DESIGN FOR ASSEMBLY (DFA) ANALYSIS AND APPLICATION FOR COLD-GAS THRUSTERS OF A SPACE RE-ENTRY VEHICLE MODULE

by

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B.S., Mechanical Engineering
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ABSTRACT

Design for Assembly (DFA) is a way of analyzing and designing, or redesigning, a product from the perspective of assembly in order to reduce cost and increase reliability and quality.

A review was performed on the design of cold-gas thrusters of a space re-entry vehicle module project from MIT Lincoln Laboratory. This review was performed from an assembly standpoint, and focused on a redesign through DFA principles. Accordingly, it evaluated the effectiveness of DFA and specific methodologies in applications such as this "non-conventional" aerospace/defense application, in which cost is not as primary of an issue as reliability and quality. Improvements to the methodology which might be better suited for these types of applications were also explored.

General Design for Assembly framework and guidelines were reviewed, followed by specific reviews of two methodologies. These were then implemented for the case study. A DFA redesign of the cold-gas thruster was developed through the results of the two methodologies. Through this process, important issues of the original design were identified and examined. The approach to these issues was strictly from a DFA perspective. Resolutions and design modifications to these issues were developed for assistance in future creation of improved assembly-oriented designs.

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But He said to me, "My grace is sufficient for you, for my power is made perfect in weakness." Therefore I will boast all the more gladly about my weaknesses, so that Christ's power may rest on me... For when I am weak, then I am strong.

2 Corinthians 12:9-10

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1
Introduction

"The best design is the simplest one that works." Albert Einstein

1.1 Motivation and Goals

It is widely accepted that 75-80% of the cost of a product is committed during the design and planning activities.[1] Thus, no matter how clever manufacturing engineers, production managers, and other manufacturing personnel are, they can affect no more than 25% of the cost of a design. Therefore, consideration of manufacturing and assembly issues at the design stage is the most efficient way of streamlining the product development process.

But a common mistake with many designers, especially recently with the improvements in technology, is they design products that are quite functional, but very difficult or sometimes impossible to assemble.[2] This difficulty can make a product both costly and unreliable.

Design for Assembly (DFA) is a way of analyzing and designing, or redesigning, a product from the perspective of assembly in order to reduce cost and increase reliability and quality. Typical benefits claimed by DFA users include: [3]

- Parts count reduced by 60%
- Manufacturing cost reduced by 75%
- Assembly cost reduced by 50%

It has been found by designers using DFA principles and techniques that, typically, 20 to 30 percent of assembly cost can be eliminated, compared to the cost of a "traditional design." [4]

1.1.1 More than just Cost

But cost is just one of the issues involved with design and assembly. Another major benefit of DFA is reliability, as shown in Figure 1-1 by Motorola in a study done in 1991[5] that shows how the application of DFA corresponded to a reduction of their failure rates.

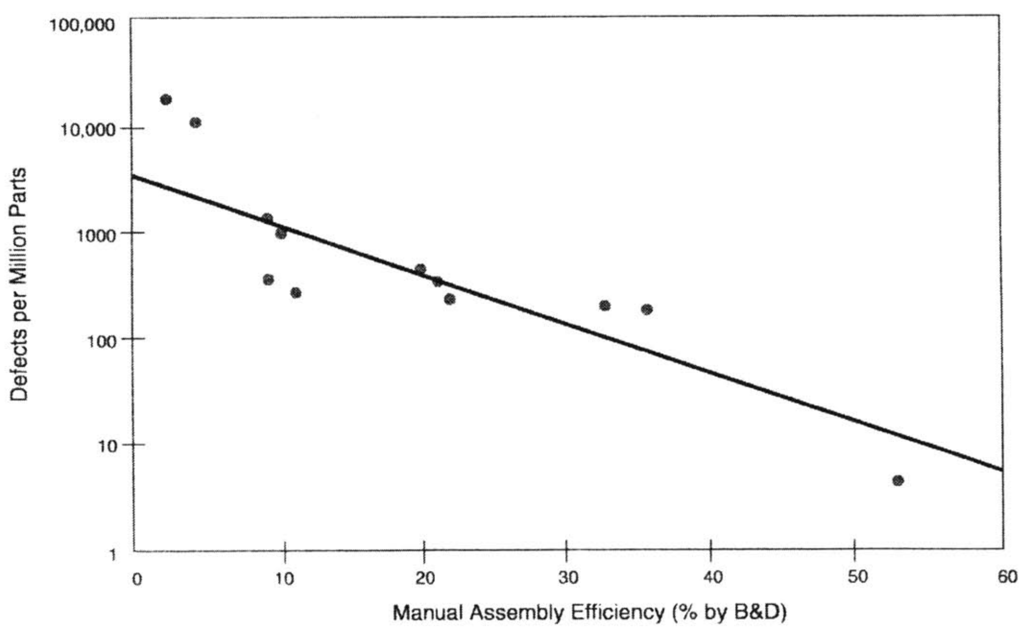


Figure 1-1: Reliability Increase with Application of DFA [6]

So far, DFA principles and practices have been mostly implemented in the industries involved in mass production. It is fairly obvious the need for DFA application in such industries, such as the automobile industry. Not as obvious are applications in which the products are used in extremely critical applications, where cost is not the primary issue, projects such as satellites and missile defense systems. The aerospace and defense industries would be leading examples of such cases.

What still remains to be confirmed is the effectiveness of DFA on such non-mass production industries. As noted, current DFA methods and principles revolve mainly around the issue of cost. But in these industries, cost is a secondary matter to other issues such as reliability and quality.

1.1.2 Design for Manual Assembly

The analysis of a design for ease of assembly usually depends on whether the product is to be assembled manually or with automation. In most cases, both aspects have to be taken into consideration and weighed. For the purposes of this thesis, however, when referring to DFA, it refers primarily to Design for Manual Assembly. Therefore such issues as automatic transfer systems, vibratory feeders, mechanical feeders, tracks, and assembly robots will not be addressed. As described above, this is done because of the industry that this thesis addresses. In the aerospace/defense industry, due to the uniqueness of its products, automation is not a reasonable solution. For the most part, manual assembly is used for its products.

1.2 Problem Statement

The goal of this thesis is to provide a review of the design of the cold gas thrusters from an assembly standpoint, and focus on a redesign through DFA principles. Accordingly, it will evaluate the effectiveness of DFA and specific methodologies in applications such as this, in which cost is not as primary of an issue as reliability and quality. Improvements to the methodology which might be better suited for these types of applications is explored.

This thesis will focus on:

- a better understanding of Design for Assembly and DFA methodologies.
- analyzing a case from the defense industry to provide a redesign of the product through DFA and measure the effectiveness of DFA on the sample case study.
- a better understanding of "non-conventional" applications of DFA such as this aerospace/defense project, where the key metric is not cost but reliability.
- recommending corresponding revisions to DFA methodology

1.3 Organization of Thesis

Chapter 2 reviews the history and past work relevant to this thesis. This chapter is divided into two sections: a history of assembly, and overview of Design for Assembly. It summarizes the scope of the assembly oriented design approach by providing a background of DFA, and presenting the benefits and needs that are addressed by the methodologies presented in the following chapters.

Chapter 3 presents the Design for Assembly framework. General design guidelines and rules of DFA are presented through categorization and examples.

Chapter 4 provides an overview of a Design for Assembly evaluative mechanism and a thorough Design for Assembly analysis methodology:

1) Xerox Producability Analysis
2) Boothroyd-Dewhurst DFA Analysis

The chapter also describes a software tool developed by Boothroyd Dewhurst, Inc. (BDI) to implement the Boothroyd-Dewhurst DFA Analysis methodology

Chapter 5 begins the in-depth review of the case study with the description and history of the cold-gas thrusters, and an overview of its design. This proceeds the introduction of the main design issue associated with the thrusters, the leakage problem, and its history throughout the various TCMP projects.

Chapter 6 examines the design and assembly of the thrusters, and various issues associated with its assembly. A description of the design issues is given by pinpointing problem areas, areas where basic DFA rules have been violated. An evaluation of the overall design is given through the Xerox Producability Analysis.

In Chapter 7, the application of the Boothroyd-Dewhurst DFA methodology described in Chapter 4 is presented. The conclusions of the methodology are presented, as well.

Chapter 8 presents possible design improvements according to the methods. A proposed redesign of the cold gas thrusters is presented, based on the findings of the previous chapters. Descriptions of the design modifications as well as a comparison between the redesign and the original design are presented.

Finally, the Conclusion summarizes all the findings and evaluates possible future applications. It measures the effectiveness of DFA on an aerospace/defense design such as this case study. The DFA methodologies are evaluated, and recommendations are proposed that could improve it to be better suited for these types of applications.

[1] Redford, A. and Chal, J., Design for Assembly: Principles and Practice, McGraw Hill, London, 1994.

[2] *Ibid.*

[3] Jack, H., "Design Engineer," http://claymore.engineer.gvsu.edu/~jackh/eod/design/dfx/dfma-2.html, 1999.

[4] Boothroyd, G., Dewhurst, P., Machine Design, Penton Publishing, Cleveland, OH, 1984.

[5] Brannan, B., "Six Sigma Quality and DFA-DFMA Case Study/Motorola Inc.," Boothroyd & Dewhurst DFM Insight, Vol. 2, Winter 1991.

[6] *Ibid.*

2

Background and History

2.1 Manufacturing Systems Development

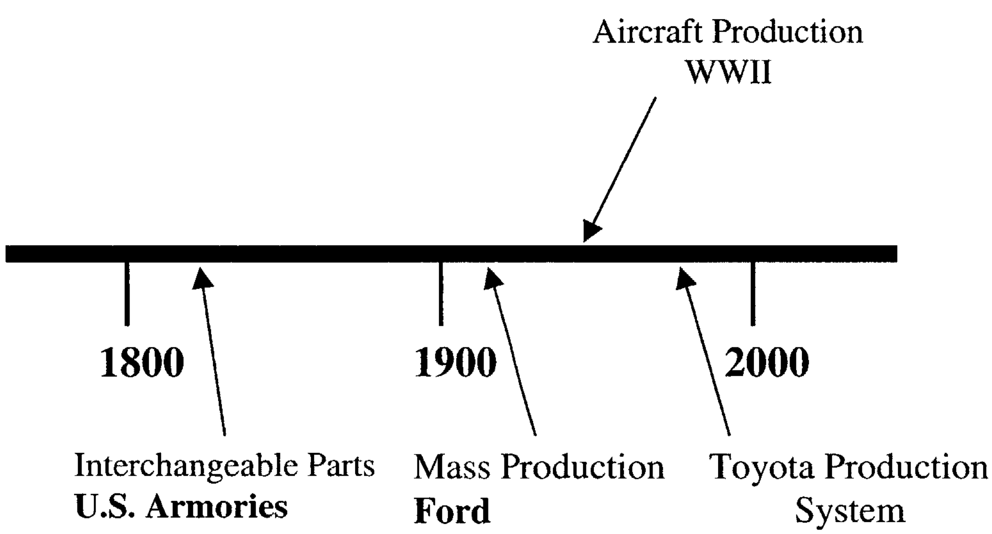


Figure 2-1: History of Manufacturing [1]

Until the late eighteenth century, manufacturing and assembly were carried out by expert craftsmen. These craftsmen learned their trade, had intimate knowledge of their parts, and so, each part could be tailored to fit its mating parts. Production, therefore, was limited by nothing else than the availability of these craftsmen. [2]

With the advent of the Industrial Revolution, there began an increasing need for products in large quantities which corresponded with the rapid advancements in technology. There were two main consequences resulting from this increase in manufacturing technology:

1) Concept of interchangeability of parts
2) Increase in production rate

Accordingly, this led to the beginning of the separation between main manufacturing and assembly, which continues on to this day.

2.1.1 Interchangeable Parts

The development of the system of interchangeable parts arose primarily from military needs towards the end of the eighteenth century.

John Hall invented the breech loading rifle in 1811, and produced 1000 interchangeable rifles at Harper's Ferry, VA in 1827. 5000 rifles produced by Simeon North of Middleton, CT were shown to be interchangeable with Hall's in 1834.[3] Along with Harper's Ferry, Springfield Armory helped pioneer the development and application of the system of interchangeable parts.

2.1.2 Henry Ford

From this sprung another major development, assembly process efficiency. It was discovered that the efficiency of assembly dramatically improved with repetitive actions. And it was mainly this knowledge that Henry Ford adopted, developed further, and eventually popularized into the concept of manual line assembly in the early 1900's. He was behind the first application of large-scale modern assembly, which was the assembly of flywheel magnetos for the famous Model T. Henry Ford is the man most acknowledge as the one who brought together the advances brought about in the nineteenth century into the twentieth century to pioneer the concept of mass production.[4]

The moving assembly line was instituted in 1913, along with the continued division of labor and standardization of work. The work pace greatly increased, but the turnover rate increased as well.

2.1.3 Toyota Production System

Many of Ford's mass production methods were analyzed and adopted by Japan's Taiichi Ohno, the man behind the Toyota Production System.[5] Ohno, when asked what had inspired his thinking, says that he learned it all from Henry Ford.

As such, many aspects of the Ford mass production system can be seen in the Toyota Production System, in a more streamlined or "lean" system through Ohno. Such characteristics are the concept of elimination of waste, machine tools and equipment placed in the sequence of operations rather than in job shop arrangement, reduced inventory, production to demand not to stock, continuous improvement, and lean organization.

It is in this system and other lean organizations like it that we begin to see the application of modern, more efficient design tools such as Design for Manufacture and Design for Assembly.

2.2 Development of DFA

For various reasons, throughout the history of design, the assembly aspect of the design process has been one of the most neglected. Some argue that designers have too many tasks to perform, too many categories they need to "design for" that they need to be concerned about.[6] Some of these are design for functionality, design for manufacturability, design for appearance, design for reliability, and of course, design for assembly. Apart from design for assembly and design for manufacturability, all these other aspects are ones clearly apparent to the user. Therefore, it would make much more sense to prioritize these "apparent" goals ahead of the others.

Others cite the lack of time. There's the ever-increasing demand for shorter lead time, and it's all up to the designer to work within the limited time. Thus, corners must be cut from the least important design activity, which for many is assembly.

Finally, there's the conception that assembly is easily done. People who assemble are generally good at it, and even if it's a somewhat difficult assembly, designers believe that they can and should be able to accommodate any kind of assembly situation.

Only recently has it been discovered that one of the most effective methods of reducing end design and manufacturing issues was through good product design from an assembly perspective.

2.2.1 Beginnings of DFA

In the sixties, some books on assembly automation appeared, but it was only about twenty years ago that the first design "systems" appeared. These are different from the unstructured advice that was present in the earlier times, incorporating formal methods and procedures to systematically determine assembly problems of a design and show how these problems could be avoided.

Within the past twenty years, many DFA methodologies have been developed and are used more prevalently throughout various companies and industries.

2.2.1.1 Boothroyd and Dewhurst

Geoffrey Boothroyd was one the pioneers of DFA.[7] His analysis of part feeding physics in the 1960's and experiments in part handling and insertion in the 1970's led to a systematic concept of DFA for the first time.

Boothroyd and Dewhurst were the first to analyze part simplification in detail and demonstrate its importance in design. They argued against other design guidelines that suggested using more parts that were easier to manufacture.

In the past, Iredale (1964) and Tipping (1965) suggested the importance of part simplification as a significant design heuristic, but it was Boothroyd and Dewhurst who first took it to a systematic level through their methodology.

The Boothroyd-Dewhurst DFA methodology was conceived, followed by a software of the methodology in 1982. This led to development of their own company, Boothroyd Dewhurst Inc. (BDI),[8] which was primarily formed as the result of the development of the DFA software, which allowed the methodology to be applied rapidly and efficiently.

[1] Gutowski, T., "2:810 Lecture: Manufacturing Systems Development, 1800 to 2000," November, 2000.

[2] Hounshell, D. A., From the American System to Mass Production 1800-1932, Johns Hopkins University Press, Baltimore, 1991.

[3] Smith, M. R., Harpers Ferry Armory and the New Technology: The Challenge of Change, Cornell University Press, Ithaca, 1977.

[4] Gutowski, T., "2:810 Lecture: Manufacturing Systems Development, 1800 to 2000," November, 2000.

[5] Gutowski, T., "2:810 Lecture: Manufacturing Systems Development, 1800 to 2000," November, 2000.

[6] Redford, A. and Chal, J., Design for Assembly: Principles and Practice, McGraw Hill, London, 1994.

[7] Boothroyd Dewhurst Inc., Design for Manufacturing and Assembly, http://www.dfma.com, 2001.

[8] *Ibid.*

3

Basic Method

3.1 Design Guidelines

Otto and Wood[1] have compiled the following list of general DFA guidelines from various different sources, including Iredale, Crow, Tipping, and Paterson.[2] These are the fundamental principles and thought processes that exemplify assembly-oriented design. And it is upon these principles, using these types of guidelines, that the systematic DFA methodologies, which are discussed in the next chapter, were borne.

Applying these types of design guidelines is the simplest way to approach and understand DFA. Any of these guidelines can be applied to a design. However, there is one caution. The following guidelines are provided to approach and better understand DFA. By no means is it a comprehensive list, but these guidelines, like all guidelines are heuristics that generally hold true. The designer needs to be mindful of the fact that to every rule and guideline there are exceptions. This holds true for this list given, as well. Design guidelines should be approached and used in parallel with clear delineation of the design goals.

The following guidelines are further explored in this chapter. They will be discussed corresponding to the following four categories: System (Minimum Number of Parts), Handling, Insertion, Joining. Subsequent discussion with illustrations follow.

Table 3-1: General DFA Guidelines [3]

1	Minimize part count by incorporating multiple functions into single parts
2	Modularize multiple parts into single sub-assemblies
3	Assemble in open space, not in confined spaces. Never bury important components
4	Make parts identify how to orient them for insertion
5	Standardize to reduce part variety
6	Maximize part symmetry
7	Design in geometric or weight polar properties if non-symmetric
8	Eliminate tangly parts
9	Color code or otherwise mark parts that are different by shaped similarly
10	Prevent nesting of parts
11	Provide orienting features on non-symmetries
12	Design the mating features for easy insertion
13	Provide aligning features
14	Insert new parts into an assembly from above
15	Insert from the same direction, or very few. Never require the assembly to be turned over
16	Eliminate fasteners
17	Place fasteners away from obstructions
18	Deep channels should be sufficiently wide to provide access to fastening tools. No channel is best
19	Provide flats for uniform fastening and fastening ease
20	Proper spacing insures allowance for a fastening tool

3.2 System Guidelines

The system guidelines refer to general guidelines that do not specifically deal with the insertion or handling of parts.

3.2.1 Reducing Part Count

It is common knowledge that many designs have more parts than the necessary amount. When considering the importance of two parts for their distinctiveness, rather than unifying the parts into one, three questions can be asked with respect to the two parts.[4]

1. Do the parts move relative to one another?
2. Must the parts be made of different materials?
3. Must the parts be separable for maintenance or manufacture?

In the case of negative answers to the questions, certain steps can be taken to reduce the part count, such as incorporating multiple functions into one part or modularizing multiple parts into one subassembly, as shown in Figures 3-1 and 3-2.

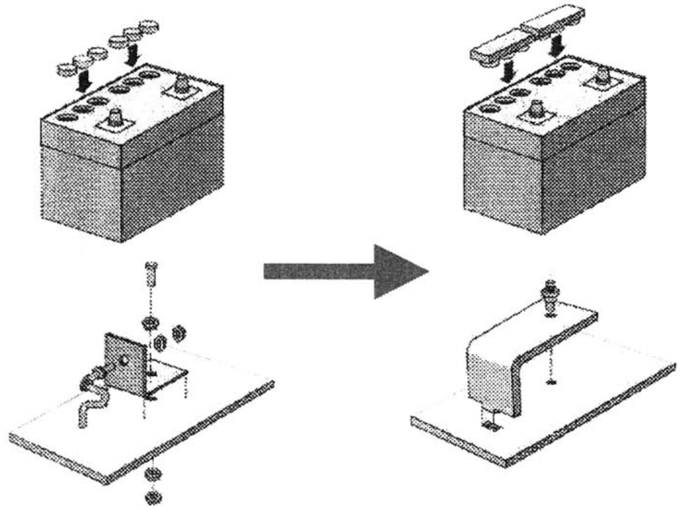


Figure 3-1: Incorporating Multiple Functions Into Single Parts [5]

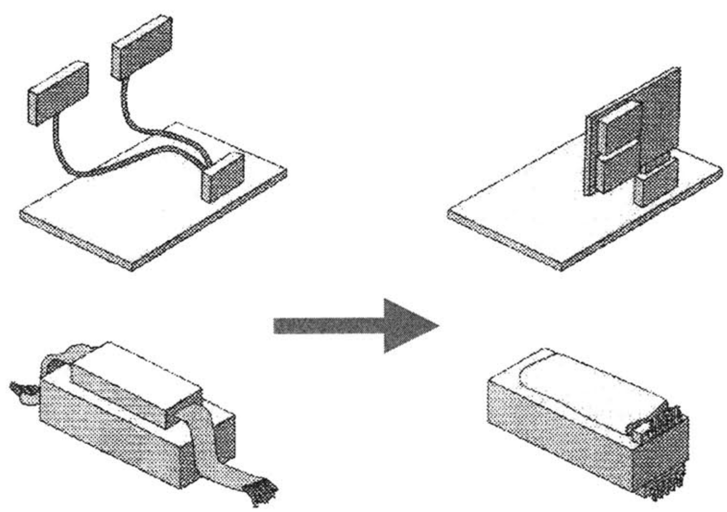


Figure 3-2: Modularization Into Single Sub-Assemblies [6]

Minimum Number of Parts

Boothroyd and Dewhurst proposed the concept of the theoretical number of parts for a product. This concept measures the importance and requirement of a part. Generally, a part is needed only when, relative to other parts of the assembly, a kinematic motion is required, electric isolation is required, or thermal isolation is required. If the part fits none of these requirements, then by this concept, the part need not be a separate entity and should be combined with another part.

In the early days, as described in the previous chapter, a common design guideline was to use more parts that are individually easier to fabricate. But we now know, through the research of the pioneers of DFA and their findings, that the opposite is true.

In general, it is better and more efficient to make fewer parts that are more complex and expensive. It is because the added individual part cost is more than made up in the cost and complexity reduction of the actual assembly. Additionally, each part requires documentation, control, and inventory.

Actual reduction of the number of parts was addressed in section 3.2, *System Guidelines*. The questions posed there should be asked in parallel with the requirements of the Boothroyd-Dewhurst theoretical minimum number of parts. If the part does not meet those requirements, more than likely it is a perfect candidate for elimination or combination with its neighboring part.

3.2.2 Orientation

If a product is assembled outwardly, as in Figure 3-3, important components are not buried or in cramped spaces. Therefore, re-orientation is not required during assembly, as fasteners and parts will not have to be fit into buried or tight spaces.

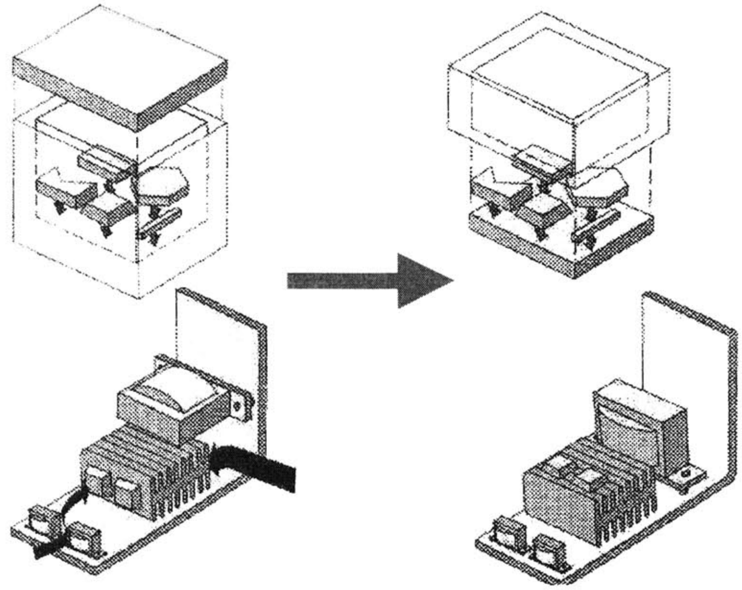


Figure 3-3: Open Enclosures for Open Space Assembly [7]

Parts should also be designed to allow easy orientation, as shown in Figure 3-4. Ideally, all the parts would have self-locating features to allow simplicity and accuracy during the assembly.

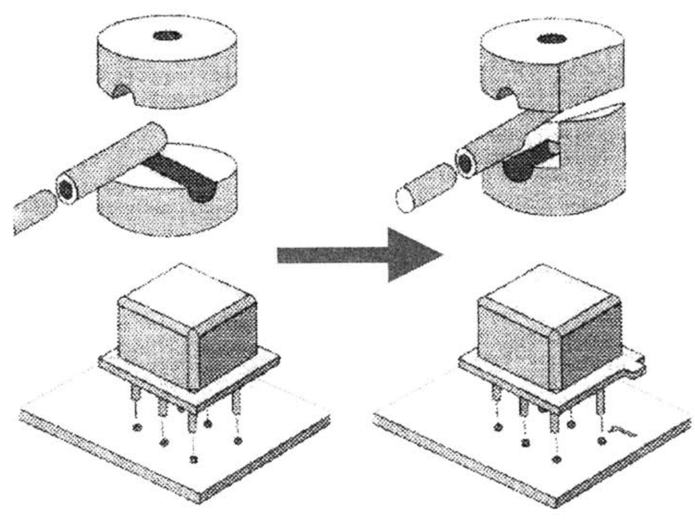


Figure 3-4: Indicating Orientation for Insertion [8]

Another orienting feature is in maximizing part symmetry. By having a symmetrical part, orientation is unnecessary. But in the case that it cannot be symmetrical, the part should be designed to augment its asymmetry by designing in weight polar properties across non-symmetries or using the non-symmetry to provide orienting features, such as Figure 3-5.

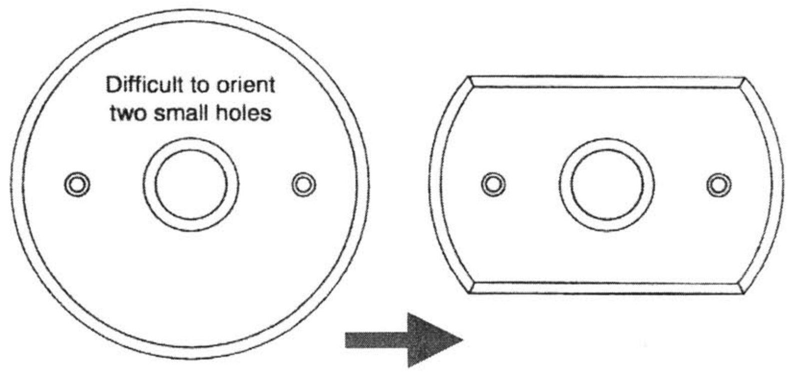


Figure 3-5: Non-Symmetry as Orienting Features [9]

3.3 Handling Guidelines

During an assembly process, all parts must be handled, some easier to handle than others. Through the following guidelines, easier handling of parts can lend itself to easier, more efficient assembly.

3.3.1 Part Tangling/Nesting

If there is any feature of a part that is prone to tangling, the part should be changed to eliminate tangling, or the part should be replaced with a non-tangling part as shown in Figure 3-6. Similarly, nesting parts should be replaced or redesigned with features to prevent nesting as shown in Figure 3-7. Nesting is when parts clamp to one another when stacked together. An example of parts that nest are vacuum formed plastic coffee lids.

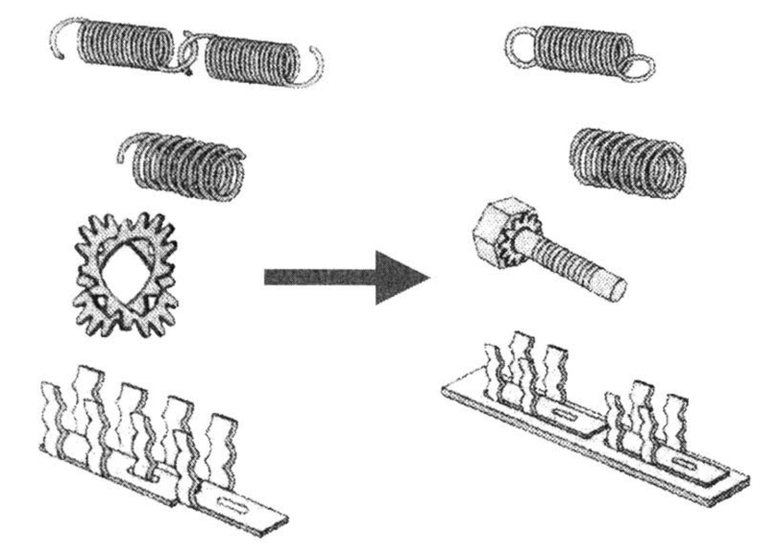


Figure 3-6: Eliminating Parts Likely to Tangle [10]

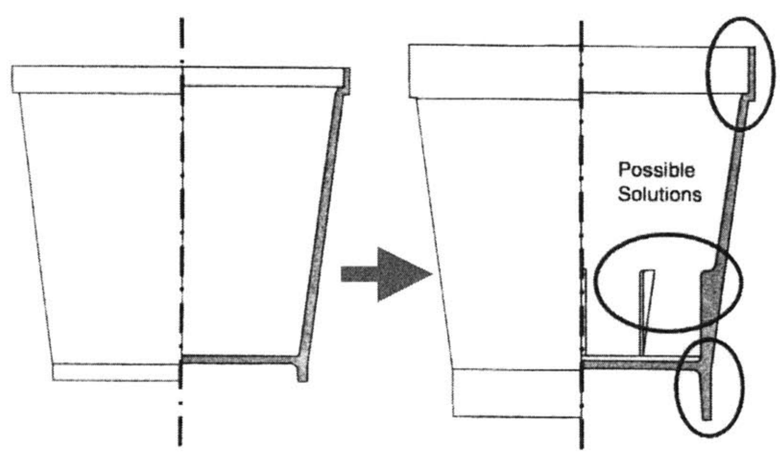


Figure 3-7: Preventing Nesting of Parts [11]

3.4 Insertion Guidelines

Insertion guidelines suggest how to mate parts together through designing alignment, alignment directions to allow accurate and simple insertion.

3.4.1 Mating Features

Designing in chamfers can make insertion of parts easier. The geometries of traditional conical chamfers of a peg and hole are shown in Figure 3-8. In the geometry of the chamfered peg, "d" is the diameter of the peg, "w_1" is the width of the chamfer and "θ_1" is the semiconical angle of the chamfer. In the chamfered hole, "D" is the diameter of the hole, "w_2" is the width of the chamfer, and "θ_2" is the semiconical angle of the chamfer.

Figure 3-9 shows the effects of various chamfer designs on the time taken to insert a peg in a hole. One conclusion from the figure that could be implemented later in the case study is that a curved chamfer can have advantages over a conical chamfer for small clearances.

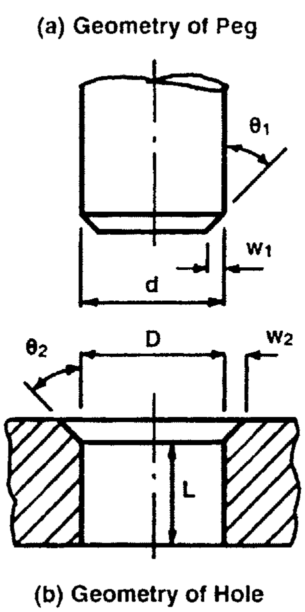


Figure 3-8: Geometries of Peg and Hole [12]

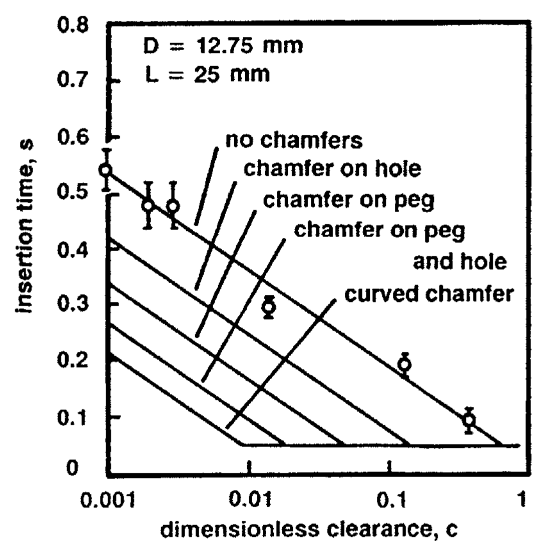


Figure 3-9: Effect of Clearance on Insertion Time [13]

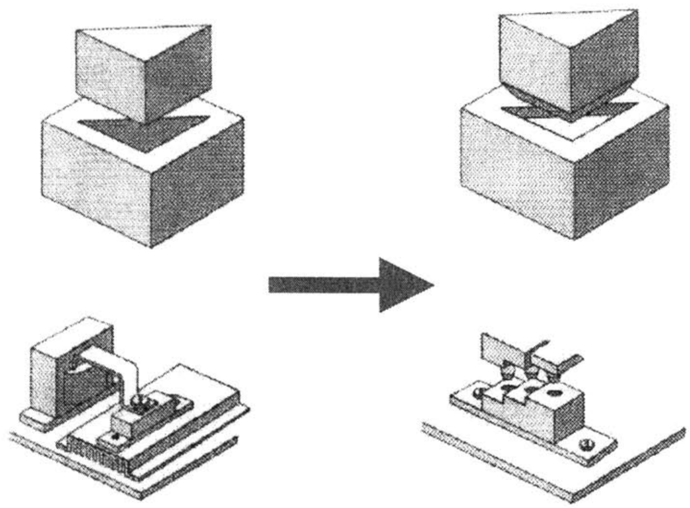


Figure 3-10: Chamfer for Easy Insertion [14]

New parts can be easily oriented without measuring, by aligning features designed into the parts to be mated, as shown in Figure 3-11. One method for doing this is suggested by Otto and Wood, a kinematic attachment scheme called the 3-2-1 alignment process.[15]

> First, you provide 3 points on the assembly that a new part is placed against. The part is slid along the three points up against 2 more points that are in a perpendicular plane on the assembly. Then the part is slid along the 5 points up against a final sixth point, thereby kinematically constraining the new part into the assembly in a predictable way. Also, the geometry defining these six points is candidate geometry for tighter tolerance control as compared to other points on the part and assembly.

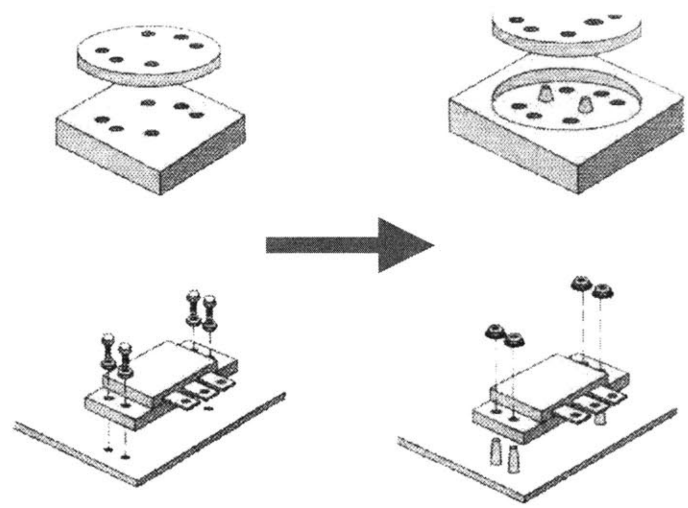


Figure 3-11: Alignment Features [16]

3.4.2 Insertion Approach and Direction

The best rule of thumb is that all assembly work is best done by setting down a large base, and slowing dropping more parts on top of the base, as demonstrated in Figure 3-12. Each part should be fed by gravity, and the work base should not have to be moved to put the part on. Parts also should not be held from below or from the side while being assembled.

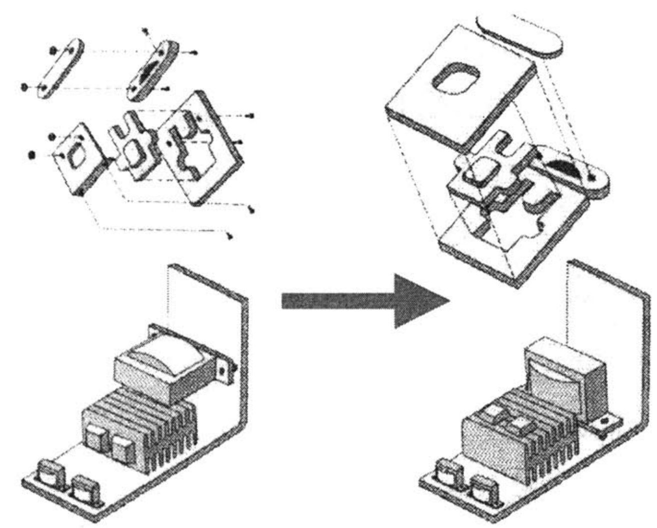


Figure 3-12: Top Down Insertion Direction

If the above guideline cannot be met, exclusively assembling from top down, then efforts need to be made to minimize the number of insertion directions, as Figure 3-13 shows. Re-orientation during assembly should be minimized or avoided. All the possible insertions of a particular orientation should be performed while in that position without having to come back to that same orientation. Also, the system should avoid having to undergo upside-down orientation for assembly.

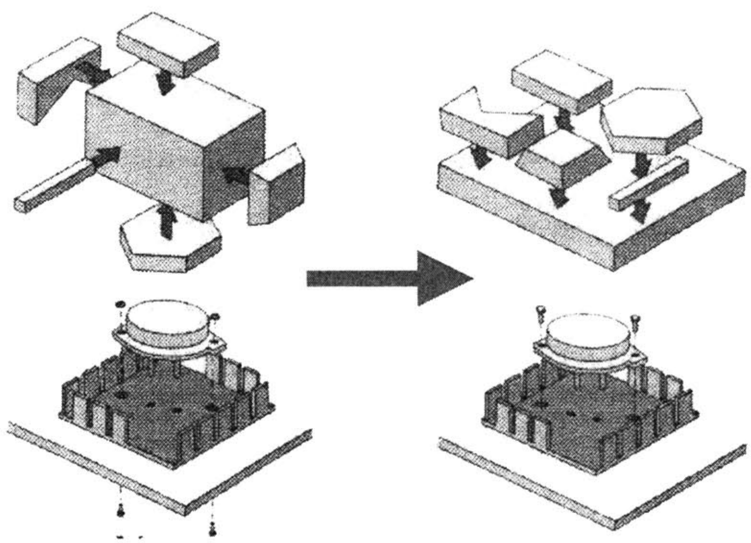


Figure 3-13: Minimizing Insertion Directions [17]

3.5 Joining Guidelines

Joining is the final attachment of a part after it has been inserted onto the assembly. Fastening can be done through a variety of means, such as screws, solder, adhesive, tape, nuts, pins, welding, and many others.

One common guideline with respect to this is in Figure 3-14, that the number of fasteners should be minimized. But one caution with this guideline is that the factor of safety should never be compromised.

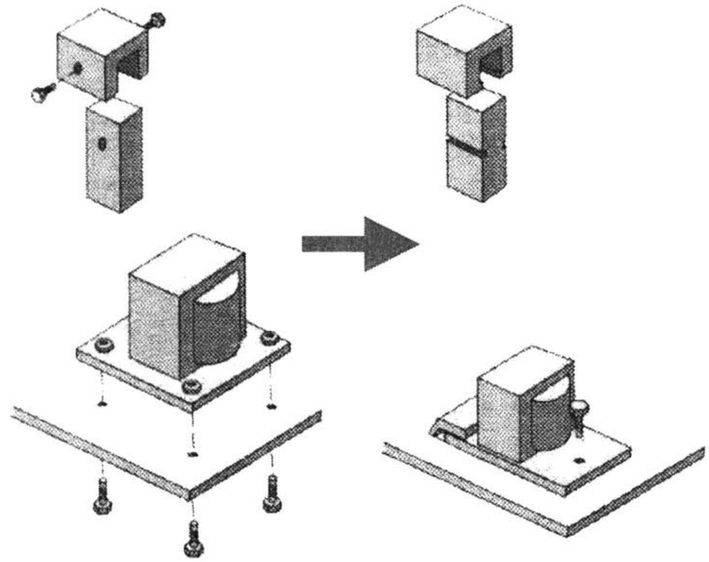


Figure 3-14: Minimizing Fasteners [18]

Other guidelines suggest placing fasteners away from obstructions, and designing parts for ease of fastening, as shown in Figures 3-15 and 3-16.

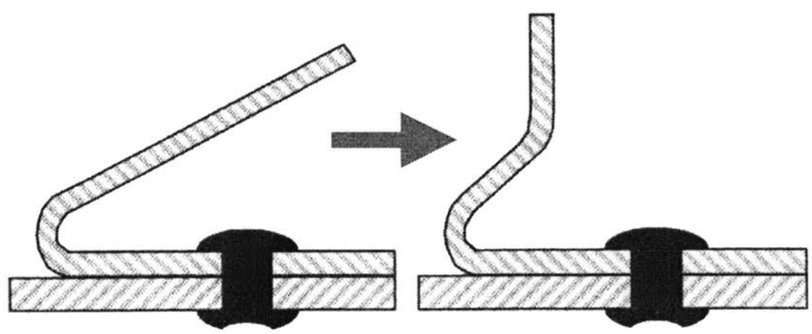


Figure 3-15: Fasteners Away From Obstructions [19]

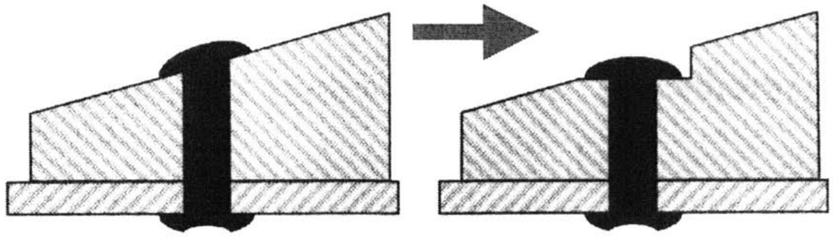


Figure 3-16: Avoiding Angled Fastening [20]

Access is an important aspect of joining, as proper fastening is very dependent on sufficient access of the fastening tool to the fastener, shown below in Figure 3-17.

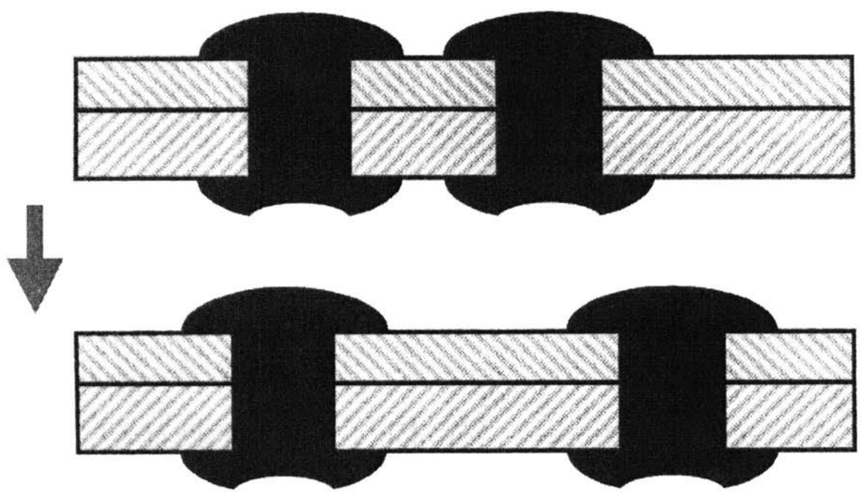


Figure 3-17: Proper Spacing for Access [21]

[1] Otto, K. N. and Wood, K. L., Product Design, Prentice Hall, New Jersey, 2001.
[2] Iredale, R., "Automatic Assembly-Components and Products," Metalwork. Prod., April 8, 1964.
[3] Otto, K. N. and Wood, K. L., Product Design, Prentice Hall, New Jersey, 2001.
[4] *Ibid.*
[5] Otto, K. N. and Wood, K. L., Product Design, Prentice Hall, New Jersey, 2001.
[6] *Ibid.*
[7] *Ibid.*
[8] *Ibid.*
[9] *Ibid.*
[10] *Ibid.*
[11] *Ibid.*
[12] Boothroyd, G., Assembly Automation and Product Design, Marcel Dekker, New York, 1992.
[13] *Ibid.*
[14] Otto, K. N. and Wood, K. L., Product Design, Prentice Hall, New Jersey, 2001.
[15] *Ibid.*
[16] *Ibid.*
[17] *Ibid.*
[18] *Ibid.*
[19] *Ibid.*
[20] *Ibid.*
[21] *Ibid.*

4 Methodologies

4.1 Method properties

Throughout the years, many DFA methodologies have been developed and implemented. Some are more effective with certain applications than others. But from the designers' perspective, according to Redford and Chal,[1] the following are properties that a good DFA methodology should fulfill.

1 *Balanced method* There are two aspects of an assembly that the DFA method should fulfill, the objective aspect and the creative aspect. Objectivity refers to the general procedures for evaluating the assembly. Creativity refers to the general procedures for improving the assembly. Creativity aspect of a method is not expected to automatically redesign a product for the designer, but a good methodology will feed the designer's creativity with its own "creativity", appropriate advice and suggestions during the method, to allow an interaction of sorts.

2 *Systematic method* A systemized method allows a step-by-step analysis of all the relevant issues.

3 *Measurability method* Performing an abstract analysis of a design is quite simple. But to quantifiably measure the design becomes more complicated. Most methodologies measure two key metrics: cost and quality. One issue is that with so many methodologies, a standard measure of these metrics does not exist, each one

having its own. Therefore, it is up to the method itself to clearly define its measures for these metrics and how it arrived at these definitions.

4 *"User-friendly" method* A major barrier to DFA is time, time to implement, time to train and learn. Therefore, ease of use of a methodology is critical. But this should never compromise the thoroughness and quality of the methodology.

As stated, there are a number of design for assembly methodologies and evaluative mechanisms that have been developed over the years. The following methods will be analyzed and implemented for the purposes of the thesis:

- Xerox Producability Analysis
- Boothroyd-Dewhurst DFA Analysis

4.2 Xerox Producability Analysis

The Xerox Producability Analysis is used primarily as an assembly difficulty indicator. It is a simple, but very useful method for analyzing and arriving at design modifications. The following is an adaptation by Otto and Wood of the method originally developed at the Xerox Corporation.[2] The main driving force of the method is a tabulation of efficiency values.

The first step is to draw an assembly sequence diagram of the product. Then, for each subassembly, create a table consisting of:

1) Each part down each row,
2) A column of assembly approach direction (top, side, rotated, bottom),
3) A column of whether the part must be held during assembly (yes/no),
4) A column of tightening required (weld, solder, stake, adhesive, pin, nut, tape, screw, ring, snap),
5) A column of number of repetitions of the operation,
6) If there are more than one operation for each part, use multiple rows.

An example of such a table is shown in Table 4-1.

Table 4-1: Adapted XPI Worksheet

Subassembly/ Part	Operation	Approach	Held?	Tightening	Repetitions	XPI Score
					SUM:	

The next step is to use the data from the table and the numbers from the XPI Scoring Sheet shown in Table 4-2. These numbers are derived by Xerox Corporation to assess an XPI score to a part according to the information filled in the above XPI worksheet for that part. For example, a part that is assembled from the top, needs to be held (Y), and is tightened by a screw (Screw) is assessed an XPI score of 40.

Table 4-2: Adapted XPI Score Sheet [3]

			Assembly Tightening and Tooling									
			Special Tool			Small Tool						No Tool
		Hold?	Weld	Solder	Stake	Adhesive	Pin	Nut	Tape	Screw	Ring	Snap Insert
Assembly Approach	Assemble from Top	N	1	10	20	30	40	70	60	70	90	100
		Y	0	1	10	20	30	40	50	40	70	90
	Assemble from Side	N	0	0	5	10	20	50	40	50	75	80
		Y	0	0	1	5	15	25	35	25	55	75
	Assemble from Bias	N	0	0	0	1	10	40	30	40	65	70
		Y	0	0	0	0	5	15	25	15	45	85
	Rotated Parts	N	0	0	0	1	10	40	30	40	65	70
		Y	0	0	0	0	5	15	25	15	45	65
	Assemble from Bottom	N	0	0	0	0	0	30	0	30	20	60
		Y	0	0	0	0	0	0	0	0	0	55

These numbers are used to determine the XPI score for each part as shown in Equation 4.1a.

$$XPI_{part} = \frac{\sum_{\substack{part\\operations}} XPI_{operation}}{number\ operations}$$

(4.1a)

If there are multiple operations, subtract 10 from the score for each multiple approach and multiple tightening required for the simultaneous insertion operation as shown in Equation 4.1b.

$$XPI_{part} = \frac{\sum_{\substack{part\\operations}} XPI_{operation} - 10n_{repeated}}{number\ operations}$$

(4.1b)

Repeat the above steps for each sub-assembly, and for the final step, average the XPI scores for all the sub-assemblies to arrive at an XPI index for the full assembly.

The XPI score can also be used to estimate assembly cost by converting the score to an equivalent assembly time so that a labor rate can be applied, as developed by Otto and Wood. This is beyond the intent of the original development of the method at Xerox, but their adaptation is shown in Equation 4.2.

$$t = T_{nominal} e^{K(XPI_{nominal} - XPI)}$$

(4.2)

where t is the converted time estimate, K is the scaling factor, XPI is the new XPI rating, and $XPI_{nominal}$ is the old XPI rating of the original design before any modifications, and $T_{nominal}$ is the assembly time for the original design. A reasonable value of K is $K =$

$ln(2.0)=0.69$, which indicates that the converted time estimate will always be greater than $1/2T_{nominal}$, and always smaller than $2T_{nominal}$.

This time is not meant to estimate an accurate new design time, but is intended more as a comparative model, to compare time trend as increased or decreased from the original design. But through the comparisons, inefficient areas are highlighted, thus pointing the redesign in the right direction.

4.3 Boothroyd-Dewhurst DFA Methodology

The Boothroyd-Dewhurst DFA methodology centers on establishing the cost of handling and inserting component parts. The process can be applied to manual or automated assembly, which is further subdivided into high speed dedicated or robotic. An aid to the selection of the assembly system is also provided by a simple analysis of the expected production volume, pay back period required, number of parts in the assembly, and number of product styles.

Regardless of the assembly system, parts of the assembly are evaluated in terms of ease of handling, ease of insertion and a decision as to the necessity of the part in question. The findings are then compared to synthetic data and from this a time and cost is generated for the assembly of that part. An analysis is performed by completing a worksheet, such as the one shown in Figure 4-1.

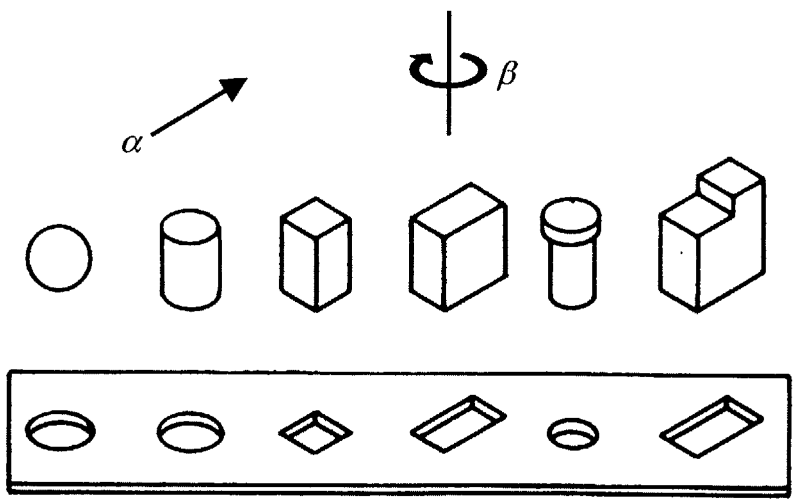
1	2	3	4	5	6	7	8	9	
part I.D. No.	number of times the operation is carried out consecutively	two-digit manual handling code	manual handling time per part	two-digit manual insertion code	manual insertion time per part	Operation Time in Seconds (2) x [(4) + (6)]	operation cost, cents 0.4 x (7)	figures for estimation of theoretical minimum parts	Remarks
						TM	CM	NM	design efficiency = $\frac{3 \times NM}{TM}$ =

Figure 4-1: Boothroyd-Dewhurst DFA Analysis Worksheet [4]

Once the parts have been added to the worksheet the first stage of any analysis is an attempt at part reduction. The opportunity for this reduction is found by examining each part in turn and identifying whether each exists as a separate part for fundamental reasons, as discussed in Chapter 3.

If a part is justified by any one of these reasons, it is deemed to be a necessary part and receives a "1" in the worksheet. If justification is not possible, then the part is non essential, receiving a "0" in the worksheet, and should be designed out or combined with another essential part.

The second stage of the analysis is to examine the handling and insertion of each component part. For manual assembly, a two digit handling code, and a two digit insertion code are identified from synthetic data tables. The tables categorize components with respect to their features for handling such as size, weight, and required amount of orientation. This is the symmetry of the part in terms of α and β, the angles of symmetry along the two planes perpendicular to the insertion direction, as shown in Figure 4-2.



α	0	180	180	90	360	360
β	0	0	90	180	0	360

$$Angle \cong \frac{360°}{\#\ correct\ \ positions}$$

Figure 4-2: Alpha and Beta Rotational Symmetries [5]

MANUAL HANDLING—ESTIMATED TIMES (seconds)

Key

ONE HAND

			parts are easy to grasp and manipulate					parts present handling difficulties (1)				
			thickness > 2 mm			thickness ≤ 2 mm		thickness > 2 mm			thickness ≤ 2 mm	
			size >15 mm	6 mm ≤ size ≤ 15 mm	size <6 mm	size >6 mm	size ≤6 mm	size >15 mm	6 mm ≤ size ≤ 15 mm	size <6 mm	size >6 mm	size ≤6 mm
			0	1	2	3	4	5	6	7	8	9
parts can be grasped and manipulated by one hand without the aid of grasping tools	$(\alpha+\beta) < 360^\circ$	0	1.13	1.43	1.88	1.69	2.18	1.84	2.17	2.65	2.45	2.98
	$360^\circ \le (\alpha+\beta) < 540^\circ$	1	1.5	1.8	2.25	2.06	2.55	2.25	2.57	3.06	3	3.38
	$540^\circ \le (\alpha+\beta) < 720^\circ$	2	1.8	2.1	2.55	2.36	2.85	2.57	2.9	3.38	3.18	3.7
	$(\alpha+\beta) = 720^\circ$	3	1.95	2.25	2.7	2.51	3	2.73	3.06	3.55	3.34	4

ONE HAND with GRASPING AIDS

				parts need tweezers for grasping and manipulation								parts need standard tools other than tweezers	parts need special tools for grasping and manipulation
				parts can be manipulated without optical magnification				parts require optical magnification for manipulation					
				parts are easy to grasp and manipulate		parts present handling difficulties (1)		parts are easy to grasp and manipulate		parts present handling difficulties (1)			
				thickness > 0.25mm	thickness ≤ 0.25mm	thickness > 0.25mm	thickness ≤ 0.25mm	thickness > 0.25mm	thickness ≤ 0.25mm	thickness > 0.25mm	thickness ≤ 0.25mm		
				0	1	2	3	4	5	6	7	8	9
parts can be grasped and manipulated by one hand but only with the use of grasping tools	$\alpha \le 180^\circ$	$0 \le \beta \le 180^\circ$	4	3.6	6.85	4.35	7.6	5.6	8.35	6.35	8.6	7	7
		$\beta = 360^\circ$	5	4	7.25	4.75	8	6	8.75	6.75	9	8	8
	$\alpha = 360^\circ$	$0 \le \beta \le 180^\circ$	6	4.8	8.05	5.55	8.8	6.8	9.55	7.55	9.8	8	9
		$\beta = 360^\circ$	7	5.1	8.35	5.85	9.1	7.1	9.55	7.85	10.1	9	10

TWO HANDS for MANIPULATION

		parts present no additional handling difficulties					parts present additional handling difficulties (e.g. sticky, delicate, slippery, etc.) (1)				
		$\alpha \le 180^\circ$			$\alpha = 360^\circ$		$\alpha \le 180^\circ$			$\alpha = 360^\circ$	
		size > 15 mm	6 mm ≤ size ≤ 15 mm	size < 6 mm	size > 6 mm	size ≤ 6 mm	size > 15 mm	6 mm ≤ size ≤ 15 mm	size < 6 mm	size > 6 mm	size ≤ 6 mm
		0	1	2	3	4	5	6	7	8	9
parts severely nest or tangle or are flexible but can be grasped and lifted by one hand (with the use of grasping tools if necessary) (2)	8	4.1	4.5	5.1	5.6	6.75	5	5.25	5.85	6.35	7

TWO HANDS required for LARGE SIZE

		parts can be handled by one person without mechanical assistance									two persons or mechanical assistance required for parts manipulation
		parts do not severely nest or tangle and are not flexible								parts severely nest or tangle or are flexible (2)	
		part weight < 10 lb				parts are heavy (> 10 lb)					
		parts are easy to grasp and manipulate		parts present other handling difficulties (1)		parts are easy to grasp and manipulate		parts present other handling difficulties (1)			
		$\alpha \le 180^\circ$	$\alpha = 360^\circ$	$\alpha \le 180^\circ$	$\alpha = 360^\circ$	$\alpha \le 180^\circ$	$\alpha = 360^\circ$	$\alpha \le 180^\circ$	$\alpha = 360^\circ$		
		0	1	2	3	4	5	6	7	8	9
two hands, two persons or mechanical assistance required for grasping and transporting parts	9	2	3	2	3	3	4	4	5	7	9

Figure 4-3: Classification, coding, and database for part features affecting manual handling time (in seconds) [6]

MANUAL INSERTION—ESTIMATED TIMES (seconds)

Key:

PART ADDED but NOT SECURED

			after assembly no holding down required to maintain orientation and location (3)				holding down required during subsequent processes to maintain orientation or location (3)			
			easy to align and position during assembly (4)		not easy to align or position during assembly		easy to align and position during assembly (4)		not easy to align or position during assembly	
			no resistance to insertion	resistance to insertion (5)	no resistance to insertion	resistance to insertion (5)	no resistance to insertion	resistance to insertion (5)	no resistance to insertion	resistance to insertion (5)
			0	1	2	3	6	7	8	9
addition of any part (1) where neither the part itself nor any other part is finally secured immediately	part and associated tool (including hands) can easily reach the desired location	0	1.5	2.5	2.5	3.5	5.5	6.5	6.5	7.5
	part and associated tool (including hands) cannot easily reach the desired location: due to obstructed access or restricted vision (2)	1	4	5	5	6	8	9	9	10
	part and associated tool (including hands) cannot easily reach the desired location: due to obstructed access and restricted vision (2)	2	5.5	6.5	6.5	7.5	9.5	10.5	10.5	11.5

PART SECURED IMMEDIATELY

			no screwing operation or plastic deformation immediately after insertion (snap/press fits, circlips, spire nuts, etc.)		plastic deformation immediately after insertion						screw tightening immediately after insertion (6)	
					plastic bending or torsion			rivetting or similar operation				
						not easy to align or position during assembly			not easy to align or position during assembly			
			easy to align and position with no resistance to insertion (4)	not easy to align or position during assembly and/or resistance to insertion (5)	easy to align and position during assembly (4)	no resistance to insertion	resistance to insertion (5)	easy to align and position during assembly (4)	no resistance to insertion	resistance to insertion (5)	easy to align and position with no torsional resistance (4)	not easy to align or position and/or torsional resistance (5)
			0	1	2	3	4	5	6	7	8	9
addition of any part (1) where the part itself and/or other parts are being finally secured immediately	part and associated tool (including hands) can easily reach the desired location and the tool can be operated easily	3	2	5	4	5	6	7	8	9	6	8
	part and associated tool (including hands) cannot easily reach desired location or tool cannot be operated easily: due to obstructed access or restricted vision (2)	4	4.5	7.5	6.5	7.5	8.5	9.5	10.5	11.5	8.5	10.5
	part and associated tool (including hands) cannot easily reach desired location or tool cannot be operated easily: due to obstructed access and restricted vision (2)	5	6	9	8	9	10	11	12	13	10	12

SEPARATE OPERATION

		mechanical fastening processes (part(s) already in place but not secured immediately after insertion)				non-mechanical fastening processes (part(s) already in place but not secured immediately after insertion)				non-fastening processes	
		none or localized plastic deformation				metallurgical processes					
							additional material required				
		bending or similar processes	rivetting or similar processes	screw tightening (6) or other processes	bulk plastic deformation (large proportion of part is plastically deformed during fastening)	no additional material required (e.g. resistance, friction welding, etc.)	soldering processes	weld/braze processes	chemical processes (e.g. adhesive bonding, etc.)	manipulation of parts or sub-assembly (e.g. orienting, fitting or adjustment of part(s), etc.)	other processes (e.g. liquid insertion, etc.)
		0	1	2	3	4	5	6	7	8	9
assembly processes where all solid parts are in place	9	4	7	5	3.5	7	8	12	12	9	12

Figure 4-4: Classification, coding, and database for part features affecting insertion and fastening (in seconds) [7]

For insertion, categories are for aligning of the part, type of securing method, and whether the part is secured on insertion or as a separate process. These codes are then cross-referenced to identify the time for that operation from the tables shown in Figures 4-3 and 4-4. The codes and subsequent times are entered into the worksheet and used to determine a number of metrics.

Assembly time (TM) is determined by summing the handling and insertion times. Assembly cost (CM) is proportional to TM by a factor that accounts for wage rate and overheads. Theoretical minimum number of parts (NM) is the summation of all those essential parts categorized by a "1".

Design efficiency is defined as the ideal assembly time divided by the estimated assembly time. The ideal assembly time is given by "3NM", where the "3" represents a handling time of 1.5 and insertion time of 1.5, for an ideal component. Though cost and times are determined, care must be taken in the use of these values in an absolute sense, as with other techniques, values are best used for comparison of re-designs.

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[1] Redford, A. and Chal, J., Design for Assembly: Principles and Practice, McGraw Hill, London, 1994.

[2] Otto, K. N. and Wood, K. L., Product Design, Prentice Hall, New Jersey, 2001.

[3] *Ibid.*

[4] Boothroyd, G., Dewhurst, P., Machine Design, Penton Publishing, Cleveland, OH, 1984.

[5] Boothroyd, G., Assembly Automation and Product Design, Marcel Dekker, New York, 1992.

[6] Boothroyd, G., Dewhurst, P., Machine Design, Penton Publishing, Cleveland, OH, 1984.

[7] *Ibid.*

5

Case Study

5.1 Description and History of the Cold-Gas Thrust Control System

The MIT Lincoln Laboratory (MIT-LL) Fly Away Sensor Package (FASP) program contains a cold-gas thrust control system that was contracted to and developed by AlliedSignal Aerospace Equipment Systems of Tempe, Arizona. This system was used in both the second and third campaigns of the TCMP project, TCMP-2 and TCMP-3. TCMP is a Lincoln Laboratory developed space re-entry vehicle project.

The cold-gas thrust control system was chosen as the case study for this thesis to demonstrate the effectiveness of Design for Assembly. Its design was brought to the forefront during a study of discrepancy data for the TCMP project. The system's history of leakage problems stemming from assembly issues warranted further exploration from a DFA perspective. The history of the cold-gas thrusters is covered later in this chapter, and its application of DFA is covered in subsequent chapters.

The TCMP Fly-Away Sensor Package (FASP) vehicle requires a cold-gas thrust system that can provide attitude control (pitch, yaw, roll, and axial velocity management) and lateral thrust. The system, therefore, is comprised of three main elements: an attitude control system, a lateral thrust system, and a gas supply system. [1]

5.1.1 Attitude Control System

Each thruster assembly consists of a solenoid control valve, a pair of poppets and a thruster nozzle. The pitch and yaw assemblies are identical. The roll assembly uses the same components as the pitch and yaw units, but has a slightly different set of nozzles due to its location in the vehicle. The six thruster assemblies are connected to a stainless steel high-pressure gas supply tube system and are mounted to a bulkhead ring.

The control valve allows pressure regulated krypton gas to be delivered to two different nozzles. A schematic diagram of the valve is shown in Figure 5-1.

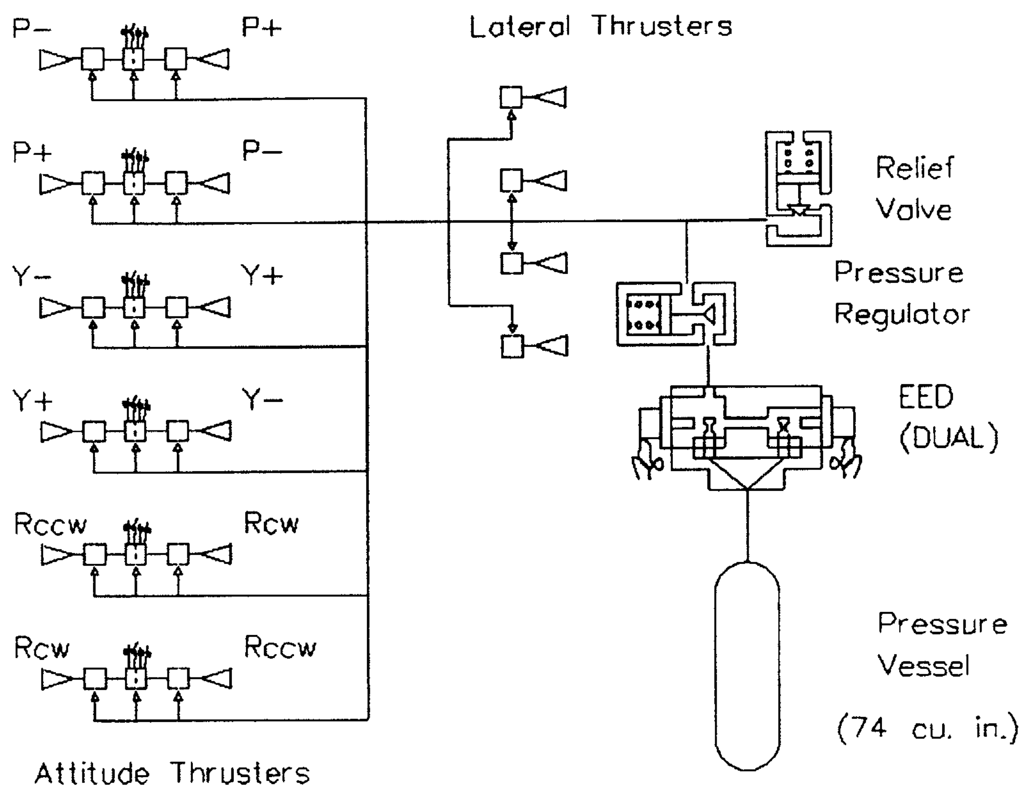

Figure 5-1: FASP Cold Gas Control System Schematic [2]

Operation of the thruster is shown in Figure 5-2. High-pressured gas is delivered to the inlet of the control valve and the outputs are connected to a pair of poppets. The poppets are a pressure-balanced design with the regulated pressure supplied to the inlet side of the spring-closed poppet. The base of the poppet is supplied with pressure from the control valve. A bypass orifice is used to pass some of the gas around the poppet. With this arrangement, very small thrust impulses can be delivered by opening the control valve for brief durations, which allows flow through the bypass orifice but does not allow the pressure to build up enough to open the poppet.

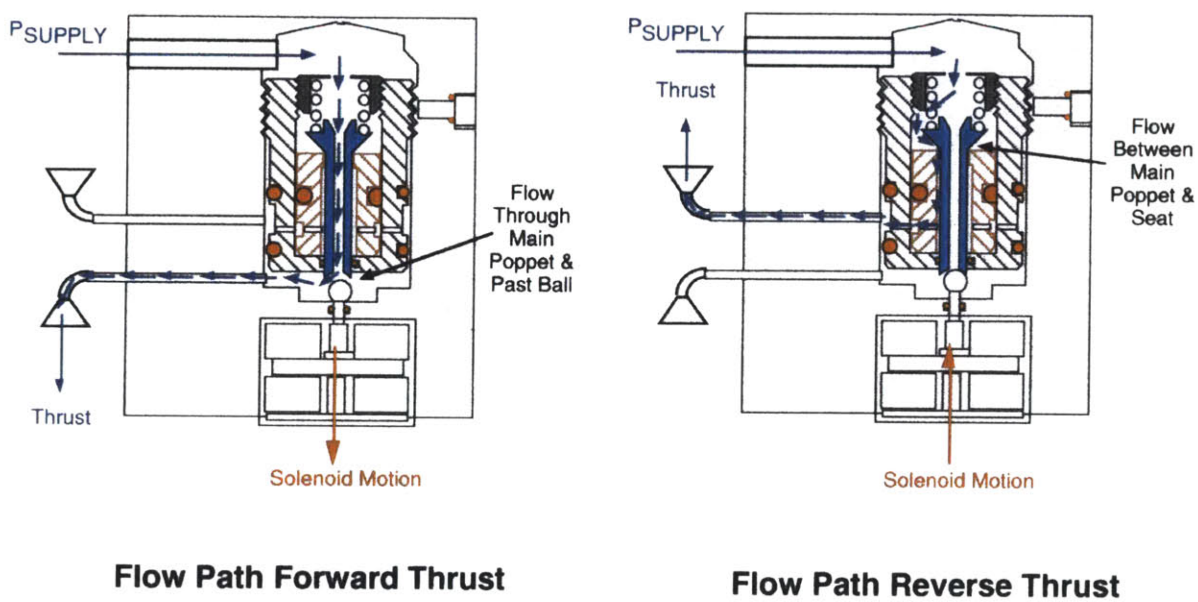

Figure 5-2: Cold Gas Thruster Operation [3]

The outputs of the pitch and yaw thrusters are connected to a pair of nozzles with short expansion cones. The nozzles are angled slightly outward, and match the vehicle contour. The roll thrusters are connected to nozzles that are positioned tangential to the body axis and are identical in size for both the clockwise and counterclockwise thrusters. Each nozzle pair is controlled by the same solenoid valve so two coils are energized to roll in one direction and the other two coils are energized to roll in the opposite direction.

Pitch and yaw thrusters provide 2 lb_f each and the roll thrusters 0.8 lb_f each at 1000 psig inlet pressure using krypton gas.[4]

5.1.2 Lateral Thrust System

Four thruster valves located at the center of gravity of the FASP have their thrust oriented in an outward radial direction in order to direct the lateral position of the FASP, shown in Figure 5-3. The lateral thruster uses a small solenoid acting on a spring loaded pressure balanced poppet. When the solenoid is energized, enough force is developed to open the pressure-balanced poppet that delivers the high-pressure gas to the outlet port.

These lateral thrusters provide up to 2 lb_f of thrust at 930 psig inlet pressure, with a response time of about 10 milliseconds.

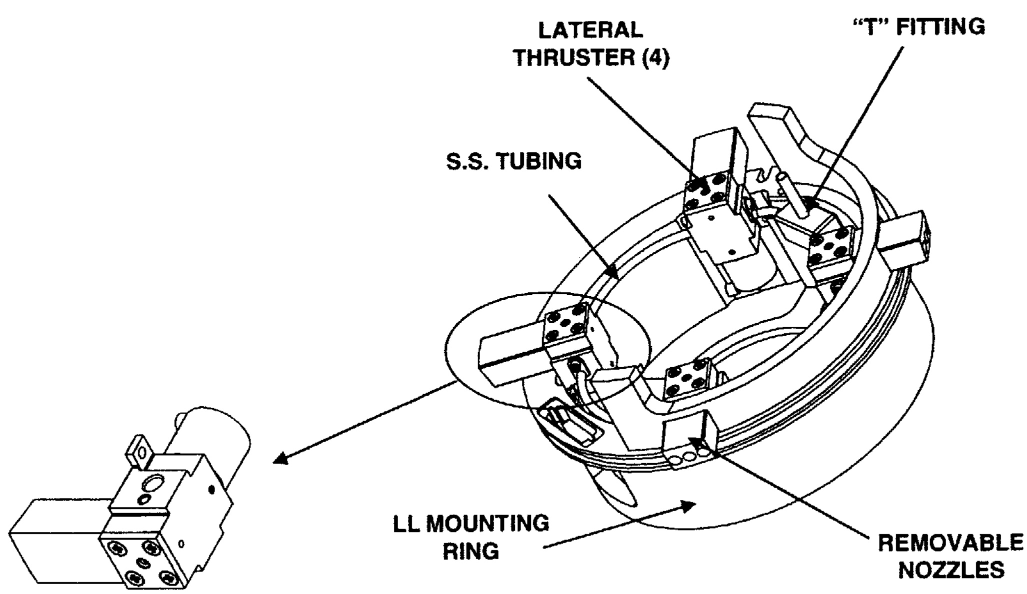

Figure 5-3: Lateral Thruster Packaging [5]

5.2 History of Leakage Problem

Following is a brief timeline of the history of the leakage problem, followed by the corrective actions taken by MIT Lincoln Laboratory. [6]

TCMP-2 Qual FASP

Leaks developed during Qual Air Bearing tests.

Thrusters shipped to Allied Signal (Tempe, AZ) for repairs.

TCMP-3A Flight FASP at Lincoln Laboratory

Leaks developed on two separate thrusters during post environmental Functional tests. Debris found on poppet seats. All thrusters disassembled, ultrasonically cleaned and reassembled in clean room at MIT Lincoln Laboratory.

TCMP-3A Flight FASP at Wake Island

Leak observed during post shipment checkout.

Leak rate measured and monitored. Determined that leak rate was small and would not impact flight performance.

TCMP-3A Flight spare FASP Post Shipment from Wake Island

Small leak observed on one thruster.

5.3 Assembly Issues

The design of the FASP cold-gas thrusters was an evolved design, arrived at by adapting and repackaging existing subcomponents from previous projects. Therefore, the assembly of the thrusters either came from excess engineering inventory that were produced previously from a past project, or other components were fabricated using external vendors. All final assembly and testing were performed in-house at Allied Signal.

The assembly was performed, in general, by fairly high-skilled assemblers. But some assemblers were subcontracted to do the assembly towards the end of production because the factory was too busy to keep up with demand. So initially, using outside people to do assembly made the process even more difficult, and assembly of one thruster could have taken a new subcontracted worker up to 3-4 days. According to Allied Signal, much of the difficulty arose from MIT Lincoln Laboratory's stringent requirements which caused much time to be needed for adjusting the valve, especially for the leak requirements.

Another issue was that the parts and subcomponents that were used from previous projects were initially built for a short run time, around five minutes. Therefore, these were not as robust as needed for the FASP project, whose run time was considerably more. The testing itself (which was performed by both Allied Signal and Lincoln Laboratory) added much more run time and fatigue than the design had originally allotted for.

Other issues involved contamination issues, and the corrective action for next time would be to change to a clean room assembly.

Between TCMP-2 and TCMP-3, one issue was addressed, and a change was made on the valve bodies. Deburring and cleaning steps were put into the assembly process, which resulted in a reduction of premature failures.

5.4 Leak Investigation

As shown above, there has been a history of leakage with the thrusters. An investigation of the leakage was performed by a group at Lincoln Laboratory, headed by Brian Languirand, the lead mechanical engineer of the FASP. The following are quoted from a an unclassified presentation by Brian Languirand on this topic on March 29, 2000. [7]

The observation is as follows:

The cartridge assembly must be precisely adjusted to simultaneously seal off flow past ball and seat. Once adjusted a locking set screw is lightly tightened (to prevent damaging the thread) to hold the cartridge from moving during vibration. We observed that additional tightening and loosening of this locking set screw after the cartridge was adjusted would cause the thrusters to leak, sometimes past the ball and sometimes past the seat.

Cause:

We observed that when the set screw contacts the threads on the cartridge it moves the cartridge assembly a very small amount (thread tolerances) up or down depending on how the end of the set screw aligns with the thread geometry.

Corrective action:

We installed a small piece of nylon between the end of the set screw and the thread on the cartridge. As the set screw is tightened the thread geometry from the cartridge is formed into the nylon.

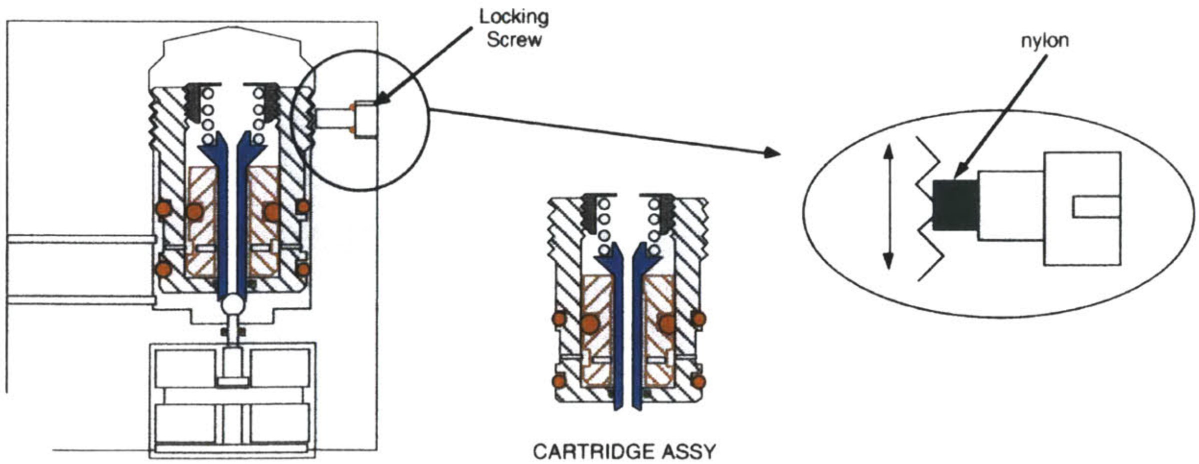

Figure 5-4: Leak Investigation [8]

As seen from Figure 5-4, the cause diagnosis and corrective action were sufficient to satisfy the leak requirements. But this cause diagnosis also demonstrates that the leakage problem lies much deeper than an outward, trivial issue, but at the design level. This design is clearly not an assembly oriented design as the leakage issues as well as various other issues described above show.

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[1] Cycon, M., Overholt, D., "Technical and Management Proposal for the Fly Away Sensor Package (FASP) Cold-Gas Thrust Control System for MIT Lincoln Laboratory," AlliedSignal Aerospace Equipment Systems, June 10, 1998.
[2] Cycon, M., "Gas Distribution Concept for FASP," AlliedSignal, April 3, 1995.
[3] Languirand, B., "Leak Investigation," MIT Lincoln Laboratory, March 29, 2000.
[4] Cycon, M., Overholt, D., "Technical and Management Proposal for the Fly Away Sensor Package (FASP) Cold-Gas Thrust Control System for MIT Lincoln Laboratory," AlliedSignal Aerospace Equipment Systems, June 10, 1998.
[5] Languirand, B., "Leak Investigation," MIT Lincoln Laboratory, March 29, 2000.
[6] *Ibid.*
[7] *Ibid.*
[8] *Ibid.*

6

Design Overview

6.1 Exploded Diagram

Figure 6-1 is an exploded view of a cold-gas thruster, modeled on Solidworks.

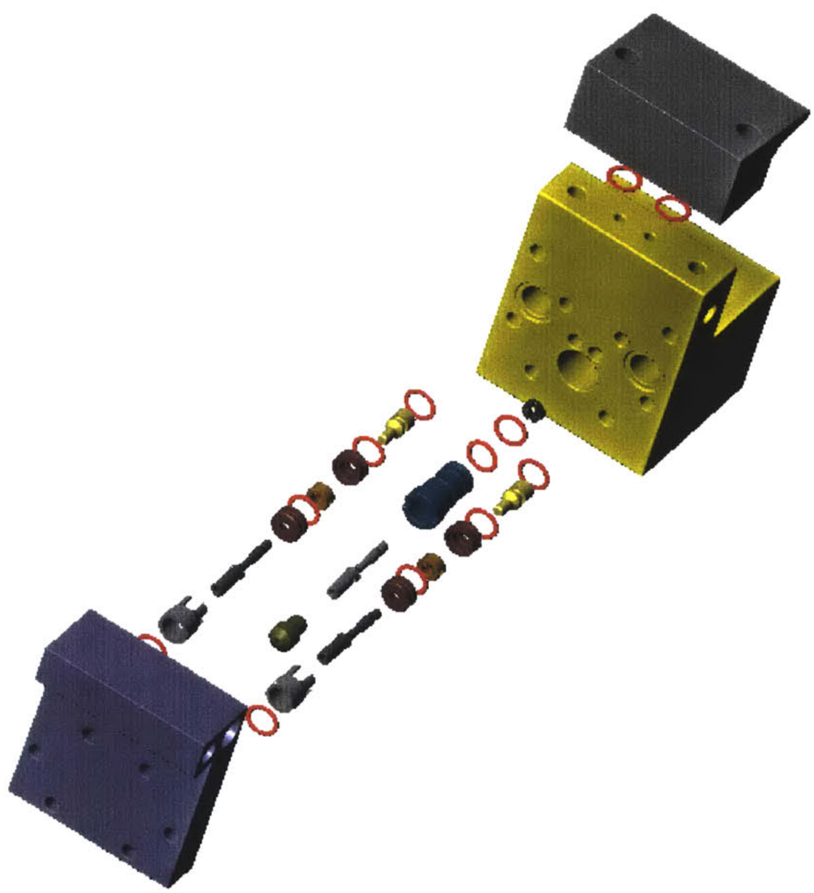


Figure 6-1: Exploded Diagram

6.2 Parts List

Table 6-1: Parts List

Parts List		
Part #	**Description**	**Qty**
1	Valve Housing	1
Main Poppet Subassembly		
2	Main Poppet Retainer	1
3	O-ring, Main Poppet Retainer	2
4	Main Poppet	1
5	Spring, Main Poppet Retainer	1
6	Main Screw	1
7	Ball Retainer	1
8	Ball	1
Side Poppet Subassembly		
9	Side Poppet	2
10	Seat, Thruster Valve	4
11	O-ring, Seat	4
12	Spacer, Thruster Valve	2
13	Screw, Thruster Valve	2
14	O-ring, Thruster Valve	2
15	Retainer Seat, Thruster Valve	2
16	O-ring, Retainer Seat	2
17	Spring, Thruster Valve	2
Set Screw Subassembly		
18	Set Screw	1
19	O-ring, Set Screw	1
Thruster Manifold Subassembly		
20	Thruster Manifold	1
21	O-ring, Thruster Manifold	1
22	Screws, Thruster Manifold	2
23	Washers, Thruster Manifold	2
Nozzle Subassembly		
24	Nozzle	1
25	O-ring, Nozzle	2
26	Screws, Nozzle	2
27	Washers, Nozzle	2
Solenoid Subassembly		
28	Solenoid	1
29	Screws, Solenoid	4

6.3 Assembly Sequence Diagram

The first step in determining the effectiveness and efficiency of an assembly is to establish an assembly sequence diagram. The final, completed assembly is the main vertical line, or "trunk", and all the successively attached parts and subassemblies are leaf nodes. The diagram accurately portrays which part or subassembly is attached and when it is attached during the sequence of the assembly process. [1]

The diagram also portrays two more concepts: fixturing or reorientation needs, and insertion direction. At each node of the process where the assembly requires fixturing, a "F" is placed. Likewise, when reorientation is required, a "R" is placed at the node.

Also, at every node, an insertion direction is denoted. The direction of the arrow, whether straight up, down, right, left, or rotation, shows the insertion direction at that point of the assembly process.

The importance of the assembly sequence diagram is twofold. One, it serves the significance of providing the designer a total overview of the design in a step-by-step fashion. Its other importance lies in the fact that it is from this type of diagram that many DFA methodologies derive their information and data.

Figure 6-2 shows the Assembly Sequence Diagram of the cold-gas thruster design.

6.3.1 Assembly Sequence Diagram of the Cold-Gas Thruster

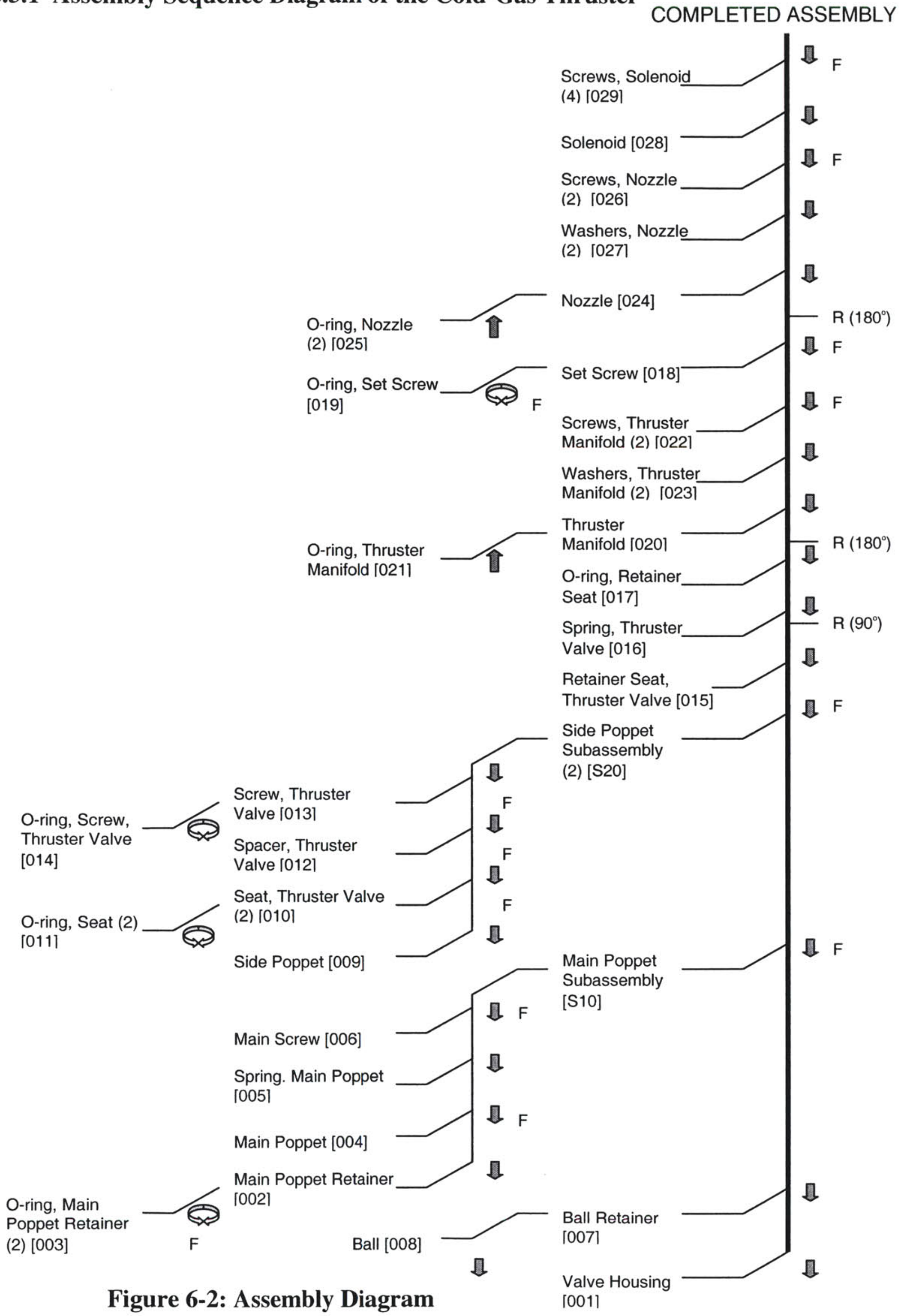


Figure 6-2: Assembly Diagram

6.4 Design Evaluation

In evaluating the design of the thruster, a good beginning process is to estimate the difficulty of assembly of the design. As stated before in Chapter 4, the Xerox Producability Index (XPI) is used as an evaluative assembly difficulty indicator. It allows the highlighting of major assembly issues and flaws through the tabulation of efficiency values. The adaptation by Wood and Otto of the method originally developed at the Xerox Corporation is used for the XPI Assembly Analysis of the cold-gas thruster, as shown in Table 6-2.

Table 6-2: XPI Assembly Analysis

Subassembly / Part	Operation	Approach	Held?	Tightening	Repetitions	XPI Score	XPI Totals
Valve Housing	01	Top	No	No	1	100	100
Ball Retainer	02a	Top	No	Adhesive	1	30	65
Ball	02b	Top	No	No	1	100	
Main Poppet Retainer	03a	Top	No	No	1	100	73
O-ring, Main Poppet Retainer	03b	Rot	Yes	Snap	2	65	
Main Poppet	04	Top	Yes	Snap	1	90	90
Spring, Main Poppet Retainer	05	Top	No	No	1	100	100
Main Screw	06	Top	Yes	Screw	1	40	40
Main Poppet Sub-Assembly	07	Top	Yes	Snap/Screw	1	40	40
Side Poppet	08	Top	No	No	1	100	100
Seat, Thruster Valve	09a	Top	Yes	No	2	90	58
O-ring, Seat, Thruster Valve	09b	Rot	Yes	Snap	2	65	
Spacer, Thruster Valve	10	Top	Yes	No	1	90	90
Screw, Thruster Valve	11a	Top	Yes	Screw	1	40	53
O-ring, Screw	11b	Rot	Yes	Snap	1	65	
Retainer Seat, Thruster Valve	12	Top	Yes	No	1	90	90
Spring, Thruster Valve	13	Top	No	No	1	100	100
Side Poppet Sub-Assembly	14	Top	Yes	Snap	2	90	70
Set Screw	15a	Top	Yes	Screw	1	40	65
O-ring, Set Screw	15b	Top	Yes	Snap	1	90	
Thruster Manifold	16a	Top	Yes	Screw	1	40	28
O-ring, Thruster Manifold	16b	Bottom	Yes	No	1	55	
Screws, Thruster Manifold					2		
Washers, Thruster Manifold					2		
Nozzle	17a	Top	Yes	Screw	1	40	18
O-ring, Nozzle	17b	Bottom	Yes	No	2	55	
Screws, Nozzle					2		
Washers, Nozzle					2		
Solenoid	18	Top	Yes	Screw	1	40	20
Screws, Solenoid					4		
						XPI TOTAL	67

To assess assembly difficulty, the parts and subassemblies with low XPI ratings in Table 6-3 should be examined as areas for possible redesign.

Table 6-3: Areas of Possible Redesign

Ball Retainer	65
Main Poppet Retainer	73
Main Screw	40
Seat, Thruster Valve	58
Screw, Thruster Valve	28
Set Screw	65
Thruster Manifold	28
Nozzle	18
Solenoid	20
Side Poppet Sub-assembly	70
Main Poppet Sub-assembly	40

These components are further examined in the next chapter through an in-depth analysis to determine its candidacy for elimination or incorporation with other parts. XPI ratings along with the results from the Boothroyd-Dewhurst DFA Analysis is used to weigh these options.

[1] Otto, K. N. and Wood, K. L., Product Design, Prentice Hall, New Jersey, 2001.

7
DFA Analysis

7.1 Assembly Design Summary

Table 7-1: Assembly Design Summary

XPI Rating	69
Total Assembly Time	1289.86 sec
Number of Different Parts or Sub-Assemblies	30
Number of Parts and Sub-Assemblies Assembled (including repeats)	48
Number of Reorientations and Standard or User Operations (including repeats)	3
Theoretical Minimum Number of Parts	3
Boothroyd-Dewhurst DFA Index (%)	2.05

The XPI Rating is given as a result of the Xerox Producability Analysis, an average of the XPI Scores of all its parts and sub-assemblies. For the analysis, refer to the XPI Assembly Analysis Table in the previous chapter.

The Theoretical Minimum Number of Parts is given by the Boothroyd-Dewhurst definition, as reviewed below in section 7.2.1. And the total assembly time is given by the Boothroyd-Dewhurst Analysis of the cold-gas thruster by summing up the assembly times of each part and sub-assembly. The analysis also produces the Boothroyd-Dewhurst DFA Index by Equation 7.1.[1]

$$EM = \frac{t_{ideal} \times NM}{TM} \qquad (7.1)$$

Where,

EM	=	the manual assembly efficiency
t_{ideal}	=	the "ideal" assembly time per part, suggested as 3 seconds
NM	=	the theoretical minimum number of parts, determined as the number of parts that satisfy at least one of the following three criteria: 1) must move during operation, 2) must be made of different material, or 3) must be separate to permit assembly or disassembly
TM	=	the total manual assembly time, in seconds

This analysis is shown in detail at the end of the chapter.

7.2 Cold-Gas Thruster Assembly Issues

Using the results of the Xerox Producability Index, the assembly of the thruster is examined in more detail. This evaluation is performed in accordance with the Design for Assembly guidelines that were discussed in Chapter 3.

7.2.1 System Guidelines

7.2.1.1 Minimum Number of Parts

As a reminder, the Boothroyd-Dewhurst concept of Minimum Number of Parts: Generally, a part is needed only when, relative to other parts of the assembly, a kinematic motion is required, electric isolation is required, or thermal isolation is required.[2]

In other words, the questions that can be asked to determine the distinctiveness of two parts: [3]

1. Do the parts move relative to one another?
2. Must the parts be made of different materials?
3. Must the parts be separable for maintenance or manufacture?

As evidenced by the 48 parts and sub-assemblies assembled (including repeats), one prominent issue of the cold-gas thruster is simply the number of parts, as seen in Figure 7-1.

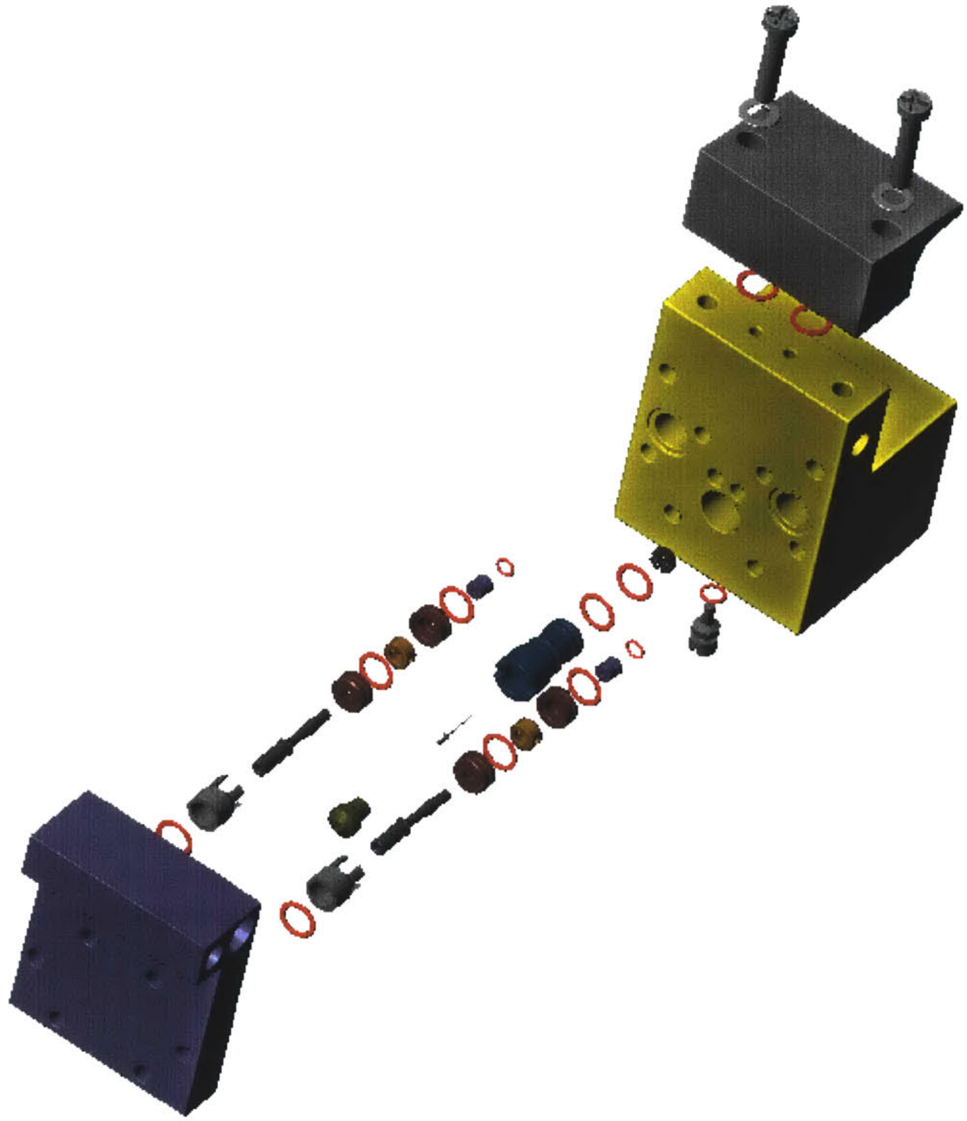


Figure 7-1: Exploded View of Original Design

7.2.2 Handling Guidelines

Handling issues are not applicable to the cold-gas thrusters. None of the parts appear to have severe tangling, nesting, or other handling issues.

7.2.3 Insertion Guidelines

7.2.3.1 O-Ring Shearing

The primary insertion issues occur at the mating surface between the valve housing and the two side poppet sub-assemblies, as well as between the valve housing and the main poppet sub-assembly, as shown in Figure 7-2. Shearing of the o-rings is the main effect of this design issue.

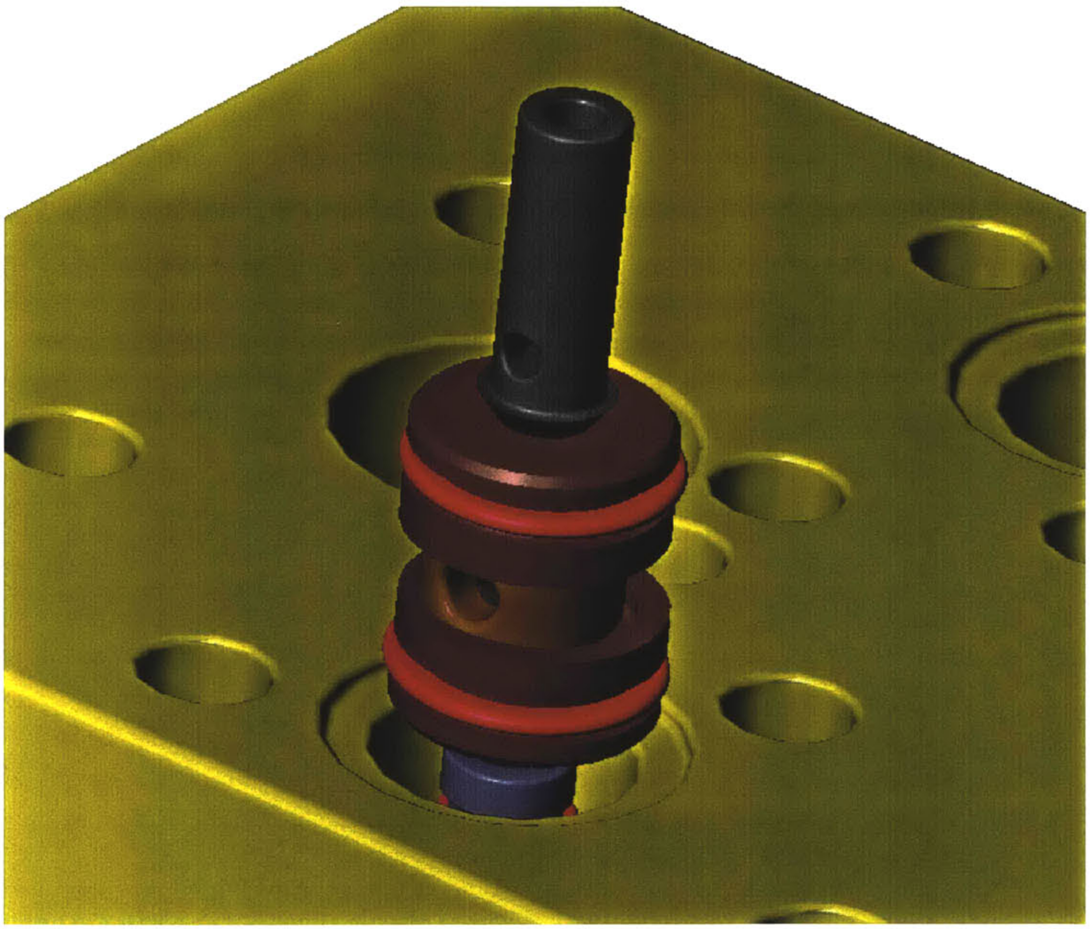


Figure 7-2: Side Poppet Sub-Assembly Insertion into Valve Housing

The tight fit of the poppet sub-assemblies and the valve housing mating holes lead to severe insertion difficulties. Due to the pneumatic nature of this design, tight tolerances are indeed required, especially the areas in which o-rings are used. However, despite this restriction, various measures can be taken to improve the insertion process and thereby reduce the risk of part damage.

Another area where insertion difficulties arise is the mating surface between the main poppet sub-assembly and the valve housing. Whereas the side poppet sub-assemblies are simply push fitted into smooth holes, the main poppet subassembly process is different.

For the insertion of the main poppet subassembly, it first needs to be push fit into the hole. It should be noted that the two o-rings of the main poppet sub-assembly are located at the push fit portion of the sub-assembly. After the initial push fit, once it reaches a certain depth, the subassembly then needs to be turned, as it is threaded at that depth, to complete the joining process.

The insertion process is shown in Figure 7-3.

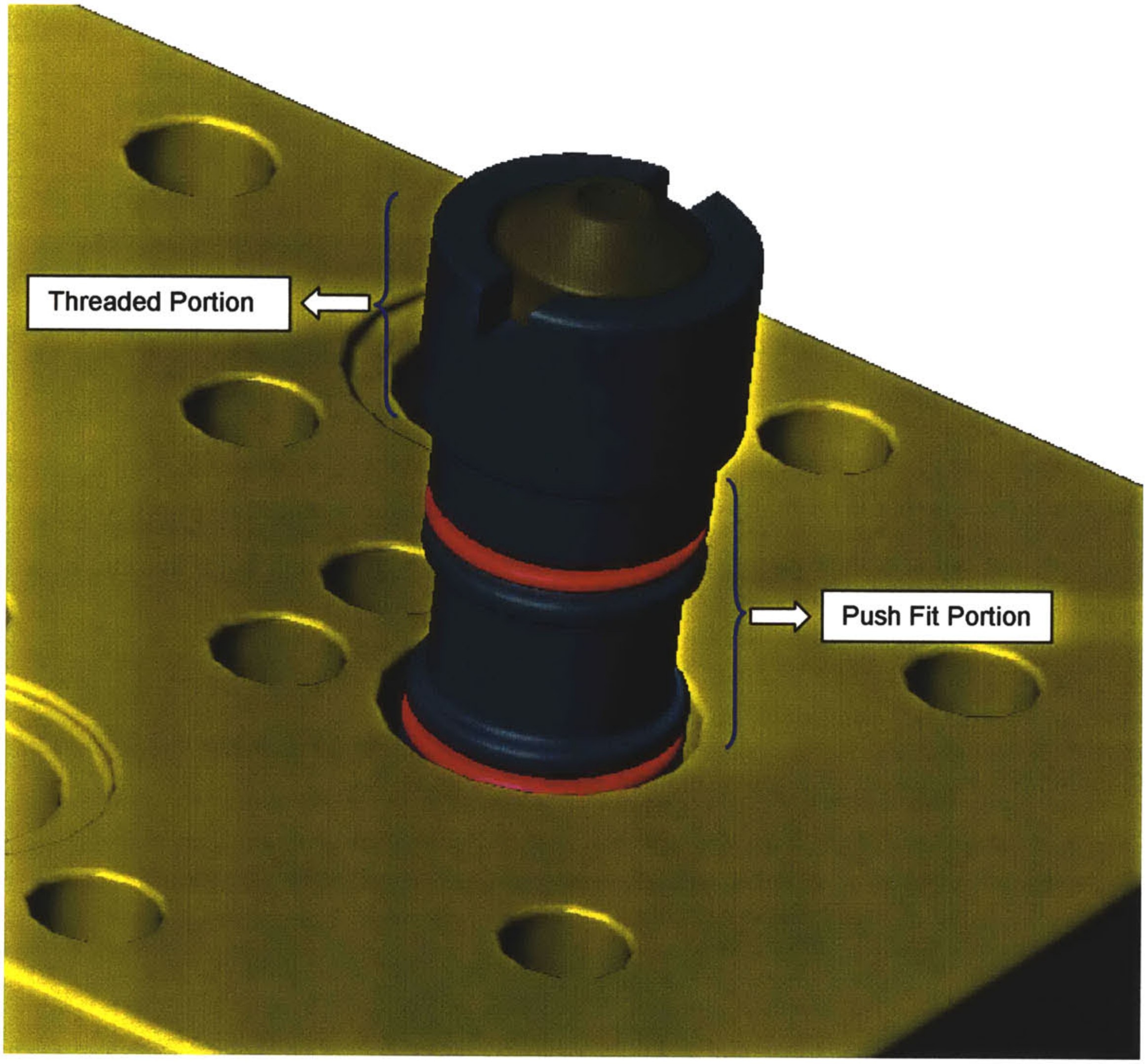


Figure 7-3: Main Poppet Sub-Assembly Insertion into Valve Housing

This of course means that the mating hole is also threaded, which results in another insertion issue. Because the diameter of the threaded portion of the main poppet subassembly is not much greater than the diameter of the push fit portion, the push fit portion could scrape along some of the threads of the mating hole while undergoing the push fit operation. This scraping can be another cause of o-ring shearing.

7.2.4 Joining Guidelines

7.2.4.1 Blind Assembly

A blind assembly is simply one in which the view of the joining point or surface is blocked from the assembler. This has a few adverse effects. One is that it greatly increases the probability of incorrect assembly, leading to damage of parts, leakage due to incorrect joining of parts, and many other issues.

Another effect is that it basically increases the amount of time required to join two parts together. Particularly in situations where the joining occurs at a small hole, this can be a major issue.

Such an example occurs within the main poppet sub-assembly, between the joining of the main poppet and the main poppet retainer, shown in Figure 7-4.

Figure 7-4: Blind Assembly of Main Poppet and Main Poppet Retainer

Other areas where blind assembly occurs has already been discussed above, between the valve housing and the side and main poppet sub-assemblies, as shown in Figure 7-5. These sub-assemblies are essentially push fit into the mating hole of the valve housing, but the depth of the amount required to push is not intuitive, as well as the precise location of the joining point inside that hole.

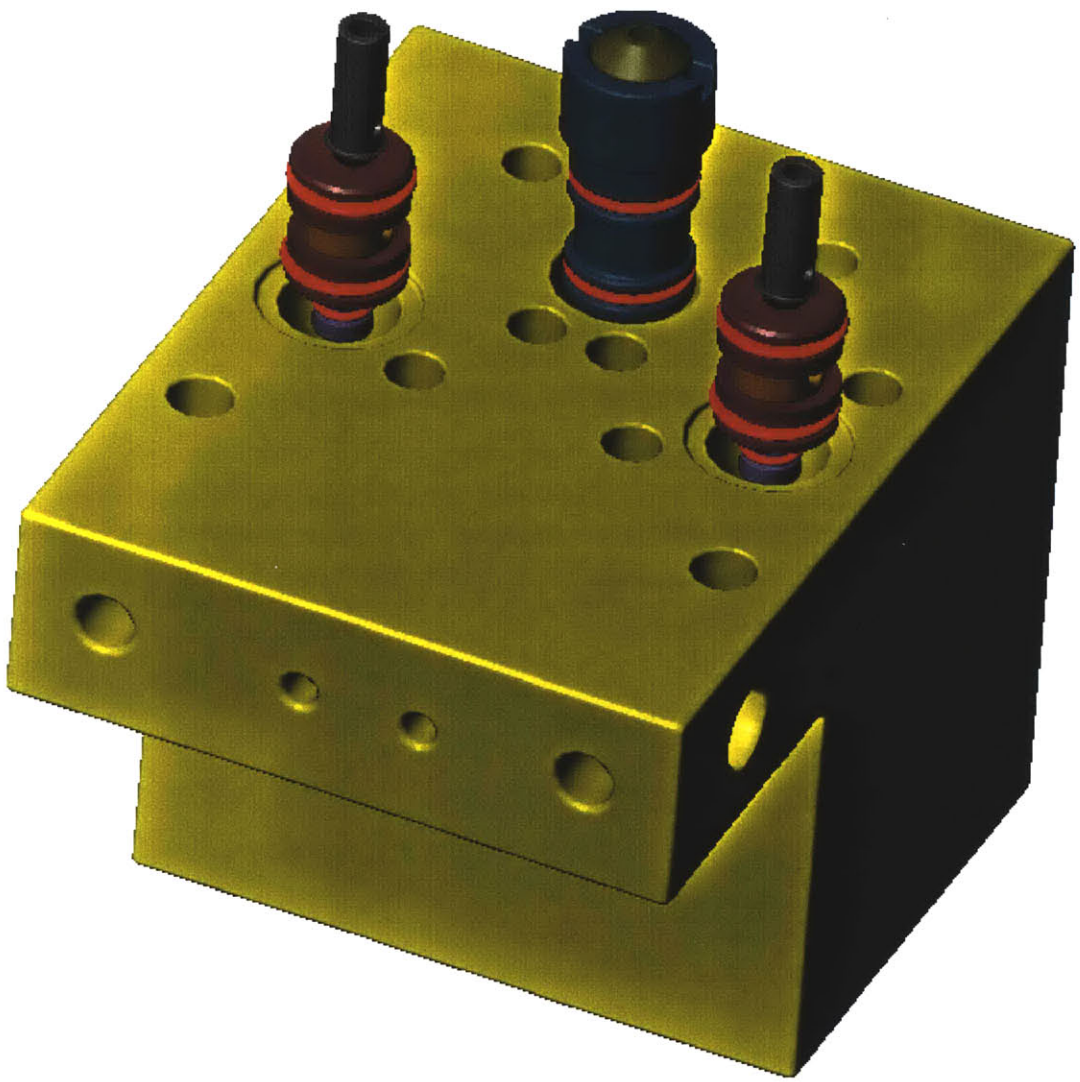
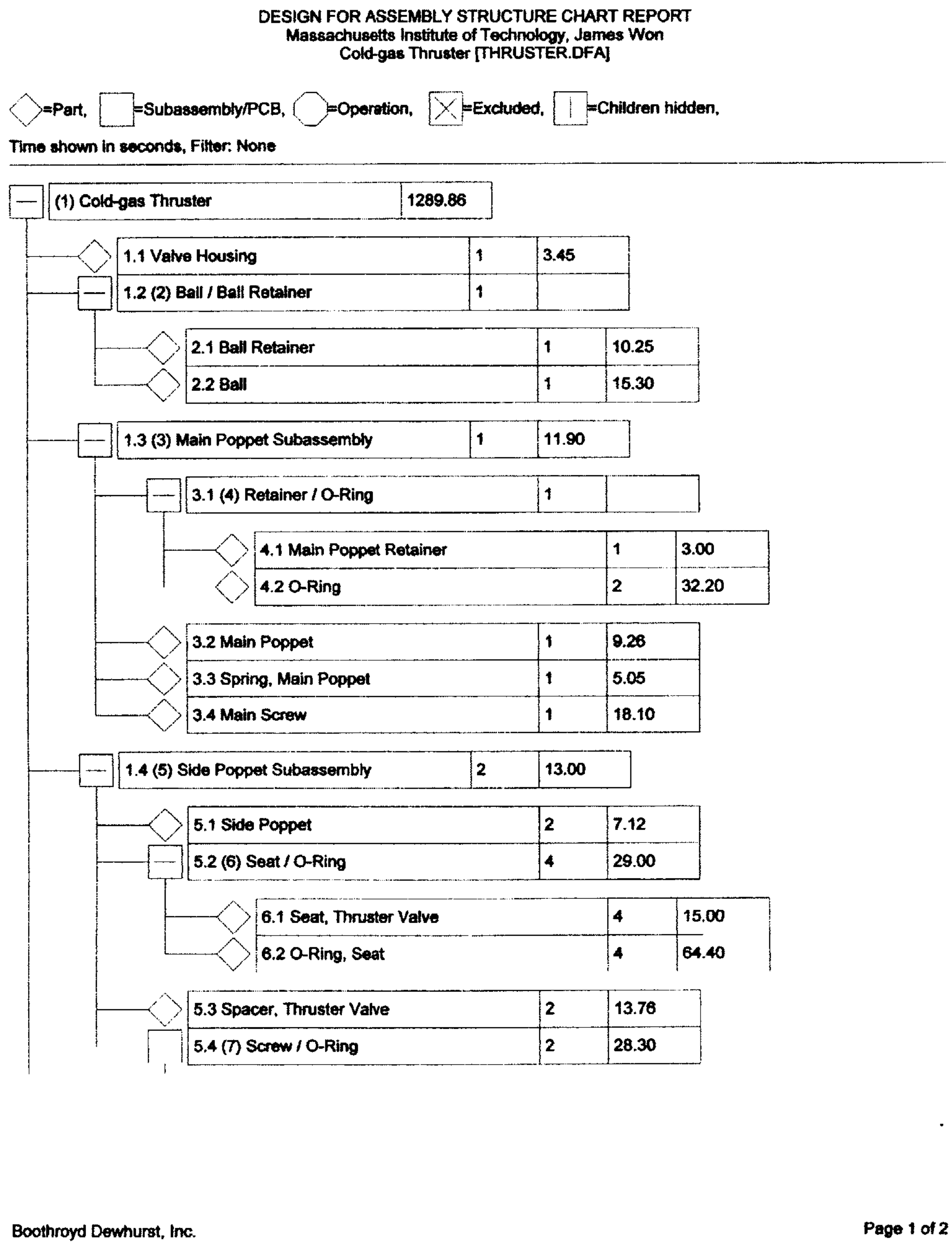


Figure 7-5: Sub-assemblies and Valve Housing

7.3 Boothroyd-Dewhurst DFA Analysis

Figure 7-6 is the Boothroyd-Dewhurst DFA structure chart report for the assembly times of the cold-gas thruster. All time are shown in seconds. Only the structure chart is shown in this chapter, and for all other charts, tables, and graphs pertaining to this analysis, please refer to the appendices.



DESIGN FOR ASSEMBLY STRUCTURE CHART REPORT
Massachusetts Institute of Technology, James Won
Cold-gas Thruster [THRUSTER.DFA]

7.1 Screw, Thruster Valve	2	7.50
7.2 O-Ring, Screw, Thruster Valve	2	32.20
1.5 Retainer Seat, Thruster Valve	2	13.60
1.6 Spring, Thruster Valve	2	7.90
1.7 (8) Thruster Manifold / O-Ring	1	4.55
8.1 Thruster Manifold	1	3.45
8.2 O-Ring, Thruster Manifold	1	10.60
1.8 Washers, Thruster Manifold	2	6.38
1.9 Screws, Thruster Manifold	2	21.70
1.10 (9) Set Screw / O-Ring	1	12.20
9.1 Set Screw	1	3.30
9.2 O-Ring, Set Screw	1	16.10
1.11 (10) Nozzle / O-Ring	1	3.45
10.1 Nozzle	1	5.70
10.2 O-Ring, Nozzle	2	22.00
1.12 Washers, Nozzle	2	7.36
1.13 Screws, Nozzle	2	25.10
1.14 Solenoid	1	7.30
1.15 Screws, Solenoid	4	47.30

Boothroyd Dewhurst, Inc. Page 2 of 2

Figure 7-6: Boothroyd-Dewhurst Structure Chart

[1] Boothroyd G., Dewhurst, P., Product Design for Assembly, Boothroyd Dewhurst Inc., Section 2, Kingston, Rhode Island, 1985.

[2] Boothroyd, G., Dewhurst, P., and Knight, W., Product Design for Manufacture and Assembly, Marcel Dekker, New York, 1994.

[3] Otto, K. N. and Wood, K. L., Product Design, Prentice Hall, New Jersey, 2001.

8
Redesign

8.1 Design for Assembly Improvements

As highlighted in the evaluation of the previous chapter, the design of the cold-gas thruster contains many areas in which improvements can be made from the perspective of an assembly-oriented design.

One must take care, however, never to compromise the safety factor or reliability and quality of the design in making these design modifications. This is where blindly following DFA guidelines and changing the design can be potentially disastrous. DFA is always intended to complement the designer's mind and creativity, not replace it.

For example, there are many o-rings in the design of the cold-gas thruster, which do not show up as an "essential" part in the DFA analysis. In certain design cases, such as the example of a sump drain pump in Redford and Chal [1] shown in Figure 8-1, designing out o-rings is a fairly simple procedure. In this example, simply a different material is used to integrate the function of the o-ring into the redesigned piston.

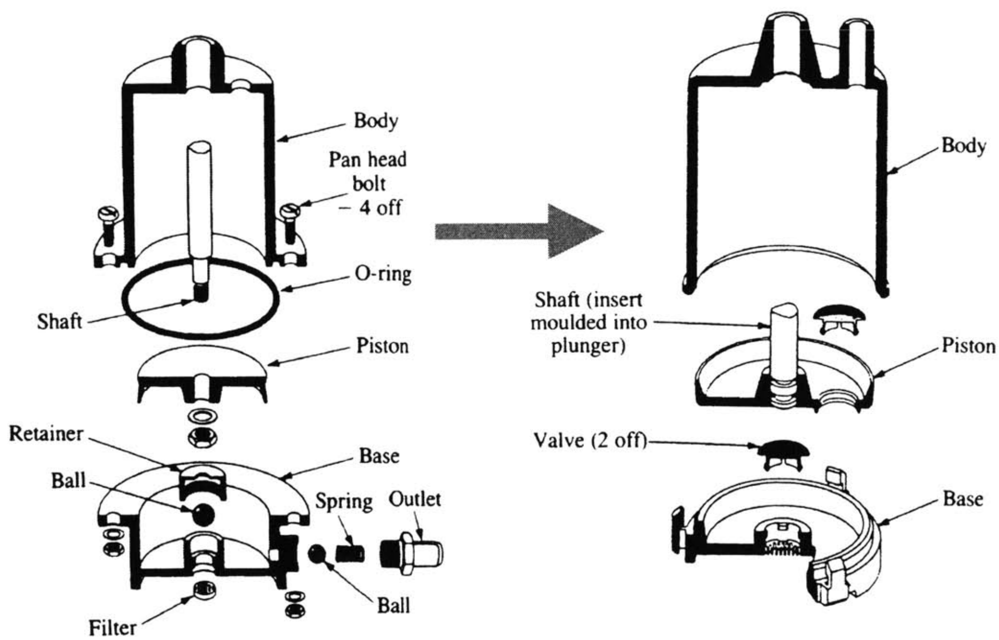


Figure 8-1: O-Ring Redesign Example [2]

However, designing out o-rings in critical applications such as the cold gas thrusters is very difficult to do, if not impossible. There are extremely stringent leak requirements that need to be met, as well as numerous other specifications and requirements that would not be applicable to the redesign of a generic drain pump.

Therefore, the following redesign suggestions are provided, being mindful of this knowledge. Each section is introduced by the redesign suggestions given by the Boothroyd-Dewhurst DFA software, based on the data of the current design, provided through the Assembly Diagram and evaluated by the Xerox Producability Index.

8.1.1 System Guidelines

8.1.1.1 Boothroyd-Dewhurst DFA Analysis Suggestions for Redesign Report

Table 8-1: Incorporate integral fastening elements into functional parts, or change the securing methods, in order to eliminate as many as possible of the following separate fastening elements

Sub No. Entry No.	Repeat Count	Name	Time Savings, sec	Relative Effect of Change
1.8	2	Screws, Thruster Manifold	21.70	4.18
1.9	1	Set Screw / O-Ring	12.20	2.35
1.12	2	Screws, Nozzle	25.10	4.84
1.14	4	Screws, Solenoid	47.30	9.12
3.4	1	Main Screw	18.10	1.41
5.4	4	Screw / O-Ring	56.60	4.41
9.1	1	Set Screw	3.30	0.26
Totals			184.30	26.57

Table 8-2: Combine connected items or attempt to rearrange the structure of the product in order to eliminate the following items whose function is solely to make connections

Sub No. Entry No.	Repeat Count	Name	Time Savings, sec	Relative Effect of Change
1.4	2	Retainer Seat, Thruster Valve	13.60	1.31
1.5	2	Spring, Thruster Valve	7.90	0.76
2.1	1	Ball Retainer	10.25	0.80
Totals			31.75	2.87

Table 8-3: Reduce the number of items in the assembly by combining with others or eliminating the following parts or subs

NOTE: Combining an item with another may eliminate further items such as fasteners or operations resulting in much larger time reductions than those indicated.

Sub No. Entry No.	Repeat Count	Name	Time Savings, sec	Relative Effect of Change
1.7	2	Washers, Thruster Manifold	6.38	1.23
1.11	2	Washers, Nozzle	7.36	1.42
3.2	1	Main Poppet	9.26	0.72
3.3	1	Spring, Main Poppet	5.05	0.39
4.1	1	Main Poppet Retainer	3.00	0.23
4.2	2	O-Ring	32.20	2.51
5.1	4	Side Poppet	14.24	1.11
5.2	8	Seat / O-Ring	58.00	4.52
Totals			135.49	12.13

According to the Boothrooyd-Dewhurst definition of Minimum Number of Parts, the cold gas thruster contains three essential parts. But as discussed above, this information is but a guide and does not mean the final redesign should consist of just three parts. It essentially points to possible reduction of other parts by combination or elimination.

8.1.1.2 Side Poppet Sub-Assembly

Following the suggestions of the XPI and Boothroyd-Dewhurst analyses, one area of redesign is the side poppet sub-assembly. Currently, there are eight parts of the subassembly. The redesign proposal is to combine all the parts apart from the o-rings into one part, such that there would be a total of four parts. There are two different materials in the side poppet sub-assembly, the Aluminum poppet and screw, and the seat and spacer made out of Vespel. The proposal is to mold it all out of Vespel or a similar material, as shown in Figure 8-2. In the previous design, the seat and spacer required a certain amount of lateral motion, which will now be covered by lengthening the part.

By reducing the number of parts in half, added benefits include the elimination of the Screw, Thruster Valve. This eliminates a time consuming part, in fastening and even in handling such a small part.

The main benefit is the integration of a significant sub-assembly to increase the reliability during the assembly process. It also reduces the time required for failure analysis, as there are half as many parts to examine in case of failure.

Figure 8-2: Side Poppet Sub-Assembly Redesign

8.1.1.3 Valve Housing

Another area of redesign is the valve housing. Since this is the base component, there are many parts that attach to it that could possibly be integrated into it. Two such parts are the set screw and the nozzle.

The functionality of the set screw is to adjust the main poppet retainer once it has been fit into the hole of the valve housing. However, the redesign of the valve housing using a different material can eliminate this need for adjustment. This material will be discussed later in this chapter. The most significant benefit of this is the elimination of one possible area of leakage. By designing out the set screw and the set screw o-ring, the reliability of the entire design is increased.

Incorporating the nozzle into the valve housing reduces two washers, two screws, and two o-rings. One cost issue that may require further exploration is the fact that there are different types of nozzles depending on the direction, pitch, yaw, and roll. Therefore, this whole part would need to be produced according to the direction of the nozzle, whereas in the original design, only the nozzle part itself needed to be considered. However, this integration of the two parts, along with the set screw integration, has the most benefit in increasing reliability through the elimination of o-rings. The reduction of the o-rings is critical as it eliminates an area of potential leakage by integrating both parts into one.

The proposed redesign integration of the valve housing is shown in Figure 8-3.

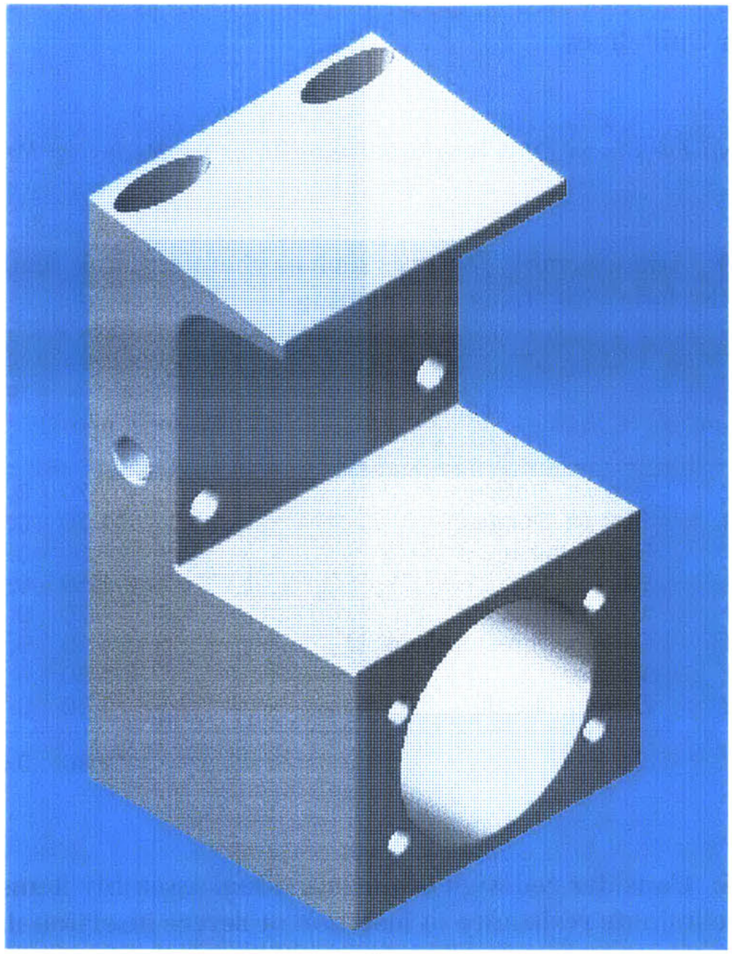


Figure 8-3: Integration of Valve Housing and Nozzle Redesign

Another feature that can be integrated onto the valve housing is the ball retainer. This can simply be done by designing in grooves at the bottom of the hole where the original ball retainer would have been joined to the valve housing.

8.1.2 Handling Guidelines

There are not significant design improvements that are applicable to handling issues.

8.1.3 Insertion Guidelines

8.1.3.1 Boothroyd-Dewhurst DFA Analysis Suggestions for Redesign Report

Table 8-4: Add assembly features such as chamfers, lips, leads, etc., to make the following items self-aligning

Sub No. Entry No.	Repeat Count	Name	Time Savings, sec	Relative Effect of Change
1.12	2	Screws, Nozzle	1.70	0.13
1.14	4	Screws, Solenoid	1.70	0.13
2.1	1	Ball Retainer	1.50	0.12
2.2	1	Ball	1.50	0.12
3.4	1	Main Screw	1.70	0.13
8.2	1	O-Ring, Thruster Manifold	1.50	0.12
10.1	1	Nozzle	1.50	0.12
10.2	2	O-Ring, Nozzle	1.50	0.12
Totals			12.60	0.98

Table 8-5: Consider redesign of the individual assembly items listed below to eliminate resistance to insertion or severe insertion difficulties

Sub No. Entry No.	Repeat Count	Name	Time Savings, sec	Relative Effect of Change
1.2	1	Main Poppet Sub-assembly	5.05	0.39
1.3	2	Side Poppet Sub-assembly	14.24	1.11
4.2	2	O-Ring	6.00	0.47
5.2	8	Seat / O-Ring	58.00	4.52
7.2	8	O-Ring, Screw	24.00	1.87
9.2	1	O-Ring, Set Screw	6.00	0.47
Totals			113.29	8.83

As highlighted by both the XPI and Boothroyd-Dewhurst analyses, the two poppet subassemblies and the mating holes of the valve housing are areas in which the insertion could be redesigned to eliminate severe insertion difficulties.

8.1.3.2 Mating Features

One simple modification that can be made is designing in larger curved chamfers at the mating holes themselves. Currently there is a very minimal chamfer.

Increasing the chamfer radius as well as creating more of a slope at the initial entrance of the hole would ease the insertion while maintaining the tolerance required.

The chamfer and slope redesign of the valve housing mating holes is shown in Figure 8-4.

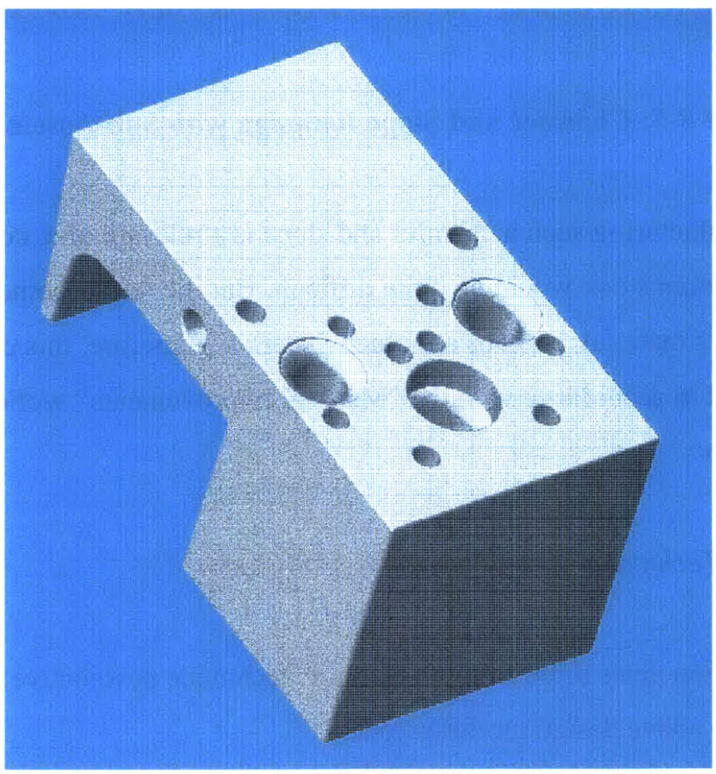


Figure 8-4: Chamfer and Slope Redesign

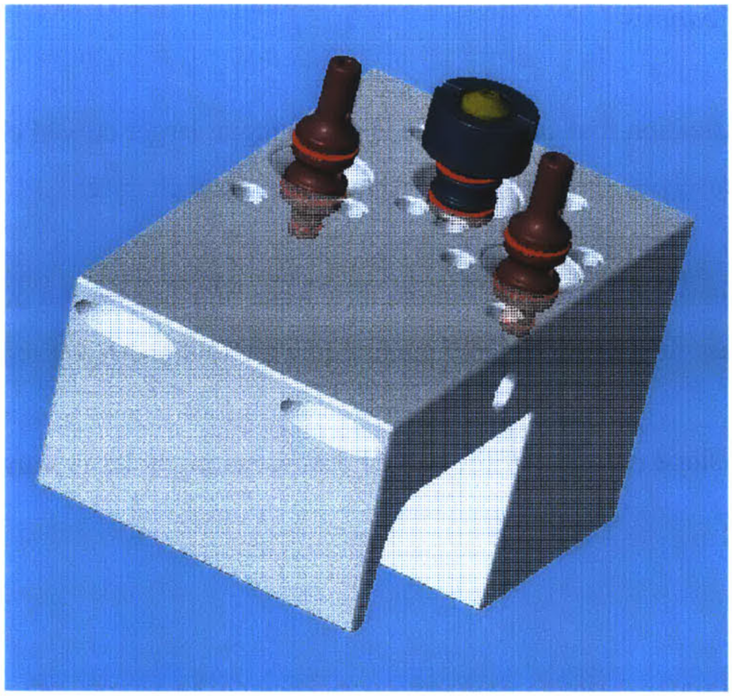


Figure 8-5: Chamfer and Slope Redesign with Sub-Assemblies

The issue of manufacturing such a chamfer and slope is a relevant one, considering that doing so on aluminum stock would be quite difficult. But it could become more efficient by using a different material, perhaps a molded material. Therefore, this chamfer redesign is to be considered in accordance with the "Material Improvements" section discussed later in this chapter.

8.1.3.3 Insertion Technique

Another modification deals more from an insertion technique perspective, which can be combined with the above design modification.

This technique is borrowed from standard piston assembly. A "stuffer" is used, as shown in Figure 8-6, which has a diameter slightly smaller than the insertion hole diameter. The "stuffer" is placed against the mating hole and the smooth, tapered inner surface of the stuffer allows the o-ring to be compressed as the sub-assembly containing the o-ring is push fit into the hole.

This process is to eliminate the location where o-ring shearing is most likely to occur, at the entrance of the insertion hole. The "stuffer" essentially allows a smooth entrance into the hole, taking advantage of the elasticity of the o-ring to compress it. By the time the o-ring expands, it is already within the insertion hole, thus bypassing the location where it most likely would have been sheared.

Figure 8-6: Stuffer Insertion Technique

8.1.3.4 Main Poppet Sub-Assembly

As discussed in the previous chapter, one design issue concerning the main poppet subassembly insertion into the valve housing is the nature of its assembly. The fact that there is a threaded turning process combined with a push fit means that great care needs to be taken to avoid the threads of the hole interfering with the push fit portion. This is another location where o-ring shearing could very easily take place.

One design modification is to create a large discrepancy between the diameter of the threaded portion and the diameter of the push fit portion, shown in Figure 8-7. This should be done such that the threaded portion diameter is significantly greater than the push fit portion diameter. This would ensure that the threads of the hole would be clear of the o-rings being push fit into the hole.

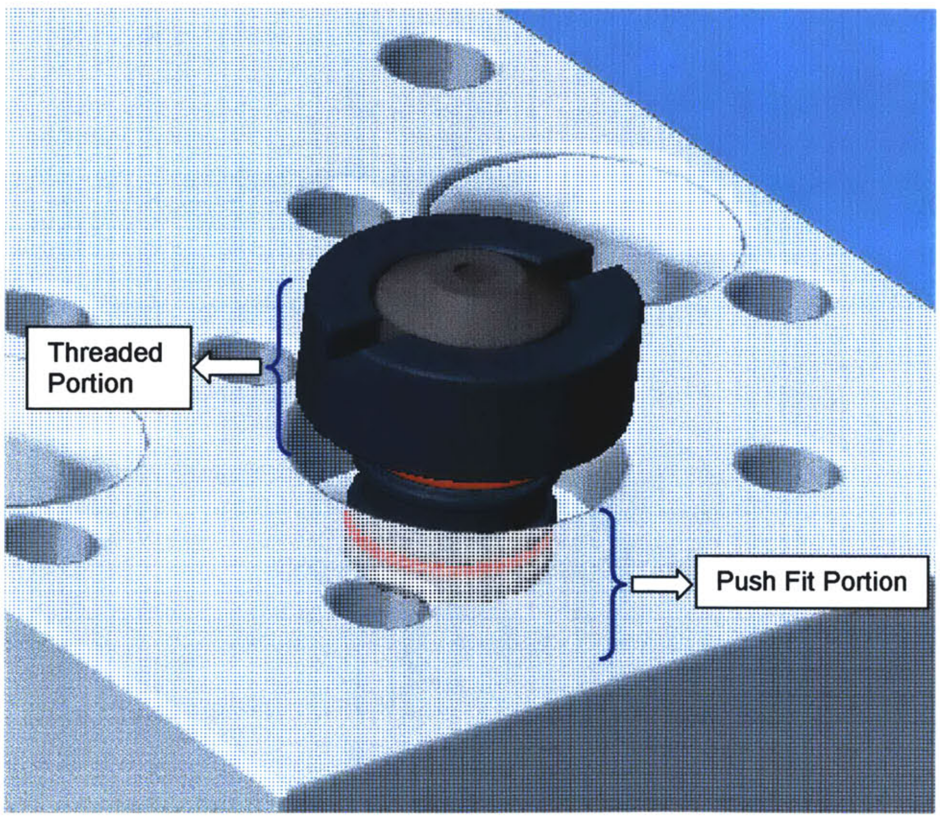


Figure 8-7: Main Poppet Sub-Assembly Redesign

8.1.4 Joining Guidelines

8.1.4.1 Boothroyd-Dewhurst DFA Analysis Suggestions for Redesign Report

Table 8-6: Redesign the assembly where possible to allow adequate access and unrestricted vision for placement or insertion of the following items

Sub No. Entry No.	Repeat Count	Name	Time Savings, sec	Relative Effect of Change
2.1	1	Ball Retainer	2.20	0.17
2.2	1	Ball	2.20	0.17
3.2	1	Main Poppet	2.20	0.17
5.4	4	Screw / O-Ring	8.00	0.62
Totals			14.60	1.13

Table 8-7: Design locating features into mating parts of the assembly to eliminate the need for holding down the following items during the assembly process

Sub No. Entry No.	Repeat Count	Name	Time Savings, sec	Relative Effect of Change
1.6	1	Thruster Manifold / O-Ring	1.10	0.21
3.3	1	Spring, Main Poppet	1.10	0.21
Totals			2.20	0.42

8.1.4.2 Blind Assembly

Designing out blind assemblies is a very tricky process because in many cases it involves modifying all other parts that interact with this assembly. It becomes an issue when these parts do not need to be modified, but rather, in this attempt to alleviate the blind assembly the designer actually complicates the overall design.

Being mindful of this, the following blind assembly redesign is given. Among the many possibilities of redesign for this blind assembly, one that requires the least modification of affiliated parts was chosen.

The side poppet sub-assembly joining with the valve housing is recommended to remain as is, with the above recommendations. Because of the requirements this sub-assembly has to meet, the push fit process needs to remain, and there is minimal redesign from a joining perspective that can be done otherwise.

As discussed in the previous chapter, blind assembly occurs at the joining of the main poppet and the main poppet retainer. One modification is to redesign the main poppet retainer to make it more shallow, combined with the above redesign of increasing the diameter of the threaded portion of the retainer, as shown in Figure 8-8. This reduces the depth of the assembly of the main poppet retainer, thus eliminating the blind assembly. This allows adequate access and unrestricted vision for the joining of the main poppet.

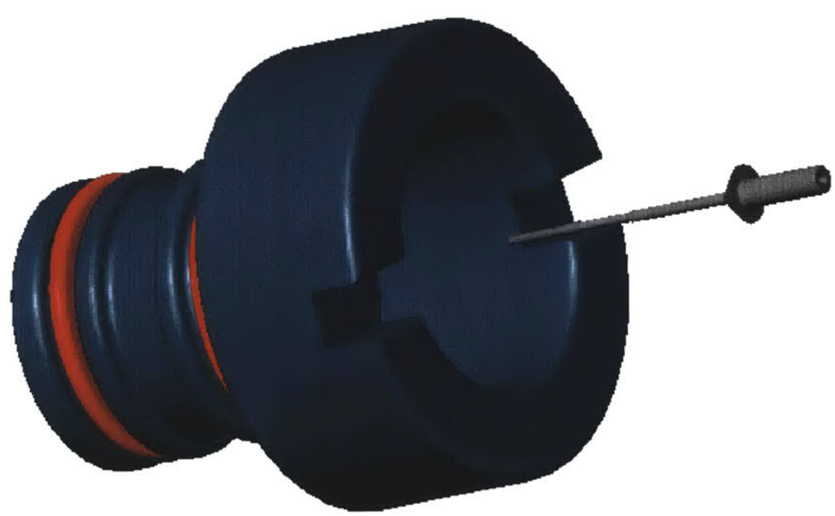


Figure 8-8: Main Poppet and Main Poppet Retainer Redesign

8.2 Material Improvements

Careful inspection of the insertion holes of the valve housing revealed a very rough inner surface finish. This inner surface is the surface that directly interacts with the o-rings of the side poppet sub-assemblies and the main poppet sub-assembly.

Turning marks and ridges were discovered in these holes, possibly from wear and assembly and disassembly procedures. These marks and ridges could easily wear out sensitive parts such as the o-rings, and even contribute to their shearing.

Currently, the valve housing is made of aluminum. Considering that aluminum is a material that is very difficult to achieve a good surface finish, another material should be considered to better suit this current application.

One possible material is an engineering plastic called Delrin. Delrin is an engineering thermoplastic with a combination of physical properties not available either in metals or other plastics. It has a balanced profile of mechanical properties, environmental resistance and processability at a moderate cost. It provides substantial strength, stiffness and creep resistance.

The following data and Figure 8-9 are specifications as provided from the Dupont website. [3]

Trade name: Delrin
Generic name: acetal
Sub class: homopolymer
Abbreviations: POM (polyoxymechylene)
Structure: highly crystalline polymerized formaldehyde

Attributes of Delrin-acetal resins:

Toughness at low temperatures (down to –40oC)
High mechanical strength and rigidity
Fatigue endurance unmatched by other plastics

Excellent resistance to moisture, petrol, solvents, etc.
Excellent dimensional stability
Natural lubricity
Resilience
Good electrical insulating characteristics
Ease of fabrication
Wide useful temperature range (in air –50 to +90°C with intermittent use up to 160°C)

Property	Units	Value
Yield stress	MPa	71
Yield strain	%	25
Strain at break	%	70
Flexural modulus	MPa	2800
Izod notched impact strength @ 23°C @-40°C	kJ/m²	12 8
Temperature of deflection under load	°C	115
Melt temperature	°C	177
Flammability		HB
Shrinkage	%	1,9 to 2,2
Melt Flow Index	g/10 min	2,2
Chemical Resistance		outstanding
Density	g/cm³	1,42

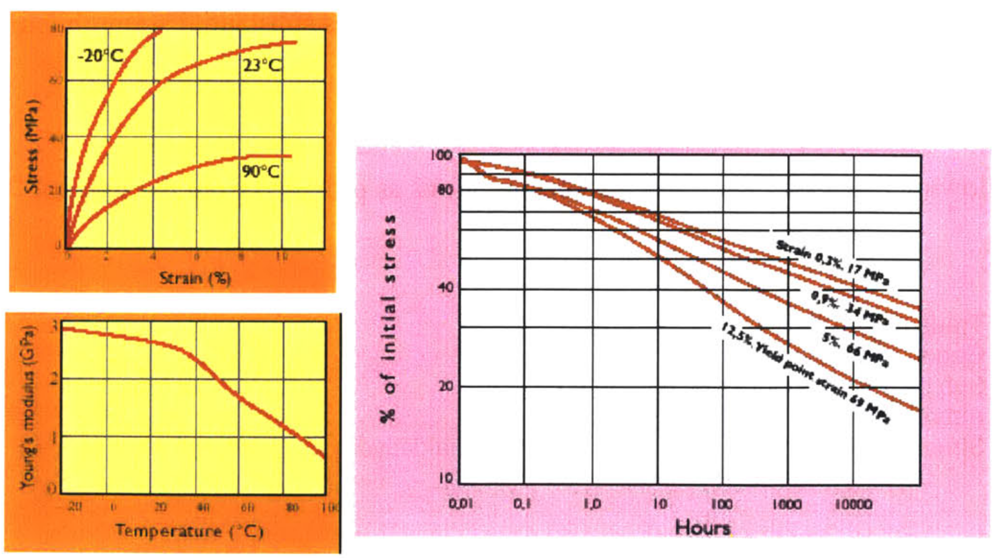


Figure 8-9: Delrin Specifications [4]

Thermal Characteristics:

Property: °C

Melt temperature	177
Vicat Softening	
10N	174
50N	160
Relative Thermal Index (w/o impact)	90
Specific Heat	0.35
Thermal Conductivity	0.30
(W/m * K)	0.37

Possible substitutes for aluminum:

Delrin 100KM	Kevlar Modified
Delrin 500CL	Low Wear/Low Friction Chemical Lubricant
Delrin 500AL	Low Wear/Low Friction Advanced Lubricant

The proposal is to use one of the above three Delrin resins to substitute for aluminum in manufacturing the valve housing. The above specifications show that Delrin would be a suitable substitute. Most importantly, the use of Delrin would allow an extremely smooth surface finish on the inner surface of the insertion hole. This would greatly reduce the type of wear that creates turning marks and ridges. It alleviates that type of unnecessary friction between the o-rings and the inner surface, while maintaining the tight fit needed to meet leak requirements.

Delrin is also easily machined, and so the creation of holes and chamfers would not be difficult.

Another added benefit of Delrin is that it addresses one of the user needs. One staff at Lincoln Laboratory mentioned that it would be beneficial to be able to see inside the valve housing during testing to visibly check the passage of gas. Delrin comes in many colors, and one is a translucent type. It would not be a crystal clear view, but could be useful during the early stages of testing.

8.3 Final Redesign Proposal

Using the previous analyses and each of the above design suggestions, the following redesign is proposed.

8.3.1 Redesign Exploded Diagram

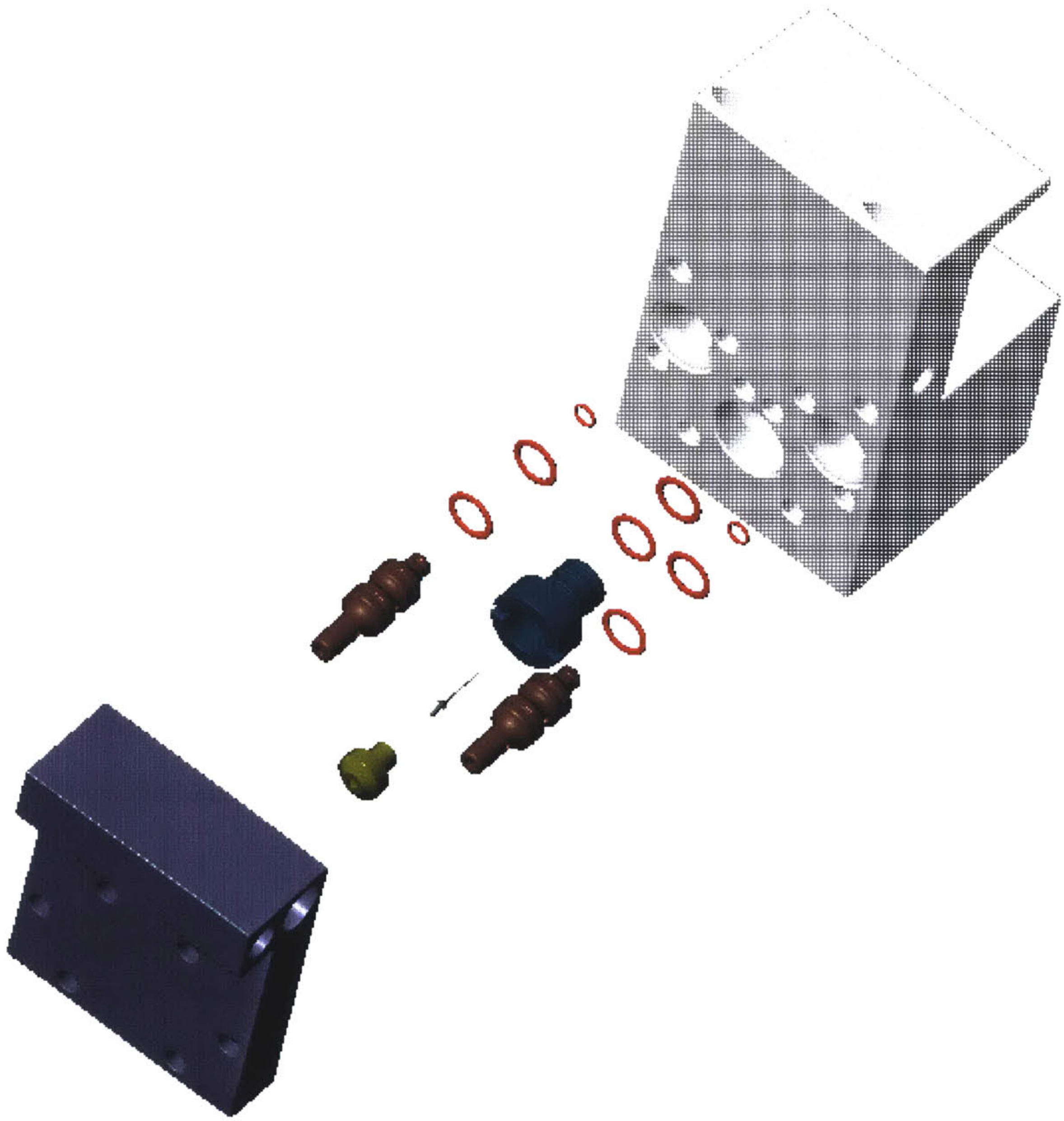


Figure 8-10: Final Redesign Exploded View

8.3.2 Redesign Parts List

Table 8-8: Redesign Parts List

Part #	Description	Qty
1	Valve Housing / Nozzle	1
Main Poppet Subassembly		
2	Main Poppet Retainer	1
3	O-ring, Main Poppet Retainer	2
4	Main Poppet	1
5	Spring, Main Poppet Retainer	1
6	Main Screw	1
7	Ball	1
Side Poppet Subassembly		
8	Side Poppet	2
10	O-ring, Seat	4
11	O-ring, End	2
Thruster Manifold Subassembly		
12	Thruster Manifold	1
13	O-ring, Thruster Manifold	1
14	Screws, Thruster Manifold	2
15	Washers, Thruster Manifold	2
Solenoid Subassembly		
16	Solenoid	1
17	Screws, Solenoid	4

8.3.3 Redesign Assembly Sequence Diagram

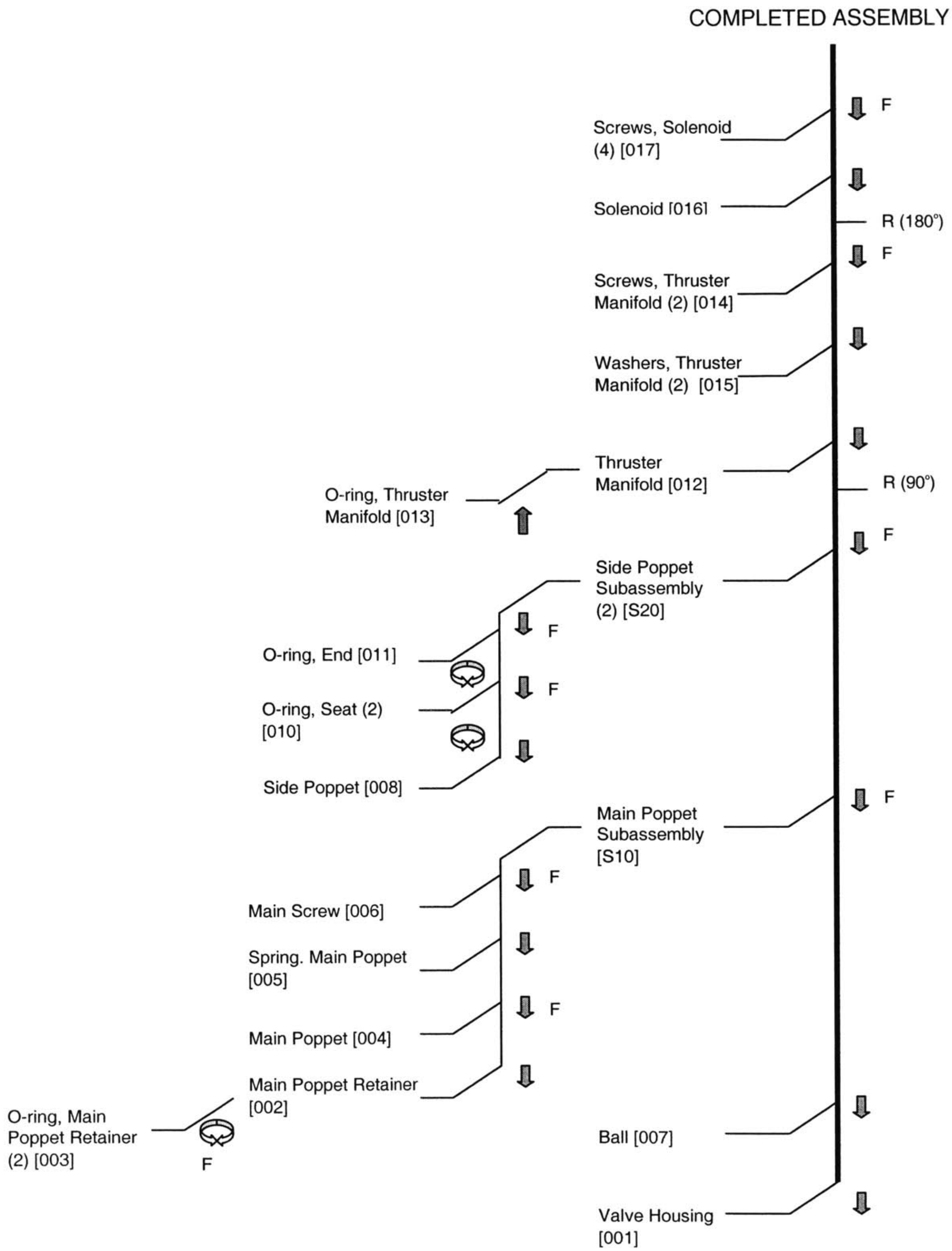


Figure 8-11: Redesign Assembly Sequence Diagram

8.3.4 Redesign Evaluation

Table 8-9 is the Xerox Producability Analysis of the cold-gas thruster redesign.

Table 8-9: Redesign XPI Assembly Analysis

Subassembly / Part	Operation	Approach	Held?	Tightening	Repetitions	XPI Score	XPI Totals
Valve Housing	01	Top	No	No	1	100	100
Ball	02	Top	No	No	1	100	
Main Poppet Retainer	03a	Top	No	No	1	100	73
O-ring, Main Poppet Retainer	03b	Rot	Yes	Snap	2	65	
Main Poppet	04	Top	Yes	Snap	1	90	90
Spring, Main Poppet Retainer	05	Top	No	No	1	100	100
Main Screw	06	Top	Yes	Screw	1	40	40
Main Poppet Sub-Assembly	07	Top	Yes	Snap	1	90	90
Side Poppet	08	Top	No	No	1	100	100
O-ring, Seat, Thruster Valve	09	Rot	Yes	Snap	2	65	
O-ring, End	10	Rot	Yes	Snap	1	65	
Side Poppet Sub-Assembly	11	Top	Yes	Snap	2	90	70
Thruster Manifold	12a	Top	Yes	Screw	1	40	28
O-ring, Thruster Manifold	12b	Bottom	Yes	No	1	55	
Screws, Thruster Manifold					2		
Washers, Thruster Manifold					2		
Solenoid	13	Top	Yes	Screw	1	40	20
Screws, Solenoid					4		
						XPI TOTAL	79

8.4 Final Redesign DFA Analysis

Figure 8-12 is the Boothroyd-Dewhurst DFA structure chart report for the assembly times of the redesigned cold-gas thruster. Like the previous chapter, all time are shown in seconds. And again, only the structure chart is shown in this chapter. For all other charts, tables, and graphs pertaining to the redesign, please refer to the appendices.

DESIGN FOR ASSEMBLY STRUCTURE CHART REPORT
Massachusetts Institute of Technology, James Won
Redesign Cold Gas Thruster [REDESIGN.DFA]

◇=Part, □=Subassembly/PCB, ○=Operation, ☒=Excluded, [|]=Children hidden,

Time shown in seconds, Filter: None

(1) Redesign Cold Gas Thruster		344.64
1.1 Valve Housing	1	3.45
1.2 Ball	1	15.30
1.3 (2) Main Poppet Subassembly	1	11.90
2.1 (3) Retainer / O-ring	1	
3.1 Main Poppet Retainer	1	3.00
3.2 O-Ring	2	32.20
2.2 Main Poppet	1	9.26
2.3 Spring, Main Poppet	1	5.05
2.4 Main Screw	1	18.10
1.4 (4) Side Poppet Subassembly	2	13.00
4.1 Side Poppet	2	6.00
4.2 O-Ring, Seat	4	40.40
4.3 O-Ring, End	2	20.20
1.5 (5) Thruster Manifold / O-Ring	1	3.45
5.1 Thruster Manifold	1	3.45
5.2 O-Ring, Thruster Manifold	1	10.60
1.6 Washers, Thruster Manifold	2	6.38
1.7 Screws, Thruster Manifold	2	21.70
1.8 Solenoid	1	7.30

1.9 Screws, Solenoid	4	47.30

Figure 8-12: Redesign Boothroyd-Dewhurst Structure Chart

8.5 Original Design vs. Redesign Comparison

As shown in Figure 8-12 and further demonstrated below, the proposed redesign is a significant improvement from the original design. The Assembly Sequence Diagram is considerably streamlined. The number of parts was reduced from 48 to 25. The assembly time decreased from 1289.86 seconds to 316.29 seconds. The XPI rating increased from 69 to 79. And the Boothroyd-Dewhurst DFA Index increased from 2.05 to 6.89.

8.5.1 Parts List Comparison

Table 8-10: Parts List Comparison

Parts List

Part #	Description	Qty
1	Valve Housing	1
Main Poppet Subassembly		
2	Main Poppet Retainer	1
3	O-ring, Main Poppet Retainer	2
4	Main Poppet	1
5	Spring, Main Poppet Retainer	1
6	Main Screw	1
7	Ball Retainer	1
8	Ball	1
Side Poppet Subassembly		
9	Side Poppet	2
10	Seat, Thruster Valve	4
11	O-ring, Seat	4
12	Spacer, Thruster Valve	2
13	Screw, Thruster Valve	2
14	O-ring, Thruster Valve	2
15	Retainer Seat, Thruster Valve	2
16	O-ring, Retainer Seat	2
17	Spring, Thruster Valve	2
Set Screw Subassembly		
18	Set Screw	1
19	O-ring, Set Screw	1
Thruster Manifold Subassembly		
20	Thruster Manifold	1
21	O-ring, Thruster Manifold	1
22	Screws, Thruster Manifold	2
23	Washers, Thruster Manifold	2
Nozzle Subassembly		
24	Nozzle	1
25	O-ring, Nozzle	2
26	Screws, Nozzle	2
27	Washers, Nozzle	2
Solenoid Subassembly		
28	Solenoid	1
29	Screws, Solenoid	4

Redesign Parts List

Part #	Description	Qty
1	Valve Housing / Nozzle	1
Main Poppet Subassembly		
2	Main Poppet Retainer	1
3	O-ring, Main Poppet Retainer	2
4	Main Poppet	1
5	Spring, Main Poppet Retainer	1
6	Main Screw	1
7	Ball	1
Side Poppet Subassembly		
8	Side Poppet	2
9	O-ring, Seat	4
10	O-ring, End	2
Thruster Manifold Subassembly		
11	Thruster Manifold	1
12	O-ring, Thruster Manifold	1
13	Screws, Thruster Manifold	2
14	Washers, Thruster Manifold	2
Solenoid Subassembly		
15	Solenoid	1
16	Screws, Solenoid	4

8.5.2 XPI Comparison

Table 8-11: XPI Comparison

Original Design XPI

Subassembly / Part	Operation	Approach	Held?	Tightening	Repetitions	XPI Score	XPI Totals
Valve Housing	01	Top	No	No	1	100	100
Ball Retainer	02a	Top	No	Adhesive	1	30	65
Ball	02b	Top	No	No	1	100	
Main Poppet Retainer	03a	Top	No	No	1	100	73
O-ring, Main Poppet Retainer	03b	Rot	Yes	Snap	2	65	
Main Poppet	04	Top	Yes	Snap	1	90	90
Spring, Main Poppet Retainer	05	Top	No	No	1	100	100
Main Screw	06	Top	Yes	Screw	1	40	40
Main Poppet Sub-Assembly	07	Top	Yes	Snap	1	90	90
Side Poppet	08	Top	No	No	1	100	100
Seat, Thruster Valve	09a	Top	Yes	No	2	90	58
O-ring, Seat, Thruster Valve	09b	Rot	Yes	Snap	2	65	
Spacer, Thruster Valve	10	Top	Yes	No	1	90	90
Screw, Thruster Valve	11a	Top	Yes	Screw	1	40	53
O-ring, Screw	11b	Rot	Yes	Snap	1	65	
Retainer Seat, Thruster Valve	12	Top	Yes	No	1	90	90
Spring, Thruster Valve	13	Top	No	No	1	100	100
Side Poppet Sub-Assembly	14	Top	Yes	Snap	2	90	70
Set Screw	15a	Top	Yes	Screw	1	40	65
O-ring, Set Screw	15b	Top	Yes	Snap	1	90	
Thruster Manifold	16a	Top	Yes	Screw	1	40	28
O-ring, Thruster Manifold	16b	Bottom	Yes	No	1	55	
Screws, Thruster Manifold					2		
Washers, Thruster Manifold					2		
Nozzle	17a	Top	Yes	Screw	1	40	18
O-ring, Nozzle	17b	Bottom	Yes	No	2	55	
Screws, Nozzle					2		
Washers, Nozzle					2		
Solenoid	18	Top	Yes	Screw	1	40	20
Screws, Solenoid					2		
						XPI TOTAL	69

Redesign XPI

Subassembly / Part	Operation	Approach	Held?	Tightening	Repetitions	XPI Score	XPI Totals
Valve Housing	01	Top	No	No	1	100	100
Ball	02	Top	No	No	1	100	
Main Poppet Retainer	03a	Top	No	No	1	100	73
O-ring, Main Poppet Retainer	03b	Rot	Yes	Snap	2	65	
Main Poppet	04	Top	Yes	Snap	1	90	90
Spring, Main Poppet Retainer	05	Top	No	No	1	100	100
Main Screw	06	Top	Yes	Screw	1	40	40
Main Poppet Sub-Assembly	07	Top	Yes	Snap	1	90	90
Side Poppet	08	Top	No	No	1	100	100
O-ring, Seat, Thruster Valve	09	Rot	Yes	Snap	2	65	
O-ring, End	10	Rot	Yes	Snap	1	65	
Side Poppet Sub-Assembly	11	Top	Yes	Snap	2	90	70
Thruster Manifold	12a	Top	Yes	Screw	1	40	28
O-ring, Thruster Manifold	12b	Bottom	Yes	No	1	55	
Screws, Thruster Manifold					2		
Washers, Thruster Manifold					2		
Solenoid	13	Top	Yes	Screw	1	40	20
Screws, Solenoid					4		
						XPI TOTAL	79

8.5.3 Exploded View Comparison

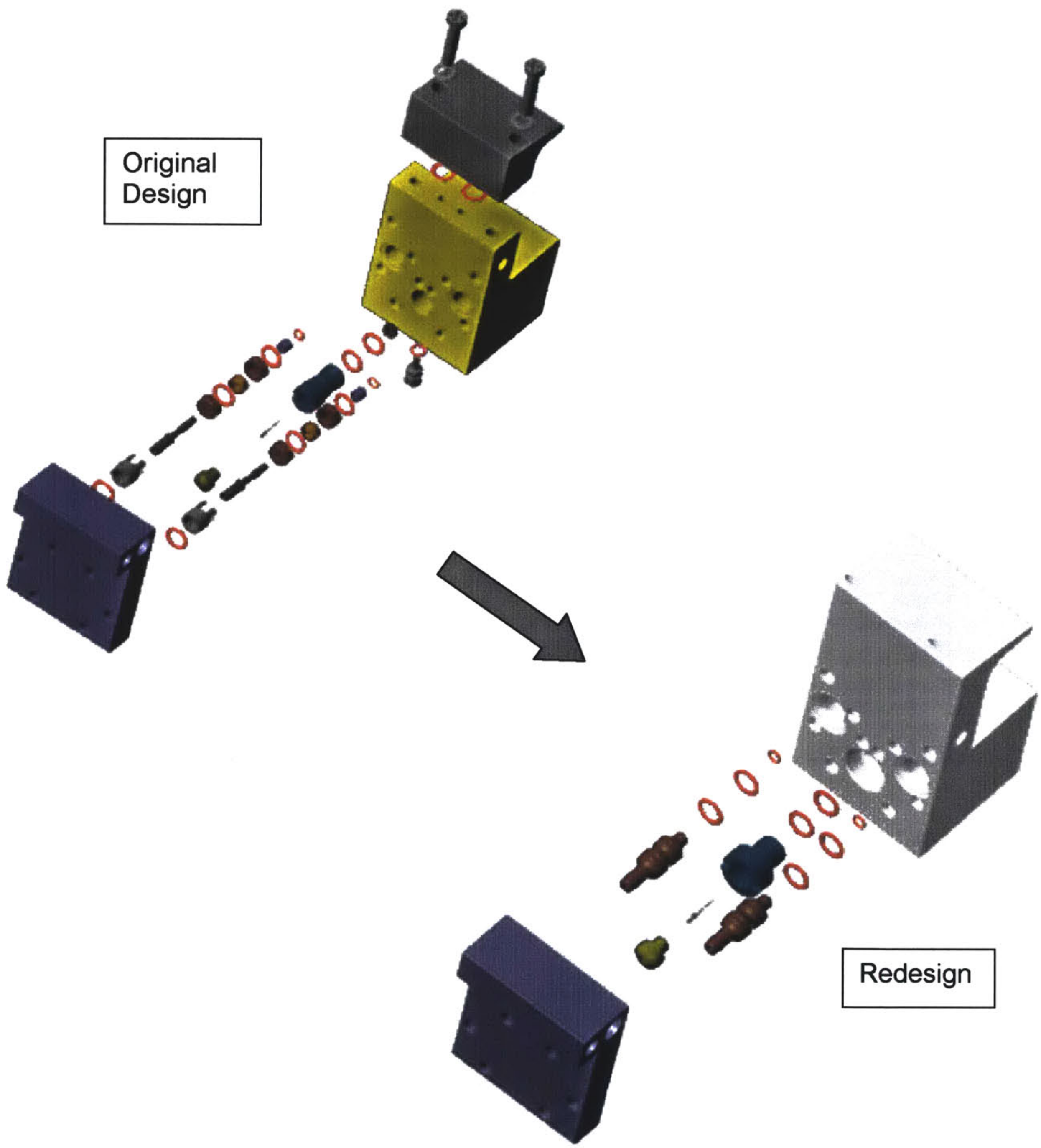


Figure 8-13: Original vs. Redesign Exploded View

[1] Redford, A. and Chal, J., Design for Assembly: Principles and Practice, McGraw Hill, London, 1994.

[2] *Ibid.*

[3] "Delrin Product Information," http://www.dupont.com, 2001.

[4] *Ibid.*

9
Conclusion

9.1 Summary of the Thesis

The goal of this thesis was to provide a review of the design of the cold-gas thrusters from an assembly standpoint, and focus on a redesign through Design for Assembly principles. The effectiveness of DFA and specific methodologies was evaluated. The evaluation was specifically targeted for a "non-conventional" aerospace/defense application in which cost is not as primary of an issue as reliability and quality.

General Design for Assembly framework and guidelines were reviewed, followed by a specific review of two methodologies. One evaluative tool, the Xerox Producability Analysis, and one thorough analysis methodology, the Boothroyd-Dewhurst DFA Analysis, were introduced and reviewed.

These tools were then implemented for a specific case study, the cold-gas thruster design. This case study demonstrated that DFA could be used to study and examine existing designs in the non-mass producing industries and accordingly develop new designs.

A DFA redesign of the cold gas thruster has been developed through the results of the two methodologies. Through this process, important issues of the original design were identified and examined. The approach to these issues was strictly from a DFA perspective. Resolutions and design modifications to these issues were recommended to create a better assembly-oriented design.

9.2 Redesign Considerations

Various issues arise as a result of redesign, as a design consists mostly of inter-related parts. Modifying or eliminating a part inevitably affects other parts.

9.2.1 Cost

One major effect or issue is cost. Integrating parts, incorporating functions as part of the DFA process is the most common issue. Various components of the cold-gas thruster, as discussed in the previous chapter, can be modularized. But the suggestions for redesign in the previous chapter were provided without an in-depth cost analysis. The improvements themselves would definitely reduce cost in terms of reduction in assembly time, as well as provide all the other benefits discussed earlier. But an aspect of cost not explicitly dealt with by the DFA analysis is the tooling and manufacturing cost, and would require further research and analysis.

9.2.2 Reducing Number of Fasteners

Reduction of fasteners is presently not a very applicable issue. This concept is actually fairly outdated. When DFA was initially conceived, most assembly was done by hand, and fastening with screws was one of the most time consuming processes. Hence, reducing the number of fasteners was one of the main goals of DFA. But with new technology, even with something like an automatic screwdriver, the issue loses much of its significance.

Also, in achieving tight tolerances and leak requirements, fasteners are presently one of the best methods. Eliminating fasteners for snap fitting would seem logical apart from such tolerances. This is primarily the reason why fasteners for the Thruster Manifold were not explicitly addressed for redesign, as they seem to be the best method for its mating onto the face of the Valve Housing as tightly as possible.

9.2.3 Blind Assembly

As mentioned in the previous chapter, alleviating or eliminating blind assemblies is a complicated process. There are many factors that one needs to consider. The designer must continue to maintain the overall picture of the design.

Blind assembly could theoretically be completely eliminated by the redesign, but in doing so, all other affiliated parts most likely will need to undergo radical changes. This could potentially result in unnecessarily complex parts, complex assembly operations, or increased tooling and production costs.

Thus, there is no one recommended method of redesigning blind assemblies. DFA can pinpoint the areas in which this may occur, but it would not be able to suggest a standard redesign, and much would be left to the designer's creativity and critical thinking.

9.3 Recommendations

The following recommendations are suggested for DFA application in critical, non-mass producing industries. Strictly following the Boothroyd-Dewhurst DFA methodology, many design modifications were considered for the cold-gas thruster. But blind application of its directions and recommendations could have resulted in a radically different design.

9.3.1 Aerospace Flight Application

Application of DFA to this application did reveal many issues. Current DFA does not consider the many specifications and requirements that are imperative to this type of aerospace flight application. These types of requirements are not as stringent, or sometimes not even existent among other industries, such as the automobile and other mass production industries, as discussed in the early chapters. This may explain why the current form of DFA reportedly has had great success in these industries. Ford even claimed that it saved one billion dollars in the early 90's by implementing DFA. [1]

But the fact is that DFA has had limited application and success in the aerospace industry, and other industries in which products are not mass produced; in many cases only one of the product is made. In these cases, for example, the DFA analysis of how many seconds it takes to grab a part or how likely a part will tangle or nest is not very applicable.

Thus, the recommendation is that DFA not be suggested as a universal application. The current model of DFA applies to the before mentioned industries, but clearly a modified DFA needs to be developed strictly for the aerospace-type industries and applications. It should still be developed upon the foundations of DFA, but modified to target reliability and quality much more than it currently does.

9.3.2 Product Defect Probability

One possibility is the introduction of Product Defect Probability as a design metric, using Equation 9.1. [2]

$$P_T = \prod_{i=1}^{a} \left[1 - c_k (t_i - t_{ideal})^k\right]\left(1 - D_{p_i}\right) \tag{9.1}$$

Where,

P_T	=	probability that the total assembly is defect free
c^k	=	a constant related to the quality control of assembly operations
t_i	=	time required to complete the ith assembly operation
t_{ideal}	=	ideal assembly time (3 seconds)
k	=	exponent relating defect sensitivity to the assembly time
a	=	number of assembly operations
D_{p_i}	=	probability that the ith part contains a defect

Most of the above data can be taken from the Boothroyd-Dewhurst DFA analysis. The defect rate per part, k, is from data published by Motorola, and is likely to range between one and three. The constant c^k, referred to as the nonconformance constant, is a measure of the ability of each manufacturer to control assembly processes to produce defect free assemblies. It is equal to the slope of the average defects per operation versus the average assembly time per operation. A value of zero for the constant would mean a perfect assembly.

Use of a measure of product quality such as the above probability equation would give greater weight to design reliability than DFA currently does. Its integration with the Boothroyd-Dewhurst Design Efficiency percentage could give an overall efficiency rating for the design encompassing all aspects, including reliability.

To achieve this, the following modifications are suggested to incorporate into the current DFA scheme or add to the inputs required for the analysis:

- Number to be produced
- Assembly Tree input
- Type of assembly format (individual, line, cell)
- Material
- Tolerances required

- More intimate connection with a 3-D CAD package. It would allow the user to modify a design a certain way as suggested by the DFA software, and the CAD package would output data to the user showing whether or not that redesign with that certain geometry would be feasible with the material specified, while meeting the tolerances.
- Since manufacturing and tooling issues are not explicitly addressed by DFA analysis, complementing DFA with Design for Manufacture principles and analysis would provide the most complete analysis of a design.
- Incorporate Product Defect Probability as a metric in parallel with the Assembly Efficiency percentage to evaluate the design.

9.4 Final Remarks

To reiterate, Design for Assembly is not a tool to be used without discretion. It is a framework for analysis that designers who have previous domain expertise can use to augment their designs. It is an analysis tool, a thought process, a methodology, a foundational way to do design. And when used properly to complement the mind of the designer, it can be quite powerful.

A global perspective must be maintained in evaluating the consequences of design decisions. "Global simplification" must be the highest priority, not localized optimization, as termed by Barkan and Hinkley.[3] To achieve this, the following factors should be considered: [4]

- The impact of design decisions on product robustness, including part complexity and producibility
- The impact on tooling, including development time and cost
- Impacts on the product line flexibility, that is, the ability to accommodate change and variety
- Product reliability

- Serviceability (ease and cost of repair and maintenance)
- Supply chain economics
- The risks associated with innovation as driven by DFA

This fact is even more critical particularly in the non-mass production industries such as the one that was addressed in this thesis. As mentioned at the beginning, for the cold-gas thruster and other products like it, the main DFA issue is not so much cost or efficiency as it is parts damage and part reliability. The thesis attempted to address its design from this assembly perspective.

DFA's main contribution in these applications is its increase in reliability and quality of a design, which was the major requirement for the cold-gas thrusters. Application of DFA to its design in preliminary stages and applying a design with characteristics such as the proposed redesign could have significantly reduced potential for test failures and leakage issues. As delineated in the previous chapters, all modifications to the thruster design was approached from the basis that blind application of DFA, such as part count, alone is not an adequate basis for defining design efficiency or predicting quality. Part count was indeed reduced in the redesign of the thruster, yet it was not an end, but a means to achieve the end result of reliability and quality.

Structured DFA and its methodologies must be implemented as tools to enhance global, critical thinking. Design decisions need to be made with all consequences and implications considered in an overall context and analytical fashion. DFA does contain specific design rules, but they are not to be accepted uncritically, and therefore preclude objective thinking by the designer. It is not simply satisfying certain rules or complying with a certain methodology. When used properly, DFA becomes the means, not the end, to produce objective inquiry and critical thought towards the creation of a high-quality, reliable design.

[1] Whitney, D., "DFA Theory," October 25, 1999.

[2] Barkan, P. and Hinckley, C.M., "The Benefits and Limitations of Structured Design Methodologies," Manufacturing Review, Vol. 6, No. 3 September 1994 pp. 211-220.

[3] *Ibid.*

[4] *Ibid.*

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APPENDICES

Appendix A: Disassembled Cold-Gas Thruster

Figure A-1: Image of Disassembled Cold-Gas Thruster

Appendix B: Original Design Boothroyd-Dewhurst DFA Analysis Totals Report

DESIGN FOR ASSEMBLY ANALYSIS TOTALS REPORT
Massachusetts Institute of Technology, James Won
Cold-gas Thruster [THRUSTER.DFA]

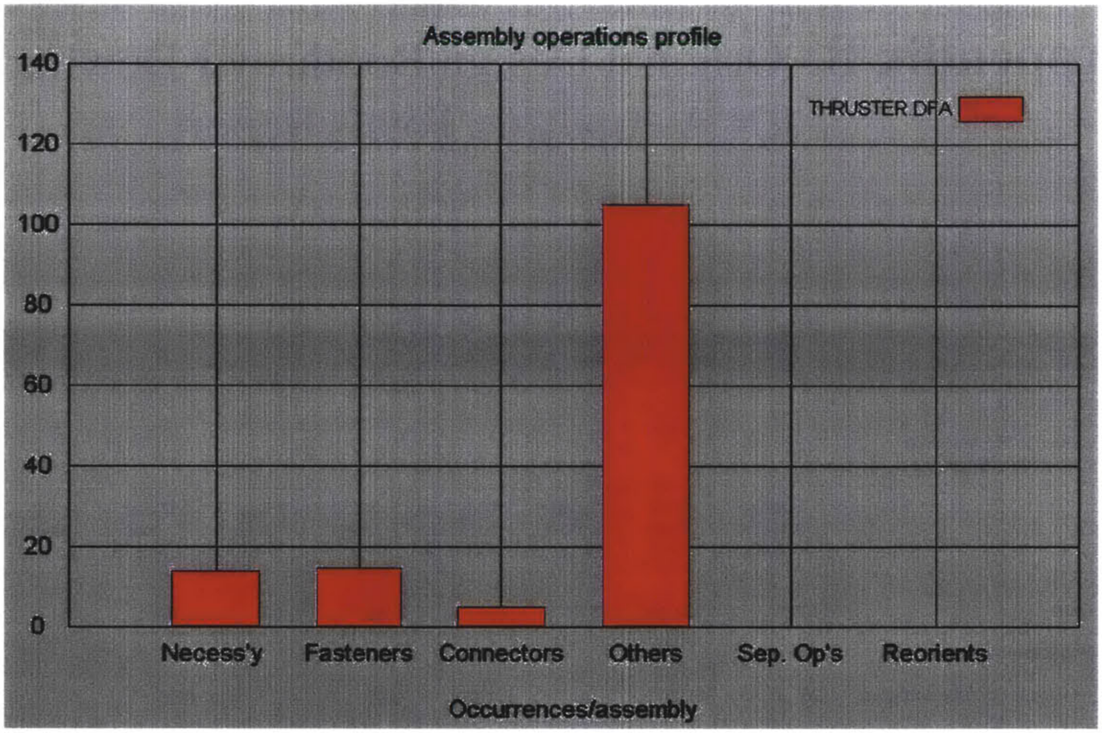
Manufacturer:
Site:
Production life, yrs: 0.00
Product life volume: 0

	Entries (including repeats)	Total Time sec	Labor Cost $	Ass'y Tool or Fixture Costs, $	Add'l Costs $	Item Costs $	Manuf. Tool Costs, $	Weight lb
Parts	121	1130.16	18.84	0.00	0.00	0.00	0.00	0.00
Subassemblies or pcbs:								
Partially or fully analyzed	20	159.70	2.66	0.00	0.00	-	0.00	-
Named only	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Excluded	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Operations:								
Reorientations	0	0.00	0.00	0.00	0.00	-	-	-
Standard	0	0.00	0.00	0.00	0.00	-	-	0.00
Library	0	0.00	0.00	0.00	0.00	-	-	0.00
Column Totals	141	1289.86	21.50	0.00	0.00	*0.00	0.00	*0.00

	Labor Cost $	Ass'y Tool or Fixture Costs, $	Add'l Costs $	Item Costs $	Manuf. Tool Costs, $
Annual Costs, $	0.00	-	0.00	*0.00	-
Production Life Costs, $	0.00	0.00	0.00	*0.00	0.00

*Data not given for some entries

Figure B-1: Original Design DFA Analysis Totals Report



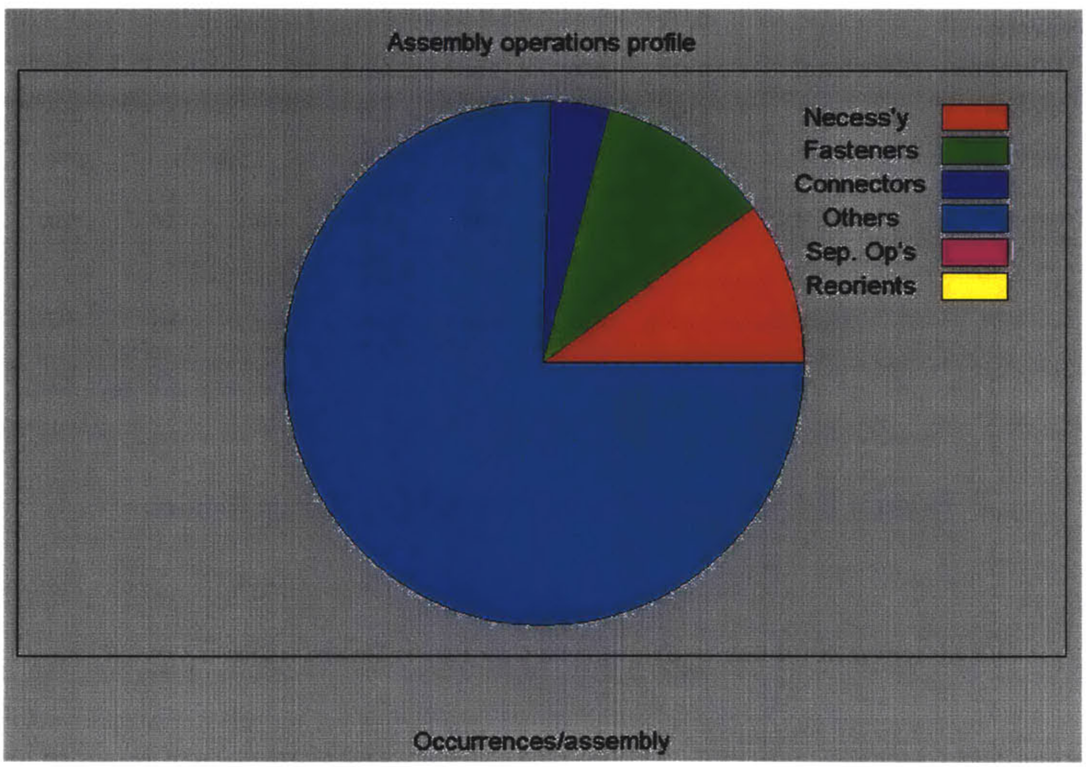


Figure B-2: Original Design Assembly Operations Profile Graphs

Appendix C: Original Design Boothroyd-Dewhurst DFA Product Review Report

DESIGN FOR ASSEMBLY PRODUCT REVIEW TABLE REPORT
Massachusetts Institute of Technology, James Won
Cold-gas Thruster [THRUSTER.DFA]

No.	Sub No. Entry No.	Type	Name	Repeat Count	Minimum Items	Tool Fetching Time, sec	Handling Time, sec	Insertion or Op'n Time, sec
1	1.1	Part	Valve Housing	1	1	0.00	1.95	1.50
2	1.2	Sub2	Ball / Ball Retainer	1	--	--	--	--
3	2.1	Part	Ball Retainer	1	0	0.00	2.55	7.70
4	2.2	Part	Ball	1	1	0.00	7.60	7.70
5	1.3	Sub3	Main Poppet Subassembly	1	--	2.90	1.50	7.50
6	3.1	Sub4	Retainer / O-Ring	1	--	--	--	--
7	4.1	Part	Main Poppet Retainer	1	0	0.00	1.50	1.50
8	4.2	Part	O-Ring	2	0	0.00	5.10	11.00
9	3.2	Part	Main Poppet	1	0	0.00	2.06	7.20
10	3.3	Part	Spring, Main Poppet	1	0	0.00	2.45	2.60
11	3.4	Part	Main Screw	1	0	7.10	1.80	9.20
12	1.4	Sub5	Side Poppet Subassembly	2	--	0.00	1.50	5.00
13	5.1	Part	Side Poppet	2	2	0.00	2.06	1.50
14	5.2	Sub6	Seat / O-Ring	4	--	0.00	2.25	5.00
15	6.1	Part	Seat, Thruster Valve	4	0	0.00	2.25	1.50
16	6.2	Part	O-Ring, Seat	4	0	0.00	5.10	11.00
17	5.3	Part	Spacer, Thruster Valve	2	0	0.00	1.88	5.00
18	5.4	Sub7	Screw / O-Ring	2	--	0.00	2.25	11.90
19	7.1	Part	Screw, Thruster Valve	2	0	0.00	2.25	1.50
20	7.2	Part	O-Ring, Screw, Thruster Valve	2	0	0.00	5.10	11.00
21	1.5	Part	Retainer Seat, Thruster Valve	2	0	0.00	1.80	5.00
22	1.6	Part	Spring, Thruster Valve	2	0	0.00	2.45	1.50
23	1.7	Sub8	Thruster Manifold / O-Ring	1	--	0.00	1.95	2.60
24	8.1	Part	Thruster Manifold	1	1	0.00	1.95	1.50
25	8.2	Part	O-Ring, Thruster Manifold	1	0	0.00	4.10	6.50
26	1.8	Part	Washers, Thruster Manifold	2	0	0.00	1.69	1.50
27	1.9	Part	Screws, Thruster Manifold	2	0	2.90	1.50	7.90
28	1.10	Sub9	Set Screw / O-Ring	1	--	2.90	1.80	7.50
29	9.1	Part	Set Screw	1	0	0.00	1.80	1.50
30	9.2	Part	O-Ring, Set Screw	1	0	0.00	5.10	11.00
31	1.11	Sub10	Nozzle / O-Ring	1	--	0.00	1.95	1.50
32	10.1	Part	Nozzle	1	1	0.00	2.70	3.00
33	10.2	Part	O-Ring, Nozzle	2	0	0.00	4.50	6.50
34	1.12	Part	Washers, Nozzle	2	0	0.00	2.18	1.50
35	1.13	Part	Screws, Nozzle	2	0	2.90	1.50	9.60
36	1.14	Part	Solenoid	1	1	0.00	1.80	5.50
37	1.15	Part	Screws, Solenoid	4	0	2.90	1.50	9.60

DESIGN FOR ASSEMBLY PRODUCT REVIEW TABLE REPORT
Massachusetts Institute of Technology, James Won
Cold-gas Thruster [THRUSTER.DFA]

No.	Sub No. Entry No.	Type	Name	Total Time, sec	Labor Cost $	Addit'l Cost $	Ass'y Tool or Fixture Cost, $	Item Cost $
1	1.1	Part	Valve Housing	3.45	0.06	0.00	0.00	0.00
2	1.2	Sub2	Ball / Ball Retainer	–	–	–	0.00	–
3	2.1	Part	Ball Retainer	10.25	0.17	0.00	0.00	0.00
4	2.2	Part	Ball	15.30	0.25	0.00	0.00	0.00
5	1.3	Sub3	Main Poppet Subassembly	11.90	0.20	0.00	0.00	–
6	3.1	Sub4	Retainer / O-Ring	–	–	–	0.00	–
7	4.1	Part	Main Poppet Retainer	3.00	0.05	0.00	0.00	0.00
8	4.2	Part	O-Ring	32.20	0.54	0.00	0.00	0.00
9	3.2	Part	Main Poppet	9.26	0.15	0.00	0.00	0.00
10	3.3	Part	Spring, Main Poppet	5.05	0.08	0.00	0.00	0.00
11	3.4	Part	Main Screw	18.10	0.30	0.00	0.00	0.00
12	1.4	Sub5	Side Poppet Subassembly	13.00	0.22	0.00	0.00	–
13	5.1	Part	Side Poppet	7.12	0.12	0.00	0.00	0.00
14	5.2	Sub6	Seat / O-Ring	29.00	0.48	0.00	0.00	–
15	6.1	Part	Seat, Thruster Valve	15.00	0.25	0.00	0.00	0.00
16	6.2	Part	O-Ring, Seat	64.40	1.07	0.00	0.00	0.00
17	5.3	Part	Spacer, Thruster Valve	13.76	0.23	0.00	0.00	0.00
18	5.4	Sub7	Screw / O-Ring	28.30	0.47	0.00	0.00	–
19	7.1	Part	Screw, Thruster Valve	7.50	0.12	0.00	0.00	0.00
20	7.2	Part	O-Ring, Screw, Thruster Valve	32.20	0.54	0.00	0.00	0.00
21	1.5	Part	Retainer Seat, Thruster Valve	13.60	0.23	0.00	0.00	0.00
22	1.6	Part	Spring, Thruster Valve	7.90	0.13	0.00	0.00	0.00
23	1.7	Sub8	Thruster Manifold / O-Ring	4.55	0.08	0.00	0.00	–
24	8.1	Part	Thruster Manifold	3.45	0.06	0.00	0.00	0.00
25	8.2	Part	O-Ring, Thruster Manifold	10.60	0.18	0.00	0.00	0.00
26	1.8	Part	Washers, Thruster Manifold	6.38	0.11	0.00	0.00	0.00
27	1.9	Part	Screws, Thruster Manifold	21.70	0.36	0.00	0.00	0.00
28	1.10	Sub9	Set Screw / O-Ring	12.20	0.20	0.00	0.00	–
29	9.1	Part	Set Screw	3.30	0.05	0.00	0.00	0.00
30	9.2	Part	O-Ring, Set Screw	16.10	0.27	0.00	0.00	0.00
31	1.11	Sub10	Nozzle / O-Ring	3.45	0.06	–	0.00	–
32	10.1	Part	Nozzle	5.70	0.09	0.00	0.00	0.00
33	10.2	Part	O-Ring, Nozzle	22.00	0.37	0.00	0.00	0.00
34	1.12	Part	Washers, Nozzle	7.36	0.12	0.00	0.00	0.00
35	1.13	Part	Screws, Nozzle	25.10	0.42	0.00	0.00	0.00
36	1.14	Part	Solenoid	7.30	0.12	0.00	0.00	0.00
37	1.15	Part	Screws, Solenoid	47.30	0.79	0.00	0.00	0.00

Figure C-1: Original Design DFA Product Review Report

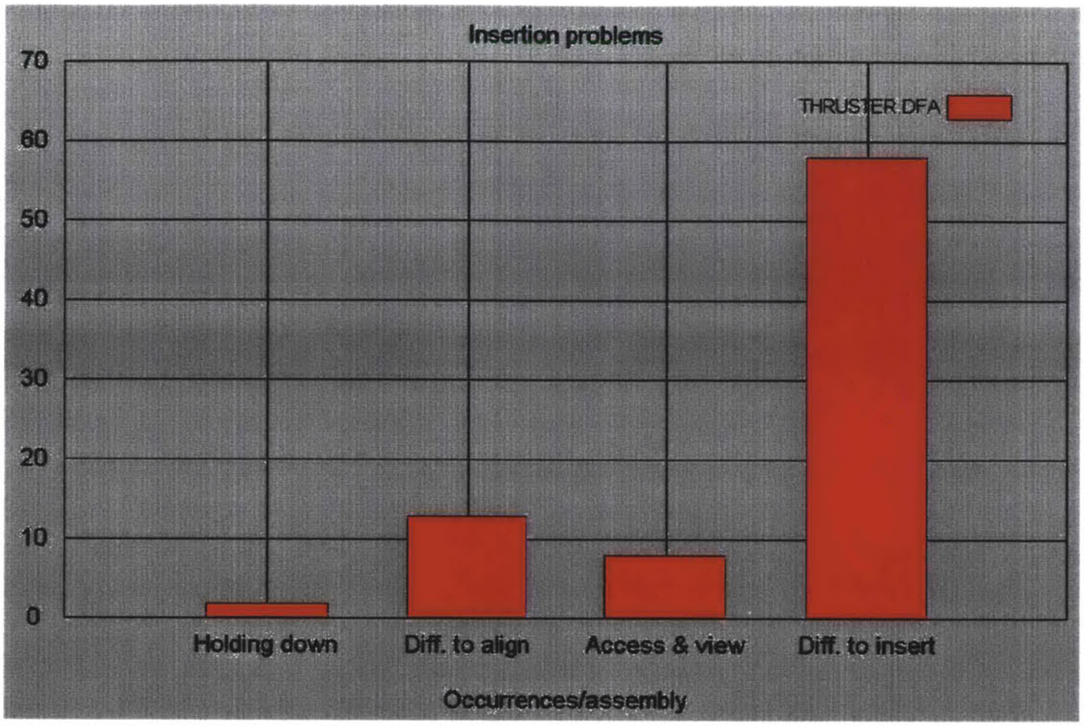
Appendix D: Original Design Boothroyd-Dewhurst DFA Worksheet Results Report

DESIGN FOR ASSEMBLY WORKSHEET RESULTS REPORT
Massachusetts Institute of Technology, James Won
Cold-gas Thruster [THRUSTER.DFA]

Name	Sub No. Entry No.	Type	Repeat Count	Min. Items	Tool Fetching Time, sec	Handling Time, sec	Insertion or Op'n Time, sec	Total Time, sec
Cold-gas Thruster		Main						
Valve Housing	1.1	Part	1	1	0.00	1.95	1.50	3.45
Ball / Ball Retainer	1.2	Sub2	1	--	--	--	--	--
Main Poppet Subassembly	1.3	Sub3	1	--	2.90	1.50	7.50	11.90
Side Poppet Subassembly	1.4	Sub5	2	--	0.00	1.50	5.00	13.00
Retainer Seat, Thruster Valve	1.5	Part	2	0	0.00	1.80	5.00	13.60
Spring, Thruster Valve	1.6	Part	2	0	0.00	2.45	1.50	7.90
Thruster Manifold / O-Ring	1.7	Sub8	1	--	0.00	1.95	2.60	4.55
Washers, Thruster Manifold	1.8	Part	2	0	0.00	1.69	1.50	6.38
Screws, Thruster Manifold	1.9	Part	2	0	2.90	1.50	7.90	21.70
Set Screw / O-Ring	1.10	Sub9	1	--	2.90	1.80	7.50	12.20
Nozzle / O-Ring	1.11	Sub10	1	--	0.00	1.95	1.50	3.45
Washers, Nozzle	1.12	Part	2	0	0.00	2.18	1.50	7.36
Screws, Nozzle	1.13	Part	2	0	2.90	1.50	9.60	25.10
Solenoid	1.14	Part	1	1	0.00	1.80	5.50	7.30
Screws, Solenoid	1.15	Part	4	0	2.90	1.50	9.60	47.30
Totals:			25	2	14.50	42.19	128.50	185.19
Ball / Ball Retainer		Sub2						
Ball Retainer	2.1	Part	1	0	0.00	2.55	7.70	10.25
Ball	2.2	Part	1	1	0.00	7.60	7.70	15.30
Totals:			2	1	0.00	10.15	15.40	25.55
Main Poppet Subassembly		Sub3						
Retainer / O-Ring	3.1	Sub4	1	--	--	--	--	--
Main Poppet	3.2	Part	1	0	0.00	2.06	7.20	9.26
Spring, Main Poppet	3.3	Part	1	0	0.00	2.45	2.60	5.05
Main Screw	3.4	Part	1	0	7.10	1.80	9.20	18.10
Totals:			4	0	7.10	6.31	19.00	32.41
Retainer / O-Ring		Sub4						
Main Poppet Retainer	4.1	Part	1	0	0.00	1.50	1.50	3.00
O-Ring	4.2	Part	2	0	0.00	5.10	11.00	32.20
Totals:			3	0	0.00	11.70	23.50	35.20

Retainer / O-Ring (continued)		Sub4								
Side Poppet Subassembly		Sub5								
Side Poppet	5.1	Part	2	2	0.00	2.06	1.50	7.12	0.12	0.00
Seat / O-Ring	5.2	Sub6	4	–	0.00	2.25	5.00	29.00	0.48	0.00
Spacer, Thruster Valve	5.3	Part	2	0	0.00	1.88	5.00	13.76	0.23	0.00
Screw / O-Ring	5.4	Sub7	2	–	0.00	2.25	11.90	28.30	0.47	0.00
Totals:			10	2	0.00	21.38	56.80	78.18	1.30	0.00
Seat / O-Ring		Sub6								
Seat, Thruster Valve	6.1	Part	4	0	0.00	2.25	1.50	15.00	0.25	0.00
O-Ring, Seat	6.2	Part	4	0	0.00	5.10	11.00	64.40	1.07	0.00
Totals:			8	0	0.00	29.40	50.00	79.40	1.32	0.00
Screw / O-Ring		Sub7								
Screw, Thruster Valve	7.1	Part	2	0	0.00	2.25	1.50	7.50	0.12	0.00
O-Ring, Screw, Thruster Valve	7.2	Part	2	0	0.00	5.10	11.00	32.20	0.54	0.00
Totals:			4	0	0.00	14.70	25.00	39.70	0.66	0.00
Thruster Manifold / O-Ring		Sub8								
Thruster Manifold	8.1	Part	1	1	0.00	1.95	1.50	3.45	0.06	0.00
O-Ring, Thruster Manifold	8.2	Part	1	0	0.00	4.10	6.50	10.60	0.18	0.00
Totals:			2	1	0.00	6.05	8.00	14.05	0.23	0.00
Set Screw / O-Ring		Sub9								
Set Screw	9.1	Part	1	0	0.00	1.80	1.50	3.30	0.05	0.00
O-Ring, Set Screw	9.2	Part	1	0	0.00	5.10	11.00	16.10	0.27	0.00
Totals:			2	0	0.00	6.90	12.50	19.40	0.32	0.00
Nozzle / O-Ring		Sub10								
Nozzle	10.1	Part	1	1	0.00	2.70	3.00	5.70	0.09	0.00
O-Ring, Nozzle	10.2	Part	2	0	0.00	4.50	6.50	22.00	0.37	0.00
Totals:			3	1	0.00	11.70	16.00	27.70	0.46	0.00

Figure D-1: Original Design DFA Worksheet Results Report



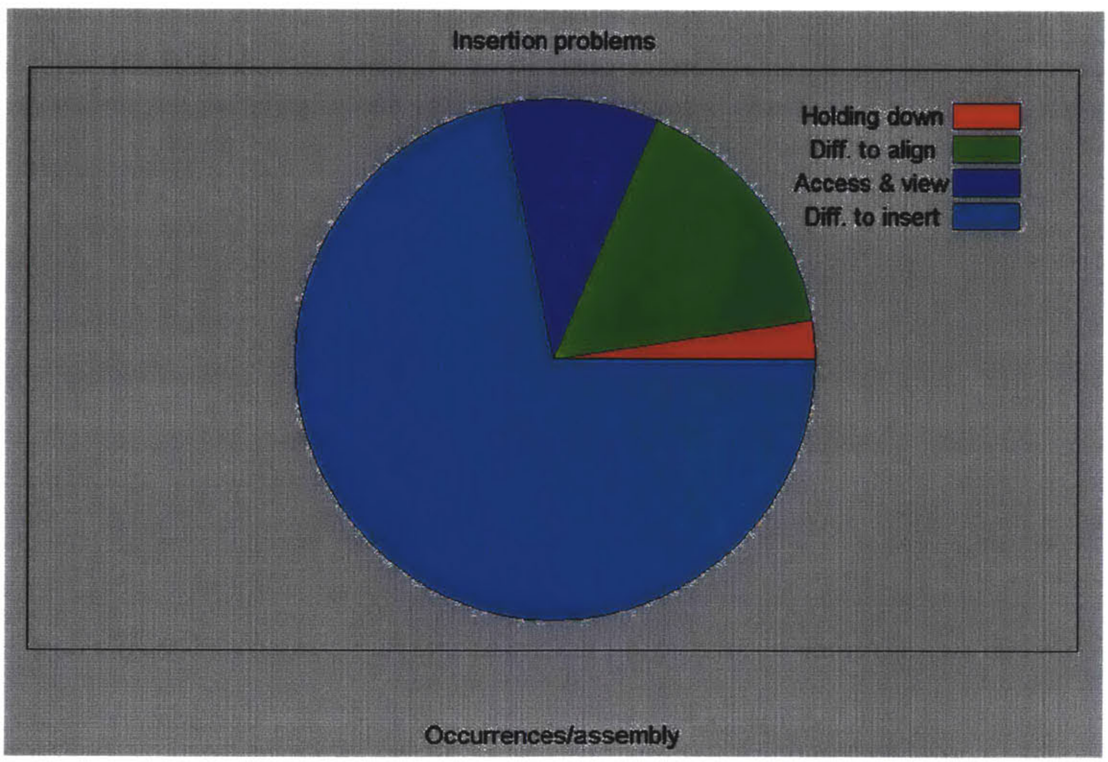


Figure D-2: Original Design Insertion Problems Graphs

Appendix E: Redesign Boothroyd-Dewhurst DFA Analysis Totals Report

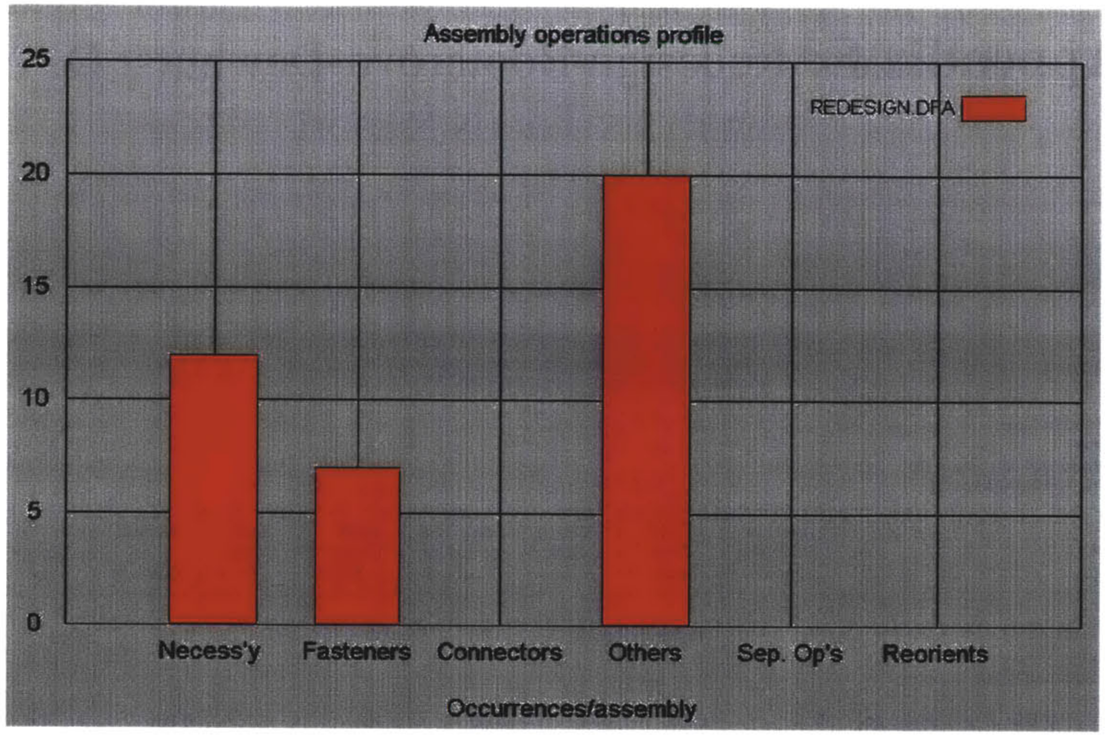
DESIGN FOR ASSEMBLY ANALYSIS TOTALS REPORT
Massachusetts Institute of Technology, James Won
Redesign Cold Gas Thruster [REDESIGN.DFA]

Manufacturer:
Site:
Production life, yrs: 0.00
Product life volume: 0

	Entries (including repeats)	Total Time sec	Labor Cost $	Ass'y Tool or Fixture Costs, $	Add'l Costs $	Item Costs $	Manuf. Tool Costs, $	Weight lb
Parts	35	316.29	5.27	0.00	0.00	0.00	0.00	0.00
Subassemblies or pcbs:								
Partially or fully analyzed	5	28.35	0.47	0.00	0.00	-	0.00	-
Named only	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Excluded	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Operations:								
Reorientations	0	0.00	0.00	0.00	0.00	-	-	-
Standard	0	0.00	0.00	0.00	0.00	-	-	0.00
Library	0	0.00	0.00	0.00	0.00	-	-	0.00
Column Totals	40	344.64	5.74	0.00	0.00	*0.00	0.00	*0.00
Annual Costs, $			0.00	-	0.00	*0.00	-	
Production Life Costs, $			0.00	0.00	0.00	*0.00	0.00	

*Data not given for some entries

Figure E-1: Redesign DFA Analysis Totals Report



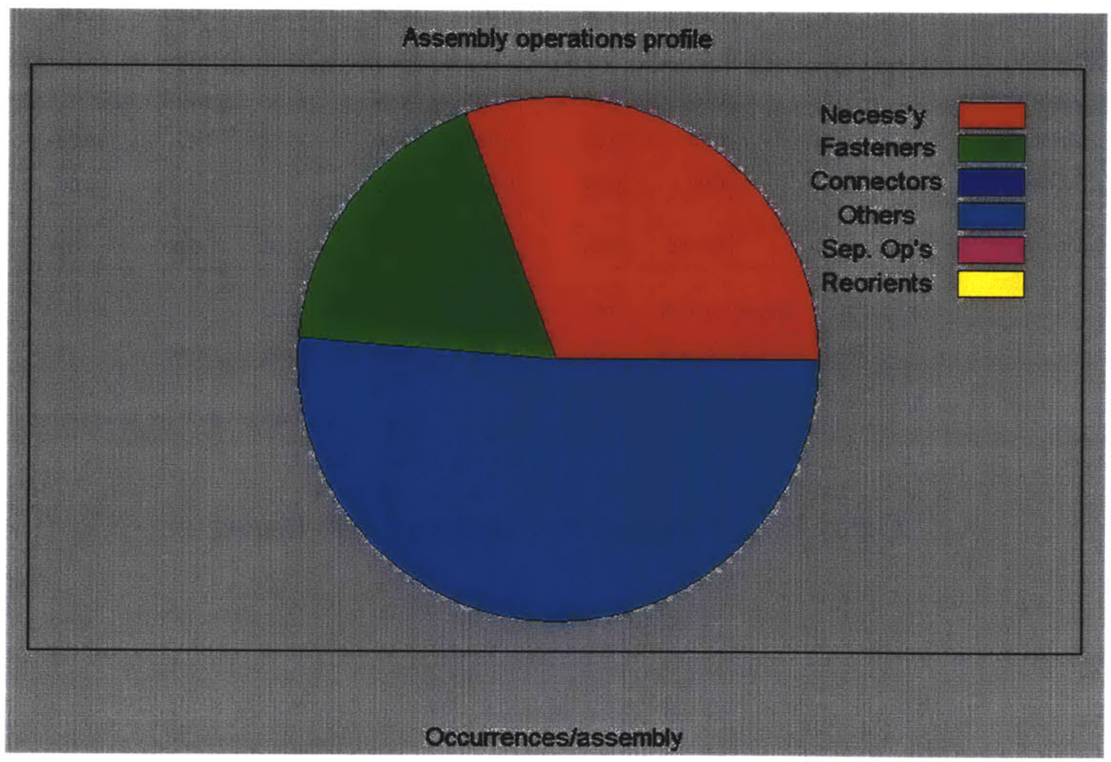


Figure E-2: Redesign Assembly Operations Profile Graphs

Appendix F: Redesign Boothroyd-Dewhurst DFA Product Review Report

DESIGN FOR ASSEMBLY PRODUCT REVIEW TABLE REPORT
Massachusetts Institute of Technology, James Won
Redesign Cold Gas Thruster [REDESIGN.DFA]

No.	Sub No. Entry No.	Type	Name	Repeat Count	Minimum Items	Tool Fetching Time, sec	Handling Time, sec	Insertion or Op'n Time, sec
1	1.1	Part	Valve Housing	1	1	0.00	1.95	1.50
2	1.2	Part	Ball	1	1	0.00	7.60	7.70
3	1.3	Sub2	Main Poppet Subassembly	1	–	2.90	1.50	7.50
4	2.1	Sub3	Retainer / O-ring	1	–	–	–	–
5	3.1	Part	Main Poppet Retainer	1	0	0.00	1.50	1.50
6	3.2	Part	O-Ring	2	0	0.00	5.10	11.00
7	2.2	Part	Main Poppet	1	0	0.00	2.06	7.20
8	2.3	Part	Spring, Main Poppet	1	0	0.00	2.45	2.60
9	2.4	Part	Main Screw	1	0	7.10	1.80	9.20
10	1.4	Sub4	Side Poppet Subassembly	2	–	0.00	1.50	5.00
11	4.1	Part	Side Poppet	2	2	0.00	1.50	1.50
12	4.2	Part	O-Ring, Seat	4	0	0.00	5.10	5.00
13	4.3	Part	O-Ring, End	2	0	0.00	5.10	5.00
14	1.5	Sub5	Thruster Manifold / O-Ring	1	–	0.00	1.95	1.50
15	5.1	Part	Thruster Manifold	1	1	0.00	1.95	1.50
16	5.2	Part	O-Ring, Thruster Manifold	1	0	0.00	4.10	6.50
17	1.6	Part	Washers, Thruster Manifold	2	0	0.00	1.69	1.50
18	1.7	Part	Screws, Thruster Manifold	2	0	2.90	1.50	7.90
19	1.8	Part	Solenoid	1	1	0.00	1.80	5.50
20	1.9	Part	Screws, Solenoid	4	0	2.90	1.50	9.60

DESIGN FOR ASSEMBLY PRODUCT REVIEW TABLE REPORT
Massachusetts Institute of Technology, James Won
Redesign Cold Gas Thruster [REDESIGN.DFA]

No.	Sub No. Entry No.	Type	Name	Total Time, sec	Labor Cost $	Addit'l Cost $	Ass'y Tool or Fixture Cost, $	Item Cost $
1	1.1	Part	Valve Housing	3.45	0.06	0.00	0.00	0.00
2	1.2	Part	Ball	15.30	0.25	0.00	0.00	0.00
3	1.3	Sub2	Main Poppet Subassembly	11.90	0.20	0.00	0.00	–
4	2.1	Sub3	Retainer / O-ring	–	–	–	0.00	–
5	3.1	Part	Main Poppet Retainer	3.00	0.05	0.00	0.00	0.00
6	3.2	Part	O-Ring	32.20	0.54	0.00	0.00	0.00
7	2.2	Part	Main Poppet	9.26	0.15	0.00	0.00	0.00
8	2.3	Part	Spring, Main Poppet	5.05	0.08	0.00	0.00	0.00
9	2.4	Part	Main Screw	18.10	0.30	0.00	0.00	0.00
10	1.4	Sub4	Side Poppet Subassembly	13.00	0.22	0.00	0.00	–
11	4.1	Part	Side Poppet	6.00	0.10	0.00	0.00	0.00
12	4.2	Part	O-Ring, Seat	40.40	0.67	0.00	0.00	0.00
13	4.3	Part	O-Ring, End	20.20	0.34	0.00	0.00	0.00
14	1.5	Sub5	Thruster Manifold / O-Ring	3.45	0.06	0.00	0.00	–
15	5.1	Part	Thruster Manifold	3.45	0.06	0.00	0.00	0.00
16	5.2	Part	O-Ring, Thruster Manifold	10.60	0.18	0.00	0.00	0.00
17	1.6	Part	Washers, Thruster Manifold	6.38	0.11	0.00	0.00	0.00
18	1.7	Part	Screws, Thruster Manifold	21.70	0.36	0.00	0.00	0.00
19	1.8	Part	Solenoid	7.30	0.12	0.00	0.00	0.00
20	1.9	Part	Screws, Solenoid	47.30	0.79	0.00	0.00	0.00

DESIGN FOR ASSEMBLY PRODUCT REVIEW TABLE REPORT
Massachusetts Institute of Technology, James Won
Redesign Cold Gas Thruster [REDESIGN.DFA]

No.	Sub No. Entry No.	Type	Name	Part Number	Description
1	1.1	Part	Valve Housing		add
2	1.2	Part	Ball		add & self-stick
3	1.3	Sub2	Main Poppet Subassembly		add & thread
4	2.1	Sub3	Retainer / O-ring		add
5	3.1	Part	Main Poppet Retainer		add
6	3.2	Part	O-Ring		add & press fit
7	2.2	Part	Main Poppet		add & push fit
8	2.3	Part	Spring, Main Poppet		add & hold down
9	2.4	Part	Main Screw		add & thread
10	1.4	Sub4	Side Poppet Subassembly		add & press fit
11	4.1	Part	Side Poppet		add
12	4.2	Part	O-Ring, Seat		add & press fit
13	4.3	Part	O-Ring, End		add & press fit
14	1.5	Sub5	Thruster Manifold / O-Ring		add
15	5.1	Part	Thruster Manifold		add
16	5.2	Part	O-Ring, Thruster Manifold		add & press fit
17	1.6	Part	Washers, Thruster Manifold		add
18	1.7	Part	Screws, Thruster Manifold		add & thread
19	1.8	Part	Solenoid		add
20	1.9	Part	Screws, Solenoid		add & thread

Figure F-1: Redesign DFA Product Review Report

Appendix G: Redesign Boothroyd-Dewhurst DFA Worksheet Results Report

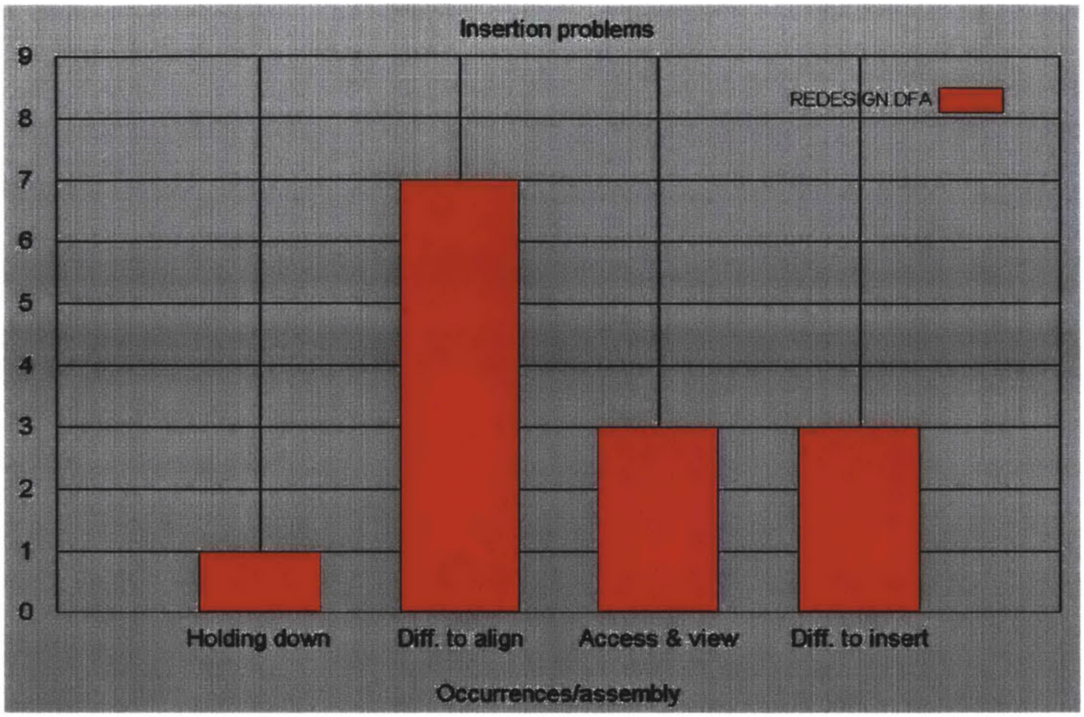
DESIGN FOR ASSEMBLY WORKSHEET RESULTS REPORT
Massachusetts Institute of Technology, James Won
Redesign Cold Gas Thruster [REDESIGN.DFA]

Name	Sub No. Entry No.	Type	Repeat Count	Min. Items	Tool Fetching Time, sec	Handling Time, sec
Redesign Cold Gas Thruster		Main				
Valve Housing	1.1	Part	1	1	0.00	1.95
Ball	1.2	Part	1	1	0.00	7.60
Main Poppet Subassembly	1.3	Sub2	1	–	2.90	1.50
Side Poppet Subassembly	1.4	Sub4	2	–	0.00	1.50
Thruster Manifold / O-Ring	1.5	Sub5	1	–	0.00	1.95
Washers, Thruster Manifold	1.6	Part	2	0	0.00	1.69
Screws, Thruster Manifold	1.7	Part	2	0	2.90	1.50
Solenoid	1.8	Part	1	1	0.00	1.80
Screws, Solenoid	1.9	Part	4	0	2.90	1.50
Totals:			15	3	8.70	30.18
Main Poppet Subassembly		Sub2				
Retainer / O-ring	2.1	Sub3	1	–	–	–
Main Poppet	2.2	Part	1	0	0.00	2.06
Spring, Main Poppet	2.3	Part	1	0	0.00	2.45
Main Screw	2.4	Part	1	0	7.10	1.80
Totals:			4	0	7.10	6.31
Retainer / O-ring		Sub3				
Main Poppet Retainer	3.1	Part	1	0	0.00	1.50
O-Ring	3.2	Part	2	0	0.00	5.10
Totals:			3	0	0.00	11.70
Side Poppet Subassembly		Sub4				
Side Poppet	4.1	Part	2	2	0.00	1.50
O-Ring, Seat	4.2	Part	4	0	0.00	5.10
O-Ring, End	4.3	Part	2	0	0.00	5.10
Totals:			8	2	0.00	33.60
Thruster Manifold / O-Ring		Sub5				
Thruster Manifold	5.1	Part	1	1	0.00	1.95
O-Ring, Thruster Manifold	5.2	Part	1	0	0.00	4.10
Totals:			2	1	0.00	6.05

DESIGN FOR ASSEMBLY WORKSHEET RESULTS REPORT
Massachusetts Institute of Technology, James Won
Redesign Cold Gas Thruster [REDESIGN.DFA]

Name	Insertion or Op'n Time, sec	Total Time, sec	Labor Cost $	Addit'l Cost $	Ass'y Tool or Fixture Cost, $	Item Cost $
Redesign Cold Gas Thruster						
Valve Housing	1.50	3.45	0.06	0.00	0.00	0.00
Ball	7.70	15.30	0.25	0.00	0.00	0.00
Main Poppet Subassembly	7.50	11.90	0.20	0.00	0.00	--
Side Poppet Subassembly	5.00	13.00	0.22	0.00	0.00	--
Thruster Manifold / O-Ring	1.50	3.45	0.06	0.00	0.00	--
Washers, Thruster Manifold	1.50	6.38	0.11	0.00	0.00	0.00
Screws, Thruster Manifold	7.90	21.70	0.36	0.00	0.00	0.00
Solenoid	5.50	7.30	0.12	0.00	0.00	0.00
Screws, Solenoid	9.60	47.30	0.79	0.00	0.00	0.00
Totals:	90.90	129.78	2.16	0.00	0.00	
Main Poppet Subassembly						
Retainer / O-ring	--	--	--	--	0.00	--
Main Poppet	7.20	9.26	0.15	0.00	0.00	0.00
Spring, Main Poppet	2.60	5.05	0.08	0.00	0.00	0.00
Main Screw	9.20	18.10	0.30	0.00	0.00	0.00
Totals:	19.00	32.41	0.54	0.00	0.00	
Retainer / O-ring						
Main Poppet Retainer	1.50	3.00	0.05	0.00	0.00	0.00
O-Ring	11.00	32.20	0.54	0.00	0.00	0.00
Totals:	23.50	35.20	0.59	0.00	0.00	
Side Poppet Subassembly						
Side Poppet	1.50	6.00	0.10	0.00	0.00	0.00
O-Ring, Seat	5.00	40.40	0.67	0.00	0.00	0.00
O-Ring, End	5.00	20.20	0.34	0.00	0.00	0.00
Totals:	33.00	66.60	1.11	0.00	0.00	
Thruster Manifold / O-Ring						
Thruster Manifold	1.50	3.45	0.06	0.00	0.00	0.00
O-Ring, Thruster Manifold	6.50	10.60	0.18	0.00	0.00	0.00
Totals:	8.00	14.05	0.23	0.00	0.00	

Figure G-1: Redesign DFA Worksheet Results Report



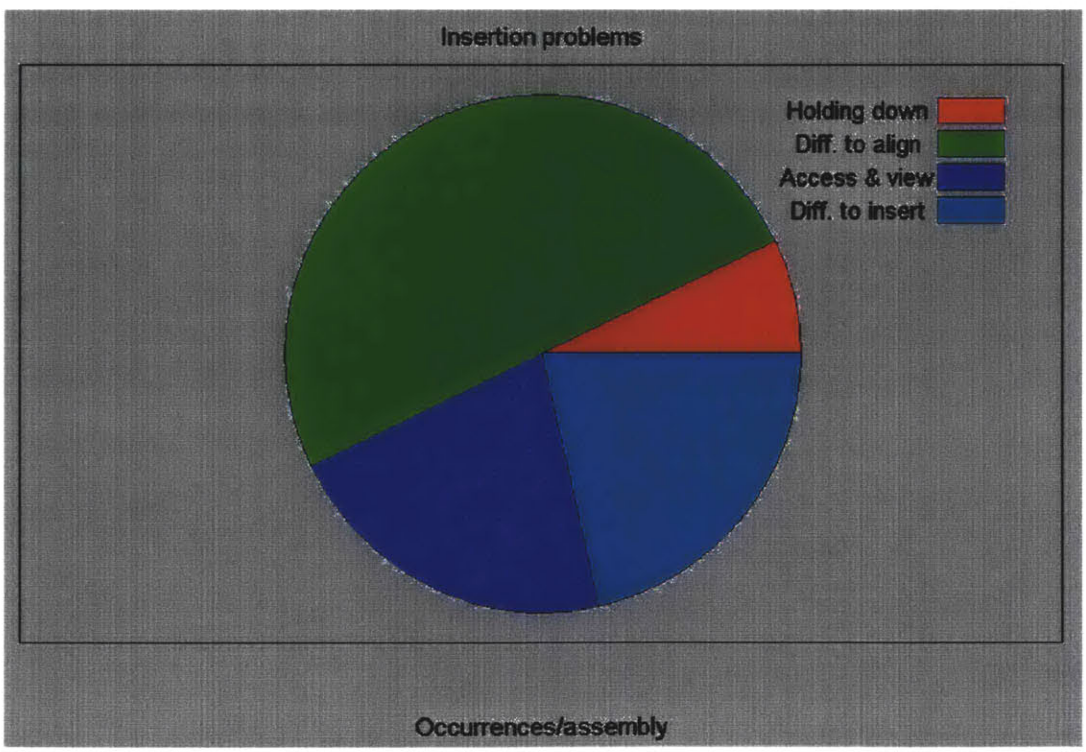


Figure G-2: Redesign Insertion Problems Graphs