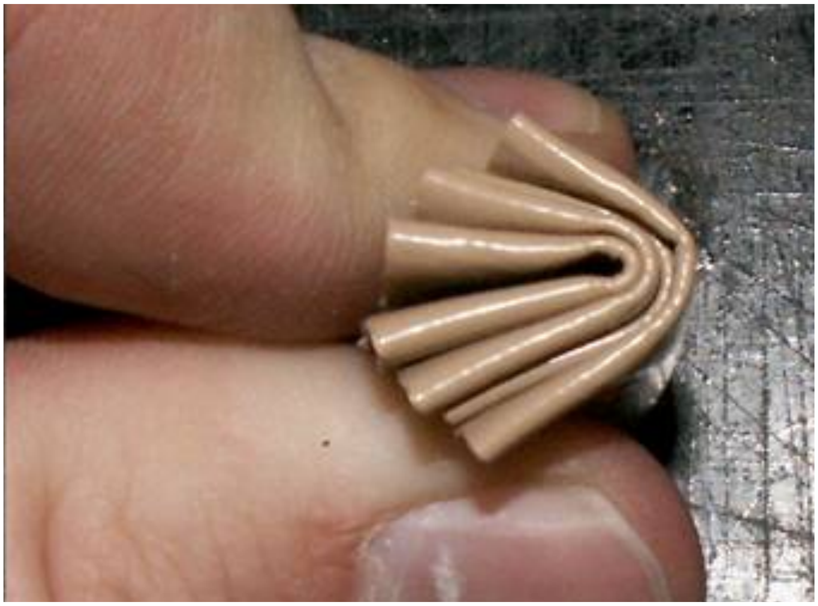

Figure 3-5—Preparation of Crinkle Sample

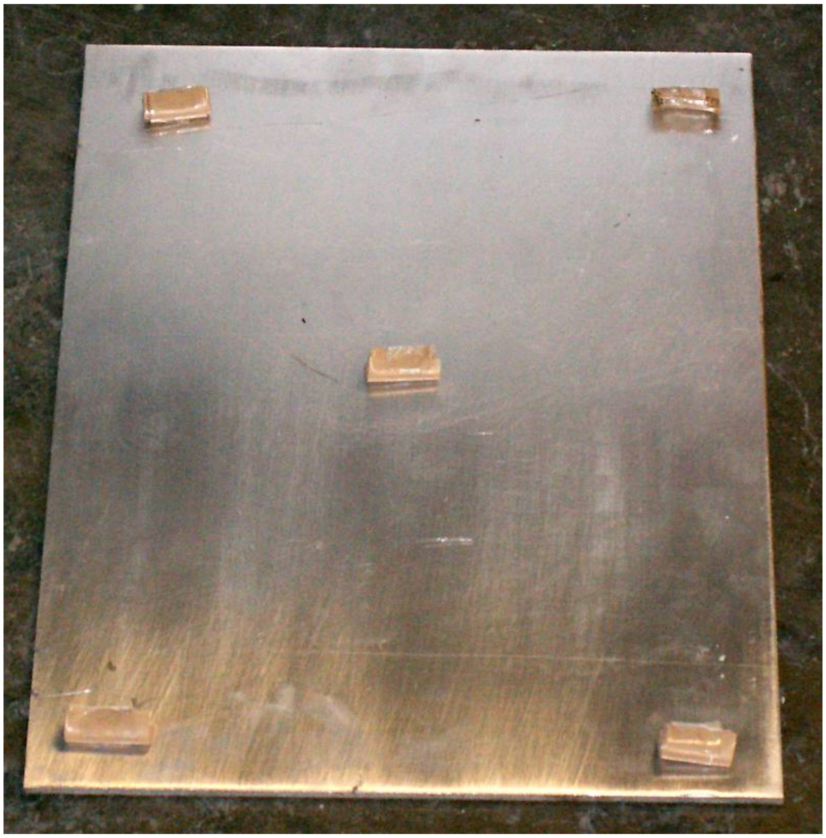

Figure 3-6—Placement of Crinkled Samples on Plate

After the samples were set between the plates, a 150-pound weight was placed on top for a period of 24 hours (see Figure 3-7). 150 pounds was chosen because that is the maximum weight of an actual section of an NCASE kit. If the product is removed from the tank and left on the ground, the weight would be dispersed over many contact points on the bottom surface of the product, so by spreading this weight over five samples this test actually provides more force than will be encountered in normal use. Therefore, if the material is not compromised through this test, it should logically not be compromised through normal use. After the 24-hour exposure period, the samples were removed from between the plates and tensile tested on the Instron machine in the same manner as previous tests.

Figure 3-7—Placement of Weight on Crinkle Samples

In addition to freeze tests and crinkle tests, we performed some combined testing to see if both freezing and crinkling the samples would lead to a further decrease in strength. Samples were frozen for a period of one, two, and three days and then subsequently subjected to the above-mentioned crinkle test for the standard period of 24 hours after which they were also tensile tested on the Instron machine.

3.1.2.5 Webbing Strength

The NCASE product contains multiple sections that are strapped onto the fuel tanks. The straps are stitched to the Kevlar fabric with a specific stitching, or webbing, pattern that must be tested to ensure that the product can withstand the adequate forces in service. To determine the maximum force, the pieces were tested for maximum tensile strength on the Instron machine.

For the testing samples, nylon straps were sewn to strips of the Old Kevlar material with the same webbing pattern to be used on the actual product. The Kevlar section was much wider than the testing clamps, so metal tabs were placed on either side to sandwich the Kevlar to ensure the entire width of the sample was gripped (see Figure 3-8). The nylon strap was thick enough that slipping in the clamps was not an issue and tabs were subsequently unnecessary. Ten samples were pulled at a rate of 1.5 inches per minute until failure and the maximum tensile strength of all the samples in the set were then averaged.

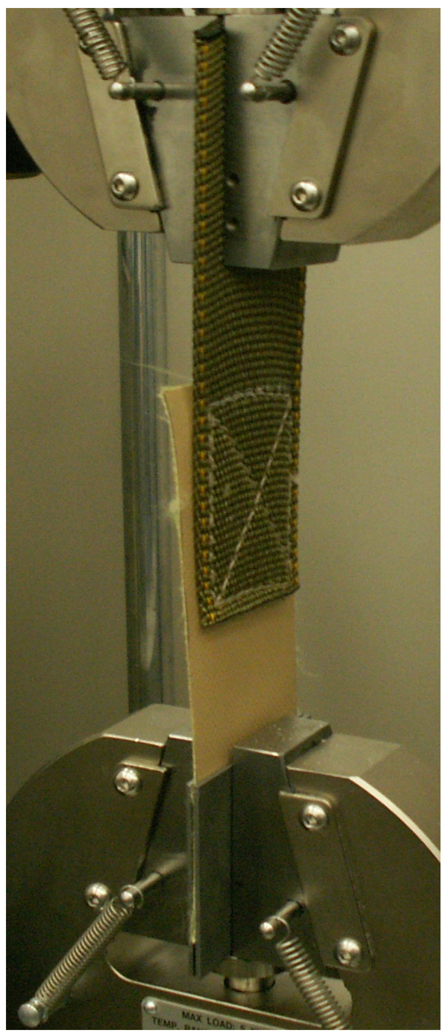

Figure 3-8—Tensile Testing a Webbing Sample

The military requires that the product be capable of withstanding forces of two times the force of gravity (2G). The weight of the product depends on the size of the fuel tank, but no single section will be over 75 lbs. Consequently, to be deemed acceptable for use, the webbing sections on the product must withstand at least 150 lbs of pulling force (75 lbs x 2G). A safety factor was then calculated by dividing the test results by the required force (Actual/Required).

3.1.2.6 Tensile Strength Testing

The test apparatus for the tensile tests was an Instron 4204, model 201. It was installed at BYU in 1988. The 5 kilonewton load cell was used for all of the testing as none of the forces approached the 1,000 lb threshold. The machine was balanced and calibrated each time the load cell was changed.

For all, the pull rate was set at 1.5 inches per minute and the test was run until the material snapped. For all tests, the maximum force required to pull the sample was the metric recorded and used for the statistical analysis.

3.1.2.7 Impact Testing

The purpose of this test was to establish the effects of rock impacts on the for the NCASE product. Because the velocity of debris impact is much higher for vehicles than the normal falling dart impact test (ASTM D 5628), the testing procedure was modified to be able to simulate the type of damage that might occur in off-road service. The setup that was used for this test is shown in Figure 3-9. The device was calibrated using an electronic speed gun. The speeds of the projectiles were known to approximately ±1 mph with some additional minor variation because of the inability of the operator to exactly match the calibration chart during the actual testing.

Figure 3-9—Impact Testing Setup at Clearplex

This apparatus is a slingshot type device that propels projectiles onto the surface to be tested. The user must place the projectile in the slingshot and then pull back to the corresponding mark for the desired speed (see Figure 3-10 & Figure 3-11); the user then releases the projectile, which hits the test sample. A 3/8-inch ball bearing and a small sharp rock were used as projectiles for this test (see Figure 3-12).

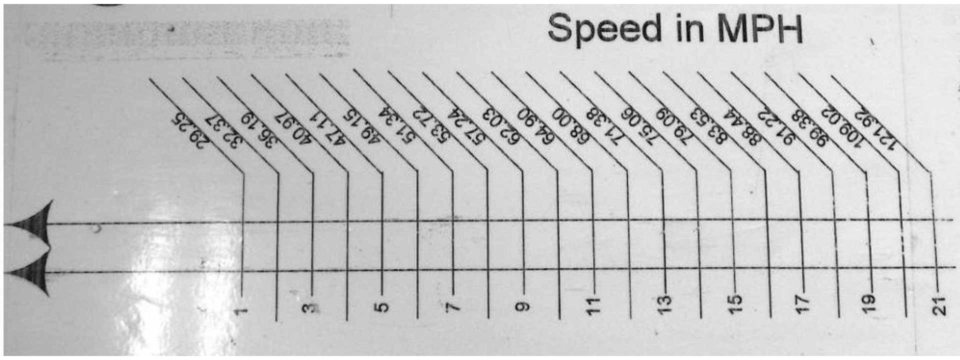

Figure 3-10—Impact Testing Speed Chart

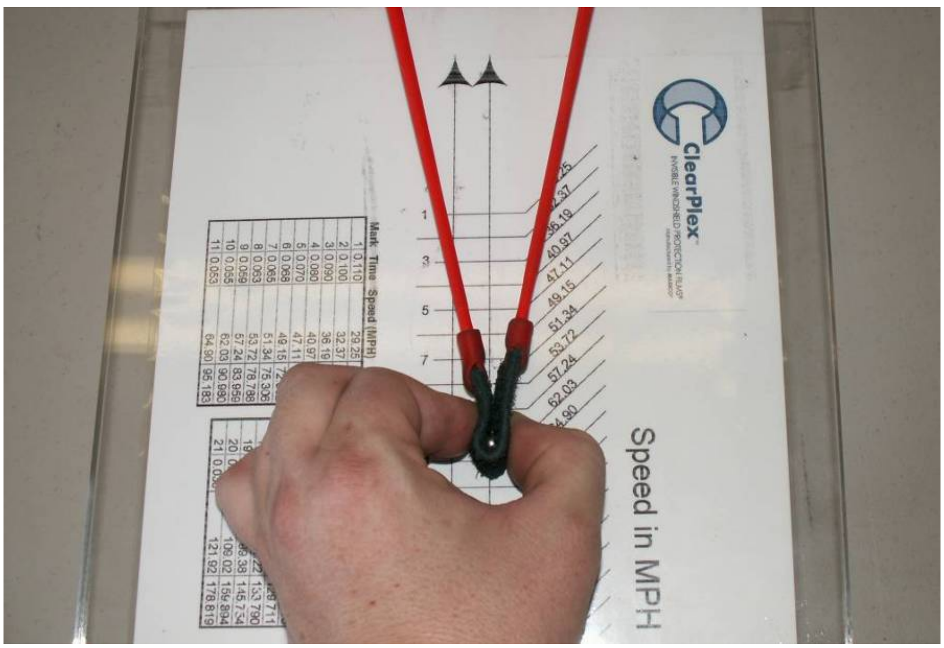

Figure 3-11—Preparing Shot for Impact Test

Figure 3-12—Impact Testing Projectiles (penny shown for size comparison)

In Phase 1, tests were conducted on a sample product that was constructed with the Old Kevlar material. In Phase 2, tests were conducted on a sample product with the New Kevlar material. The samples were tested at the following speeds: 50mph, 75mph, 100mph, and 125mph. The samples were tested five times at each speed. Speeds were started at 50mph and progressively increased by 25mph after each set of tests. After each set of tests, the sample was inspected on the surface for marks or punctures, and then the bag of powder was removed and inspected to check for leaks (see Figure 3-13).

Figure 3-13—Inspection of Internal Powder Baggie After Impact Testing

In Phase 2, an endurance test was constructed in order to more stringently test the performance of the NCASE product. After these progressive tests were performed, endurance tests were conducted to ensure that the product would be able to withstand continued exposure to its intended harsh environment. For this endurance testing, each sample was shot in the same general spot 100 times with a ball bearing and 100 times with various small rocks at the maximum speed of the testing device of 125mph. At the end of the test, each sample had been shot over 200 times in the same location at full speed. Inspections of the Kevlar material and powder packets were performed every 25 shots to assess any possible damage.

3.1.3 Acceptance Criteria

In working with the Army, HPS decided that a material must retain at least 50% of its original strength after exposure to any testing condition. Therefore, if any material does not pass the minimum criteria of retaining 50% of its strength after exposure, it will not be acceptable for use in the intended conditions. All accept/reject suggestions shown in the results section are based on this acceptance criterion that was ultimately defined by the customer.

3.1.4 Data Analysis

Even though a material might pass the minimum criteria of retaining 50% of its strength, it is still important to understand the performance characteristics of the product, which is why a statistical analysis was conducted. The statistical significance of the results was obtained by taking all of the results from testing to the statistics department on campus at BYU. All of the testing was explained to Dr. Dennis Eggett, professor in the Statistics Department, and he then wrote code for the SAS software that he used to analyze the data from the testing. The results were constructed to show whether or not the test results of exposed materials were statistically different than the control set that was tested in the same manner. In this circumstance, a 95% significance level ($p < .05$) was used to indicate whether or not the test set was significantly different from the control set.

4 RESULTS OF NCASE TESTING

4.1 Liquid Exposure

4.1.1 Results

For every condition, the exposure and subsequent tensile test was performed on five samples and those results were averaged for each data point shown below.

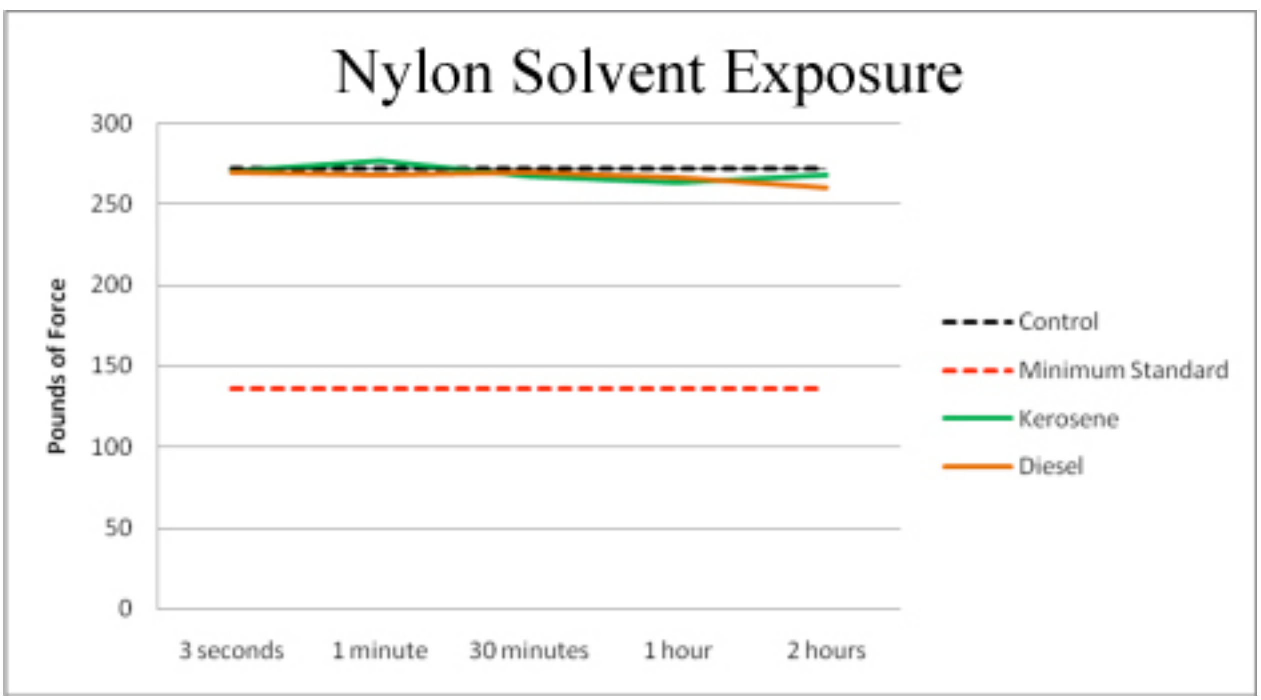

Figure 4-1—Nylon Solvent Exposure

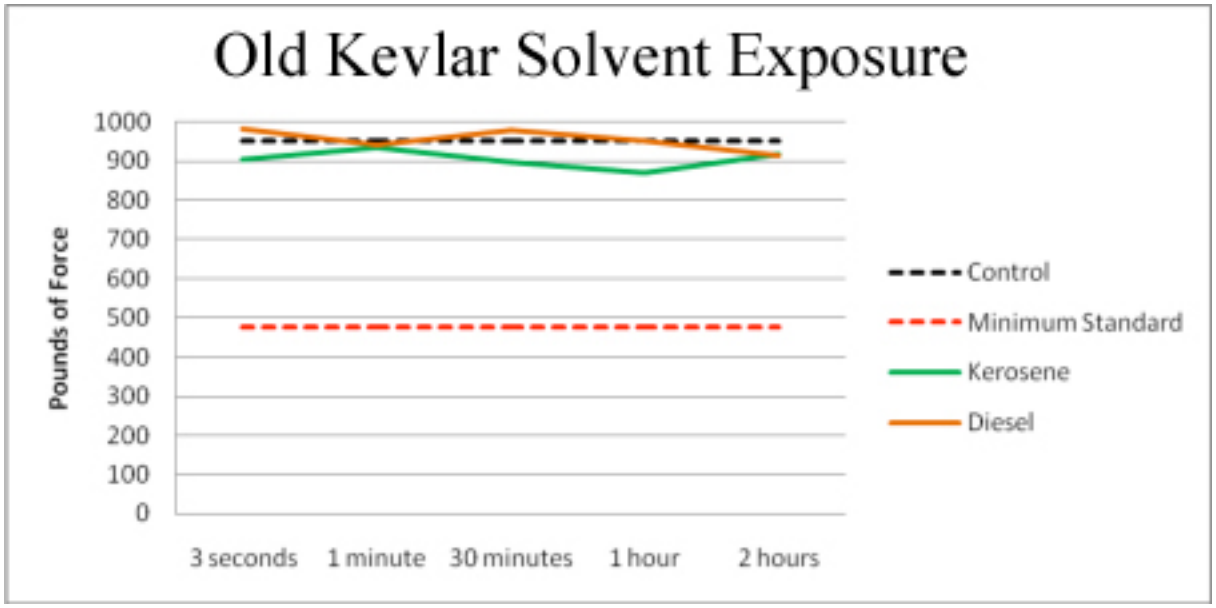

Figure 4-2—Old Kevlar Solvent Exposure

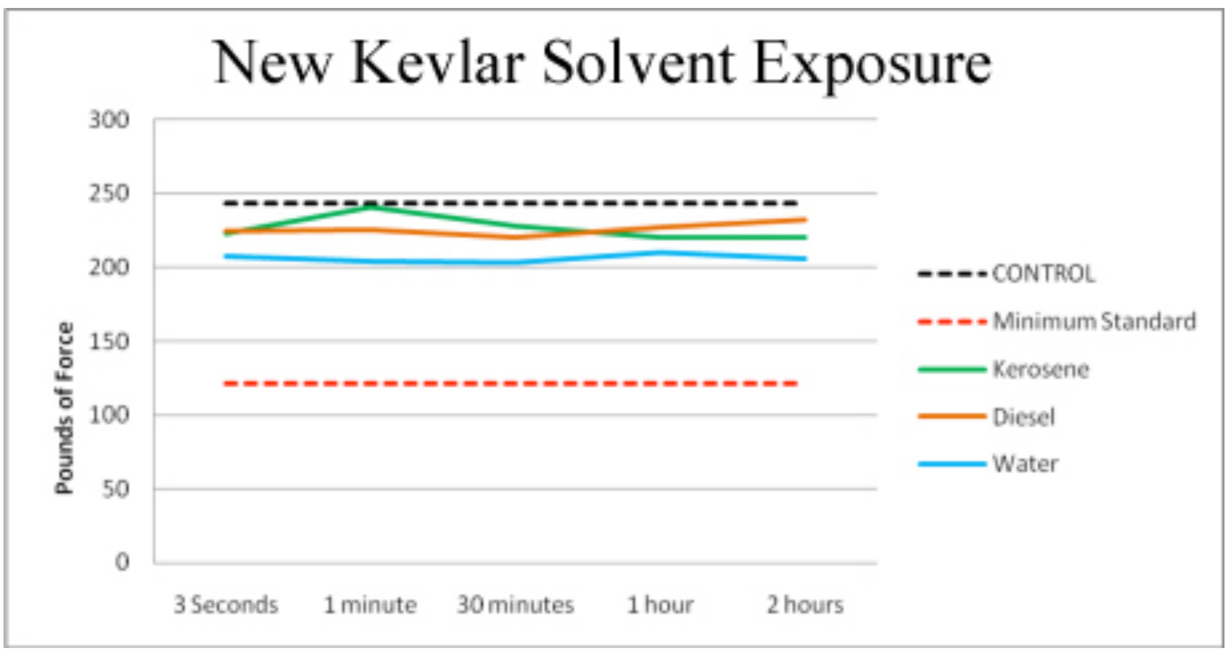

Figure 4-3—Kevlar Liquid Tests

Table 1—Statistical Significance of Liquid Exposures

Statistical Significance of Liquid Exposures		
		α Value for Pr>|t|
Exposure	**Time**	**New Kevlar**
Diesel	*3 Seconds*	0.193
	1 Minute	0.219
	30 Minutes	0.110
	1 Hour	0.251
	2 Hours	0.426
Kerosene	*3 Seconds*	0.159
	1 Minute	0.878
	30 Minutes	0.293
	1 Hour	0.112
	2 Hours	0.106
Water	*3 Seconds*	**0.012**
	1 Minute	**0.006**
	30 Minutes	**0.005**
	1 Hour	**0.020**
	2 Hours	**0.009**

BOLD results are significant based on 95% confidence level (p < .05)

Table 2—Statistical Significant of Liquid Exposures

Statistical Significance of Liquid Exposures			
		α Value for Pr>|t|	
Exposure	**Time**	**Nylon**	**Old Kevlar**
Diesel	*3 Seconds*	0.634	0.795
	1 Minute	0.462	0.5232
	30 Minutes	0.676	0.8731
	1 Hour	0.237	0.692
	2 Hours	**0.001**	0.25
Kerosene	*3 Seconds*	0.869	0.1761
	1 Minute	0.191	0.453
	30 Minutes	0.362	0.134
	1 Hour	0.058	**0.0418**
	2 Hours	0.472	0.2745

BOLD results are significant based on 95% confidence level (p < .05)

4.1.2 Analysis

All materials in the fuel exposure tests passed the minimum criteria of maintaining at least 50% of their original strength after exposure to the different hydrocarbons. The Kevlar strips had no significant loss of strength.

All materials in the water exposure tests passed the minimum criteria of maintaining 50% of their original strength properties. The Kevlar strips that were soaked in water experienced a slight loss of strength that was found to be statistically significant (based on a 95% confidence interval). Although the samples were patted dry before testing, the actual Kevlar fibers were likely damp because the fabric is sandwiched between thin protective layers of urethane coating and it would be difficult to remove all moisture before testing. As Kevlar is an aromatic polyamide material (also known as aramid), it is expected to absorb up to 1-2% of its weight in water, which can temporarily soften the material and reduce its strength. This condition appears to have occurred as the Kevlar experienced around a 20% decrease in strength throughout all exposure times; however, the loss of strength had no correlation to the amount of time it was submerged in the water. If the samples had been left out to dry for long periods of time and all of the moisture was evaporated, we would expect them to regain all of their strength because aramid materials typically regain all of their strength when they are completely dried. In the intended environments, the NCASE product will likely be exposed to cycles of wet and dry conditions and while the strength may be decreased by 20% at times, it is expected to regain it back when dry. In consideration of these factors, the Kevlar material is fully suitable and acceptable for use in environments where water and moisture are prevalent.

4.2 Ultra Violet Exposure

4.2.1 Results

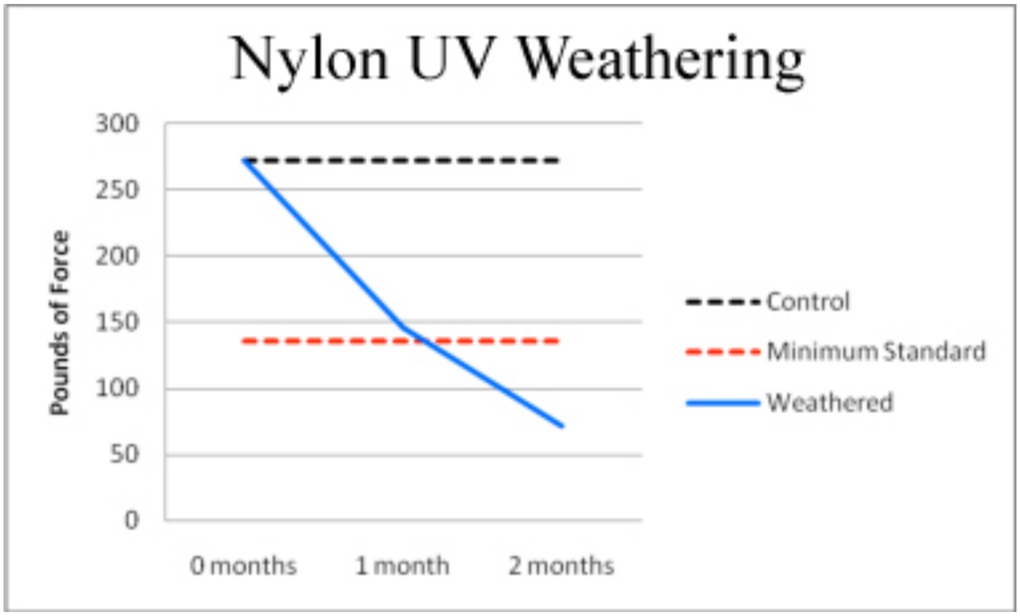

Figure 4-4—Nylon UV Weathering

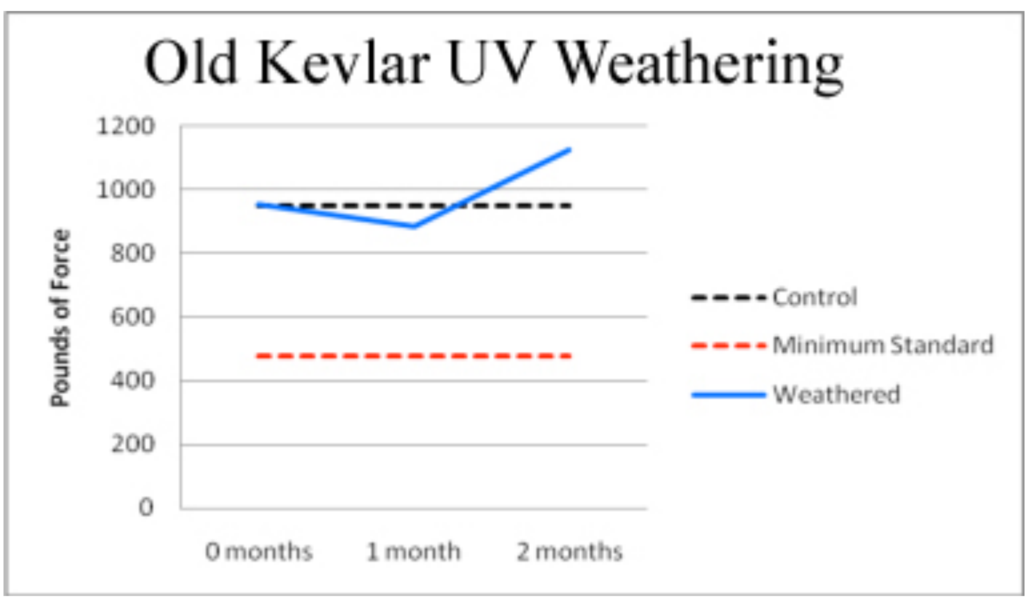

Figure 4-5—Old Kevlar UV Weathering

Table 3—Statistical Significance of UV Weathering

Statistical Significance of UV Weathering		
	α Value for $Pr>\lvert t\rvert$	
Weathering Time	**Old Kevlar**	**Nylon**
1 month	**0.0421**	**<.0001**
2 months	**0.0008**	**<.0001**

BOLD results are significant based on 95% confidence level

4.2.2 Analysis

Weathering testing was performed in Phase 1 to evaluate the Old Kevlar material and the nylon material. As expected, the nylon material did not hold up well to UV exposure and its strength was severely compromised. HPS had indicated they were skeptical about the performance of the Nylon and simply wanted to do tests to confirm that the material is not suitable for use, which it definitely is not.

The UV tested Kevlar samples had a mean that was statistically different from the control set, simply meaning that the UV tested Kevlar samples were statistically different than the control. A look at Figure 4-5 shows that after one month of UV exposure, the strength was slightly lower, but after 2 months, the strength had increased above that of the control set! These results show that while weathering may have a slight effect on the Kevlar, it is not anything that would significantly compromise the performance of the materials and should be of no concern. It may be of interest to perform tensile tests on material pulled from a product that has been in service for an extended period of time in the intended environment to see if longer exposures result in a decreased strength.

4.3 Freeze/Crinkle Exposure

4.3.1 Results

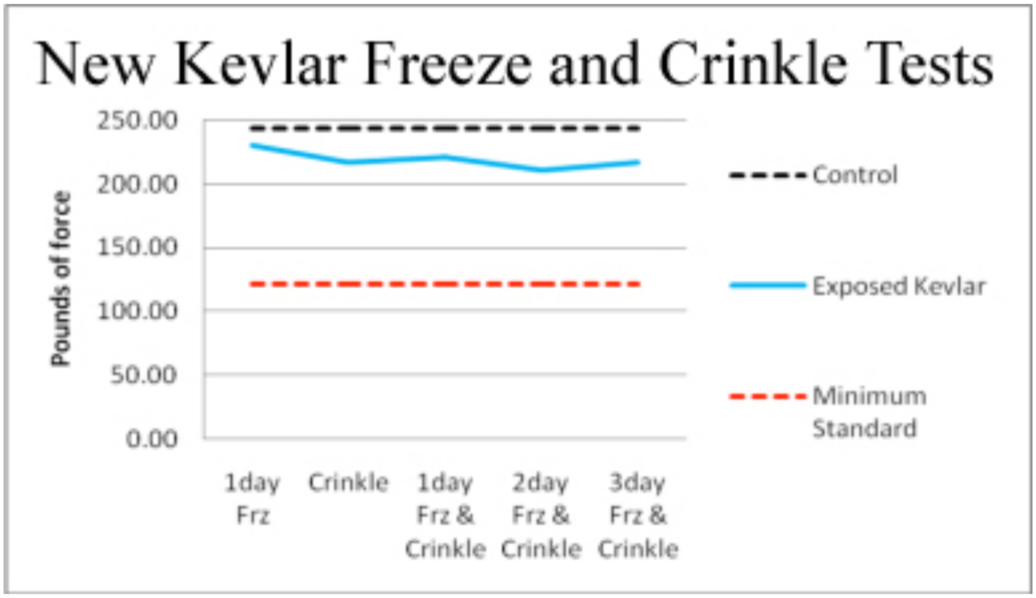

Figure 4-6—New Kevlar Freeze and Crinkle Tests

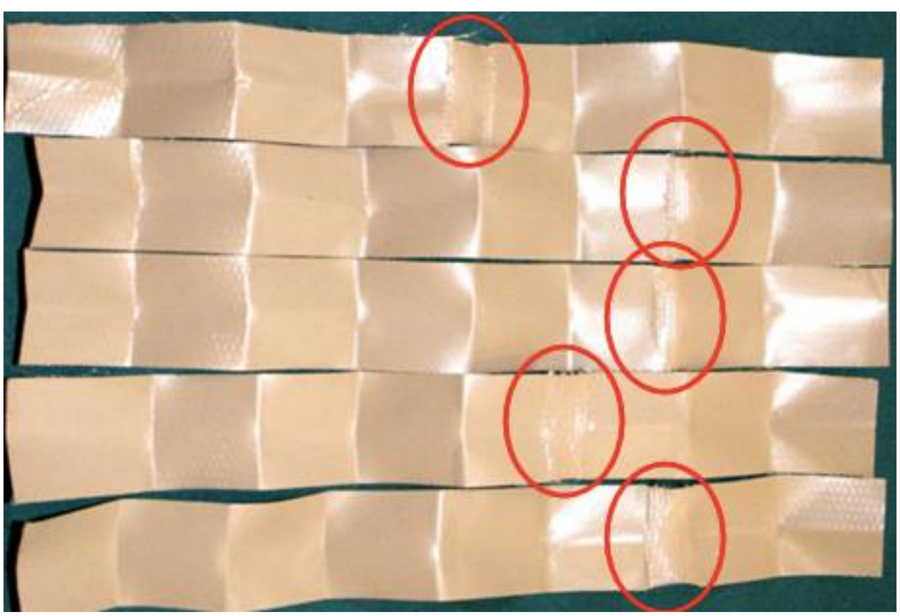

Figure 4-7—Failure Points on Crinkle Samples (shown in red circles)

Table 4—Statistical Significance of Freeze/Crinkle Testing

Statistical Significance of Freeze/Crinkle Testing		
		α Value for Pr>|t|
Freeze Time	**Crinkle Tested**	**New Kevlar**
1 Day	*NO*	0.357
1 Day	*YES*	0.124
2 Day	*YES*	**0.024**
3 Day	*YES*	0.069

BOLD results are significant based on 95% confidence level

4.3.2 Analysis

All crinkle and freeze samples passed the minimum criteria by retaining at least 50% of their strength throughout each test and in most samples there was no statistically significant difference between the samples and the control. The "crinkle" and "2-day freeze and crinkle" samples were the only sets that had strengths that were statistically different than the control (based on a 95% confidence level); however, the strength lost in each set was not more than 20%. Although there was not a consistency of reduced strength throughout the samples, it is still important to note that material that is crinkled and under pressure may become slightly weakened. An important observation during testing was that all breaks in the material occurred precisely on one of the fold lines from the crinkle testing (see Figure 4-7 with break spots outlined in red). While the material consistently maintained over 80% of its strength after being folded and under the test weight, it would be wise to avoid situations where the NCASE product is subject to sharp folds and excess force on those folds.

4.4 Webbing Strength

4.4.1 Results

Table 5—Webbing Test Results

Webbing Strength Test Results	
Minimum Strength Requirement (at 2G)	150 lbs
Average Max. Tensile Strength	**874 lbs**
Standard Deviation	34 lbs
Safety Factor	**5.83**

4.4.2 Analysis

In this specific application, the Army indicated that the product should be able to withstand at least 2 G's of force (twice the force of gravity). While any one section of the product will not exceed 75 pounds, twice the force of its own weight will be 150 pounds, which was the minimum acceptance criteria for this test. As the results show, the webbing that holds the straps to the product was able to withstand a force of 874 pounds, thereby far exceeding the acceptance criteria.

4.5 High Speed Impact Testing

4.5.1 Results

Table 6–Old Kevlar High Speed Impact Testing

Old Kevlar High Speed Impact Testing				
	Ball Bearing		Sharp Rock	
Speed (5 shots @ each speed)	Control	Weathered	Control	Weathered
50 mph	ND	ND	ND	ND
75 mph	ND	ND	ND	ND
100 mph	ND	ND	ND	ND
125 mph	ND	ND	ND	ND
	ND=No Damage			

Table 7—New Kevlar High Speed Impact Testing

New Kevlar High Speed Impact Testing		
	Ball Bearing	Sharp Rock
Speed (5 shots @ each speed)	Kevlar	Kevlar
50 mph	ND	ND
75 mph	ND	ND
100 mph	ND	ND
125 mph	ND	ND
	ND=No Damage	

Table 8—New Kevlar Endurance Impact Testing

New Kevlar Endurance Impact Testing				
	Ball Bearing		Sharp Rock	
Speed	Kevlar		Kevlar	
100 shots @ 125 mph	ND		ND	
(total of 200 shots per sample)	ND=No Damage			

4.5.2 Analysis

The impact testing samples did exceptionally well and there were no instances of the internal powder packets rupturing or leaking throughout the entire set of tests. In the Phase 1 tests (Table 6), there were no indications of any damage throughout the entirety of the testing. In Phase 2 (Table 7 & Table 8), the Kevlar material, again, did very well. In fact, it was very hard to even notice that the Kevlar sample had been shot over 200 times with projectiles at speeds of over 125mph.

5 CONCLUSION

5.1 Case Study Review: NCASE

After testing of the NCASE product was complete, full testing reports were created and submitted to Hazard Protection Systems, Inc. These reports were not only used as internal guides to validate the material selection and product design, but they were also submitted to their main customer (the United States Army) to give them confidence in the NCASE product. The fact that the materials, in general, far exceeded the Army's minimum requirements was a great selling point and further strengthened the trust that the Army had in the product. If there is any doubt as to the validity of the results, the tests are documented in such a way that any other lab can study the reports and replicate the tests.

These in-use testing reports can only help HPS in securing more contracts for outfitting military vehicles with the NCASE product. Competitors with similar products do exist and HPS must compete with them to win the bids from the military. Having highly documented tests on the product and its materials can give HPS the edge over their competitors. HPS has secured contracts for outfitting select vehicles that are deployed in Iraq and Afghanistan and they will continue to work through the product development process in order to improve their product. Throughout this cyclical, or helical, process, they will continue to rely on the testing process outlined in this thesis as it has proven successful in their business model thus far.

5.2 New Outline for Products Development Process

A detailed investigation of proposed sequences for the new product development process was conducted in Chapter 2. While the existing steps outlined in various literary sources had solid principles, none of the cited sources adequately emphasized the importance of and sequence of the testing process as a part of new product development. In Chapter 2, it was suggested that the new product development steps as outlined by Crawford and Di Benedetto should be modified to place more emphasis on the testing aspect of the process. Figure 5-1 shows the proposed process with the testing modification shown in a dashed box. This new outline better emphasizes the importance testing should play in the new products development process.

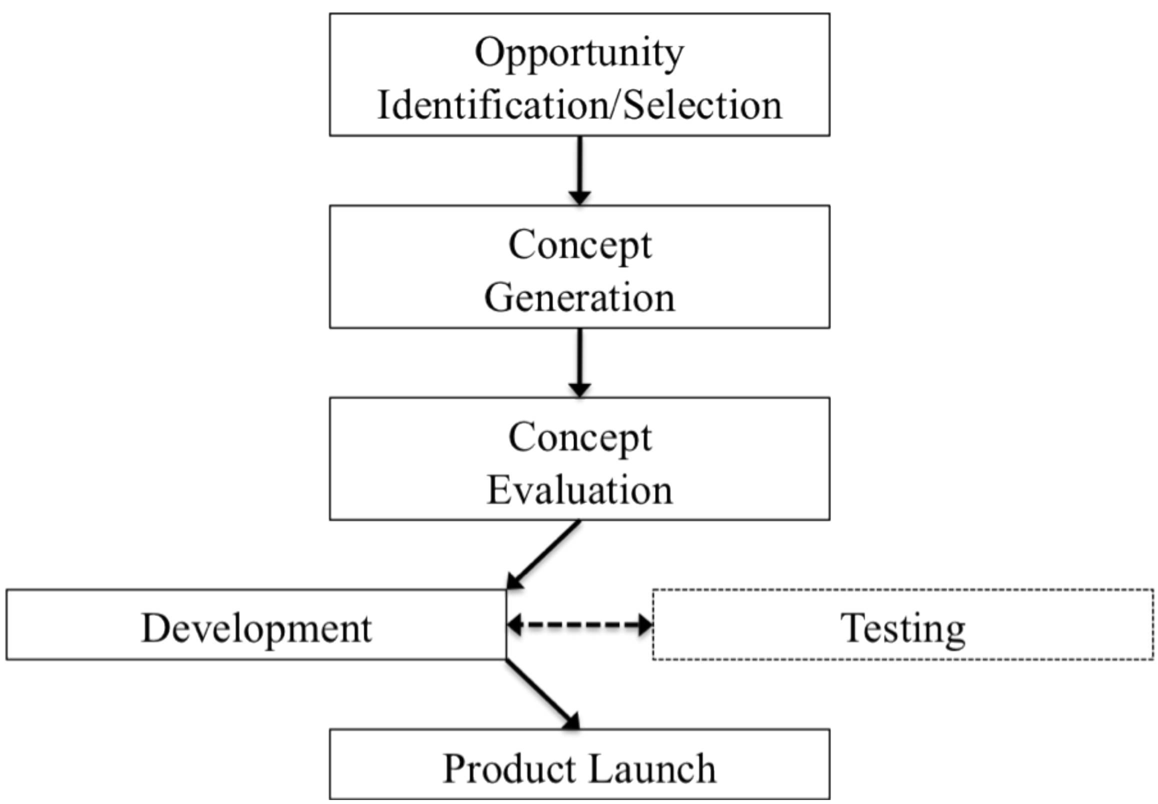

Figure 5-1—Proposed New Products Development Process

5.3 Testing Progression

While many sources stated the importance of prototyping and testing, few sources actually discussed the logical steps in the testing process. This process was addressed in Chapter 2 and is shown again in Figure 5-2. It is important to note the sequence of steps from standardized testing to in-use testing to actual product or market testing.

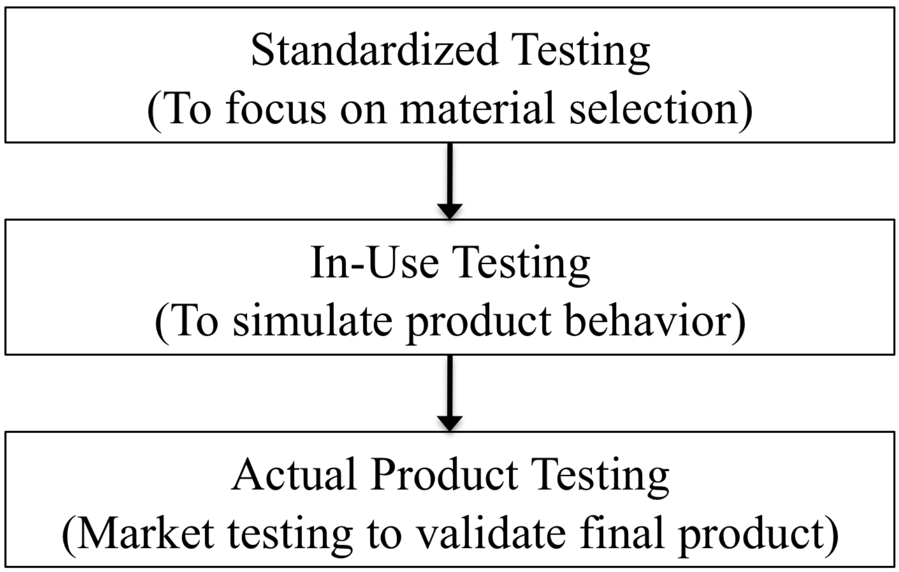

Figure 5-2—Progression of Testing

5.4 Guidelines for Product Testing

The objective of the thesis was as follows: "Through the analysis of the product testing used in the case study, a set of guidelines can be developed to assist in a generalized method for new product testing." After a thorough literature review, and through looking at the case study, certain guidelines were developed. These guidelines can be summarized as follows.

1. **Decide on critical properties that need to be tested and develop a set of acceptance criteria for evaluating the product.** It is important to first decide which product aspects are most important before moving forward with designing tests. Once the most relevant product or material traits are identified, then it is appropriate to select or develop a list of acceptance criteria either through market research or through direct communication with the customer.
2. **Begin by using standardized procedures, if possible, for your product tests.** With thousands of pre-established standardized tests from a variety of agencies, there is a possibility that testing needs can be satisfied by a procedure that is already established, saving time and money while maintaining the highest level of credibility in the testing results.
3. **When developing in-use tests, integrate components of standard tests to maintain trust and credibility.** If no standardized procedures fit your needs, use aspects of standardized tests for the in-use testing procedures. Using key pieces of standardized tests will strengthen the value of the in-use tests because the standardized aspects of the testing procedures bring a higher level of credibility to the results.
4. **Decide on an appropriate statistical analysis for the results.** Before performing tests, it is critical to outline what metrics are wanted and how they will be analyzed; it is critical that everybody who will see and use the results of the test easily understands the results. Once the metrics and procedure for the statistical analysis are identified, then it is appropriate to finalize testing design and actually perform the tests.

5. **Perform tests with accuracy and precision and document thoroughly.** If tests are not executed as they are documented, all trust in the testing procedures may be lost. Results should also be analyzed exactly as specified. If tests are documented properly and performed exactly as stated, others should be able to obtain the same results even if performed in a separate lab.
6. **Seek consensus within the industry and pursue standardization of the new testing procedures.** Once the tests are established, it may be of value to speak with others in the industry to validate the procedures, get advice on how to improve the process, or to see if others have developed similar tests. If desired, contact a standards agency (e.g., ANSI) to have the test become an industry standard. Standardizing an in-use test will provide a solid reputation for the procedure, resulting in a much higher level of trust of the test.

5.5 Review of Hypothesis

This thesis has shown that a set of guidelines can be developed from a case study that will improve the method of testing for new products.

5.6 Suggestions for Further Research

While this thesis focuses primarily on the testing aspect of the new development process, it would be valuable to further explore the following:

- The process by which in-use tests become accepted and adopted by a sanctioning body as a legitimate standardized test.

- A detailed investigation into the success of products that were previously tested before launch versus products that were not tested.

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