ALTERNATE METHODOLOGY FOR GENERATION AND USE OF KEY CHARACTERISTICS

by

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Submitted to the Departments of Mechanical Engineering
and to the Sloan School of Management in Partial Fulfillment of
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Abstract

Hardware variation reduction is an issue of paramount importance to manufacturing companies in their efforts to reduce cycle time and manufacturing costs. Hardware variation leads to increased rework, and decreased levels of customer satisfaction. The Boeing Company, the leading manufacturer of commercial jet aircraft, in the late 1980's and early 1990's introduced two separate programs to address hardware variation. Advanced Quality Systems (AQS) addressed variation in components from suppliers; Hardware Variability Control (HVC) addressed hardware variation internal to Boeing.

One of the tools utilized by both AQS and HVC is the use of Key Characteristics. Key Characteristics are defined at Boeing as "*Attributes or features of a material, part, assembly, installation or system in which variation from nominal has the most adverse affect upon fit, performance, or service life.*" Key characteristics are generated by first identifying the features or requirements of the end product which are of primary importance to the customer. These requirements are then "flowed down" through the different layers of the engineering tree and build plan to determine those attributes or features at the assembly, subassembly, or detail part level which play a critical role in delivering the product level customer requirements. This methodology therefore allows Boeing to focus on those elements of the manufacturing process where hardware variation has the most potential for causing a quality loss in customer satisfaction.

Recently a new methodology has been developed at The Massachusetts Institute of Technology. This methodology, named herein as the quadkey methodology, expands the classifications for key characteristics to include the designations of product key characteristics, assembly key characteristics, manufacturing key characteristics, and Stat key characteristics.

This new methodology was applied to the analysis of the lower gate assembly for the forward entry door for the new 737-X model airplane, currently in the product design stage at Boeing. The research showed that the added designations for keys available under the quadkey methodology offered several advantages over that included under

HVC. Additional uses for key characteristics are also discussed outside of their application for the reduction of hardware variation.

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1.0 Introduction

Hardware variation reduction started in the firearm industry: Hardware variation has been an issue which has concerned manufactures for tens of years. In earlier times, when all products were craft manufactured by hand, by artisans more than mechanics, the issue of hardware variation was not a critical issue. Each item or product was an end to itself, and the fact that it might not appear or look identical to its sibling was not important.

The military, however, as it so often has with technology, prompted a change in opinion with regards to hardware variation. Over the course of warfare, the need for quick repair of firearms became apparent. Weapons would often fail for the need of one component, and the desire was to allow quick repair of firearms from components taken from other similar weapons which had been destroyed in battle. As such, the firearm industry became the first industry to attempt to practice the art of hardware variation.

The end goal of the firearm industry was to allow a component from one gun to be used in another gun of the same type, or in other words, interchangeable parts. Interchangeable parts meant that not only did the design of the parts need to remain unchanged, the parts also had to have the same physical dimension.

Thus was born the need for hardware variation reduction. Since that time, not only have products become more complex, but so have the manufacturing methods. In turn, the methods used to address this situation have also progressed.

Variation is a Source of Hidden Costs: Variation in the production of manufactured goods carries with it several costs, some of them hidden, others so not readily visible. Figure 1.1 shows some of these associated costs. Like the iceberg shown, the invisible costs of variation are the ones which can cripple any ship of production.

Several of items shown in figure 1.1 have traditionally been attempted to be caught and eliminated by end item inspection. However, as the Japanese taught the rest of the world in the last decade, end item inspection is not addressing the source of quality issues. Rather than inspecting quality in, the Japanese proved that it was indeed possible to build quality in.

Not only can the costs of variation be expensive, but so also can be the methods to eliminate or reduce it. Statistical Process Control (SPC) became one weapon in the battle against variation. However, the costs associated with SPC include measuring equipment, and cost of time to perform the measurement. Then additional time must be spent to analyze and interpret the data. The associated costs, however, are outweighed by the benefits. Still however, manufacturers still found SPC as not the complete solution to the elimination of hardware variation. Other methodologies need to be created. This was especially true for manufacturers who produced either complex products made of several different components, or which were manufactured though the use of complex processes.

Key Characteristics are a tool to reduce the costs of hardware variation: In the 1980's, the automotive industry began to look for additional tools to help combat the problem of hardware variation. As the technology increased in the arena of manufacturing equipment, as well as in the product design arena, the technology to address hardware variation also increased.

One of the concepts which were created was that of Key Characteristics. The realization had been made that certain variation was more costly than others. This was particularly true where the variation resulted in degradation in a product feature, performance, or requirment that was of particular importance to the customer. When customer satisfaction was compromised as a result of variation, then the associated costs were higher. Key characteristics, therefore, attempt to link customer satisfaction to those product features, dimensions, characteristics etc. which produce the required levels of customer satisfaction. Then, variation in these arenas can be focused on by the entire manfuacturing value chain, in order to reduce the variation costs where they are at their potential highest.

The Boeing Company utilizes a program entitled HVC which is based in part on key characteristics to reduce hardware variation: For the same reason that firms in the automotive industry began to utilize key characteristics to reduce hardware variation, a similar move was afoot in the aerospace industry. In the late 1980's, the Boeing Company, the worlds largest manufacturer of commercial jet transport aircraft, began to utilize the principles of key characteristics as a means of reducing hardware variation in parts supplied by their external suppliers. A few years later, Boeing introduced a program entitled Hardware Variability Control (HVC) which at its foundation the use of key characteristics to reduce excessive variation resulting in a large quality cost to their customers.

In the HVC program, Boeing assigns the following definition to Key Characteristics:

"Attributes or features of a material, part, assembly, installation or system in which variation from nominal has the most adverse affect upon fit, performance, or service life."

In this definition, Boeing assigns the categories of fit, performance, and service life as addressing those features of their products which are of primary importance to their customers.

Since its implementation of HVC, Boeing has seen dramatic success. On the 777 program, which was launched prior to the introduction of HVC, but later embodied the concept of key characteristics, achieved levels of variation on the first airplane unable to be achieved on previous programs. The concepts of HVC are now being applied to the 737-X model airplane production, which incorporates the three new newest models of the 737 airplane, with first product launch scheduled for later this decade. HVC is being implemented in many aspects of this new product design, and the results of this effort are being eagerly anticipated by Boeing.

Boeing entered 1996 with the promise of an expanding market for its products, as the global airline industry began to emerge from its multi-year recessions. The environment was not without its challenges, however, as other global competitors had it as their goal to gain market share at the expense of Boeing. In response to this, BCAG continued on its efforts to cut cost and flow time. One crucial element of this move to cut cycle costs focuses on the reduction of rework, which has as its primary origin hardware variation. By utilizing tools to reduce hardware variation, Boeing will be postured to meet its aggressive cost and flow time reduction schedules, allowing it to continue its dominance in the commercial jet liner marketplace.

Alternate methodology expanding classification and generation of key characteristics offers additional advantages beyond that implemented through HVC: After the initial introduction of key characteristics, their use also began to be studied for other potential methods to increase their effectiveness. Currently, research being conducted by the Massachusetts Institute of Technology has resulted in an alternate methodology, which specifically expands the classifications of keys called out for under HVC from 2 to 3, while introducing a special designation for those keys which are either in or approaching a state of criticalness when it comes to their being successfully delivered by the manufacturing process.

1.1 Thesis Purpose:

The purpose of this thesis is to explore this alternate methodology for key characteristics, and to contrast it to Boeing's HVC methodology. In doing this comparison, it is hoped that this alternate methodology will result in areas of potential further improvement to Boeing as a means for reducing hardware variation.

The stated deliverables of this thesis are as follows:

A) Explain the competitive nature currently surrounding Boeing, and why hardware variation reduction is critical to its continued success

B) Provide an overview of the HVC program, so that a baseline can be established for further comparisons

C) Provide a description of this alternative methodology

D) Contrast this alternative methodology to HVC by applying it to an actual production part being produced by Boeing

E) Identify potential benefits offered by this new methodology with respect to HVC

F) Identify other potential applications for the use of key characteristics at Boeing other than for the reduction of hardware variation.

1.2 Thesis Chapter Overview:

In order to achieve the stated deliverables as set forth, this thesis will structured in the following order of chapters:

Chapter 2: This chapter will provide an overview of the Boeing Company, its different divisions, and its macro process structure. In addition, current and future market potential will be examined, as well as the current competitive environment facing Boeing. Boeings reactions to this competitive environment, such as its decision to decrease its amount of vertical integration will also be reviewed, as well as the impact of such decisions on its work force.

Chapter 3: This section of the thesis will present a more detailed history of the HVC program at Boeing. It will introduce the other concepts contained within HVC in addition to the practice of defining key characteristics. The process used to generate keys under HVC will also be discussed.

Chapter 4: This chapter will present an overview of this alternate methodology for the use of key characteristics as currently being defined by MIT. The new terms of Assembly Key Characteristics , Manufacturing Key Characteristic, and Stat Key Characteristics will be defined and examples presented.

Chapter 5: This is the largest chapter in the thesis, in that it follows the flowdown of keys from upper level customer requirements down to the detail part level. First the results of this process as performed under HVC by Boeing will be analyzed. Then this same flowdown process will be performed using the alternated methodology, allowing a direct comparison to be made between the two methodologies as it applies to this one particular example. In addition, tradeoffs between different keys will also be examined.

Chapter 6: This portion of the thesis will analyze issues encountered during the application of HVC at a factory within Boeing, and attempt to see if this new methodology for key characteristics could have mitigated any of these particular situations. This section of the thesis will attempt to find additional benefits for the new methodology over those found in the previous chapter

Chapter 7: This chapter will address other uses identified by the author for key characteristics outside their traditional realm of hardware variation. Keys have long been associated with this narrow focus, and have other benefits to the manufacturing organization due to their being inextricably linked to customer requirements. This would apply both to HVC as well as this methodology being developed at MIT

Chapter 8: This will serve as the conclusion for the thesis, and will summarize those items accomplished in the thesis, as well as identify potential areas for future study on this topic.

2.1 Internship Site Overview

The LFM program features a 6 month internship at the beginning of the second year of the program. The author returned to his employer, The Boeing Company, in order to conduct his internship and thesis research. This chapter will provide an overview of The Boeing Company, its market, and a description of the factory area in which the author spent his internship. The author spent his internship at the Door Responsibility Center, was in the process of implementing HVC on the 737-X. It was attempting to utilize key characteristics as a means of reducing hardware variation that they had been encountering on current products; it was therefore hoped that this thesis could assist them in achieving hardware variation reduction through the use of keys. It is necessary, therefore, that the environment that was surrounding the Door Responsibility Center be understood, before the study of the use of key characteristics at the Door Responsibility Center can be studied.

2.2 Overview of the Boeing Company

> *"Our Goal, in every product sector, is to be the value leader in our industry"*[1]

The Boeing Company, headquartered in Seattle, WA. remains today one of the dominant aerospace firms in the world. Formed in the early 1900's, the company has undergone several corporate divisional reorganizations in the last 10 years. In its current organization charter, The Boeing Company consists of the following 3 divisions: Boeing Commercial Aircraft (BCAG), Boeing Defense and Space Group (BDSG), and Boeing Information Systems (BIS)

2.3 Boeing Commercial Aircraft Group(BCAG)

BCAG is the worlds leading manufacturer of Commercial Jet aircraft for the airline Industry. With over 50% of its planes being sold to foreign customers, Boeing

[1] Frank Shrontz, Chief Executive Officer of The Boeing Company, 1995 Annual Report

ranks among the top exporters annually for the United States. Over the last 10 years, Boeing has exported more dollar value of product than any other U.S. firm, far exceeding that of the second place firm, General Motors.

With a family of products including 5 major airplane models (737, 747, 757, 767, and 777), and a total of 12 different versions of these models, BCAG has the widest family of commercial airplane products on the market. In addition to these 12 versions, Boeing currently has potentially 5 other new versions in product development (not including its work on the Future Large Airplane, or the High Speed Civil Transport programs), further widening the range of products available in it product portfolio. In addition to the widest product range, BCAG has also carved out a reputation for customer service and support unequaled in the commercial airplane industry.

1995 saw Boeing strengthen its position as market share leader. Last year BCAG captured over 65% of the total jetliner market. In addition, its 777, the first of which was delivered on time and service ready to United Airlines in 1995, captured almost 80% of total orders in which it competed. 1995 also marked the return of McDonnell Douglas as a leading competitor, as it booked more airplane orders than did Airbus, thanks to a large order from ValuJet for its new MD-90 product launch.

BCAG has broken its business activity down into 5 macro processes: Business Acquisition, Define, Produce, Support, and Business Resources. One of the major purposes for this activity was to allow BCAG to more explicitly focus on the elements and activities which comprise its value chain. Recently, the Acquire and Support macro processes were merged together, as they both focus explicitly on the customer. The Acquire macro process involves the marketing and sales aspects of the division. The Define macro process contains the product development, design engineering, and sustaining engineering efforts. Build is self descriptive, consisting of BCAG's production facilities. Support includes not only customer support, but their network of spare part facilities located world wide, as well as BCAG's on-line access to engineering drawings and manuals for the customer. Customer documentation is no small task, as the total volume of written documentation for the 747 would not fit inside a 747. Lastly, Business Resources includes functions such as Human Resources and Finance.

2.4 Overview of the Door Responsibility Center

The Door Responsibility Center (DRC), located at the Renton facility, is responsible for the design and production of several doors for all models of the 737 and 757 narrow body airliners. This responsibility includes both pressurized (cabin and cargo doors) as well as unpressurized doors (landing gear doors). It also includes hatches, such as the over the wing emergency exit hatch. The DRC is a true responsibility center, as design, quality, scheduling. planning, and production are co-located in one facility, with each organization having dotted line responsibility to the DRC shop manager.

The DRC manufactures approximately 30% of the door package for the 737 and 757 jetliners. The remaining doors are made either by other internal suppliers, such as the Wichita facility DRC, or by other external suppliers. Several of these external suppliers are located overseas, in countries such as Poland, India, Japan, China, Singapore, and Ireland.

Door Products Manufactured at the DRC

Airplane Model	DRC Doors
737	Forward Entry Door, Over the Wing Exit Doors, Air Stair Door,
757	Main Cargo door (freighter), Left and Right Hand Passenger Doors, Electrical Access, Over the Wing Exit Doors, #3 Escape Door

2.5 Current Situation for Commercial Aircraft Industry

The market for commercial airplanes is closely linked to several different factors including global economic trends, business cycles (both within the industry and without), increasing demand for leisure activities and travel, need to replace aging aircraft, airline profits, and increasing global demand for air traffic travel. Other such factors, such as the increase in telecommunications capability, which was supposed to dramatically affect air travel requirements, has not yet materialized as a major factor. In addition, the emergence of global competition in the airplane market has further increased the chances of variability for any one manufacturer's product.

The culmination of the above several factors results in a cyclic airplane market. As a result, Boeing finds itself in the position of being able to adapt (either pro-actively or reactively) to these changes in a quicker fashion. Reduction of hardware variation, in the sense that it will decrease rework time and hence cycle time and costs, will assist Boeing in being more responsive to these airplane demand trends.

2.5.1 Future Market Outlook

New orders for commercial jetliners are strongly tied to four different factors: increase in domestic and international air travel, airline profitability, increase in air cargo shipments, and replacement of older airplanes exceeding useful service or becoming too expensive to operate. The current jetliner market is coming out of a several year downturn, brought on in part by the Gulf War, as well as the U.S. recession in the early 1990's. This turnaround was exemplified by the increase in worldwide passenger traffic by 5%, and a strong increase in airliner profits as compared to 1994.

This rebound in the airline industry is cascading down to the commercial aerospace industry. Yearly total orders for new jetliner orders for the remainder of the decade are forecasted to grow at a moderate rate. In anticipation of future orders, and airline desire to take earlier delivery of backordered airplanes, BCAG has recently announced plans to increase its monthly production rate from 18.5 planes at the end of 1995, to 22.5 jetliners in early 1997.

With respect to future market demand, Boeing has forecasted that the worldwide demand for new airplanes over the next 20 years, will be nearly 16,000 airplanes. This represents a total market worth more than $1 trillion in 1995 dollars. It should be noted that Airbus's market forecasts for the next 20 years are slightly even more optimistic. It is interesting to balance this estimate of 16,000 new airplanes against Boeing's current total airplane production since the beginning of the jet age, which is less than 8,000 airplanes built.

Currently, the growth in the commercial airplane market is being strongly driven by the international market. Currently, one out of approximately every 5 airplanes Boeing manufactures is being shipped to China. Over 50% of BCAG's total airplane orders and shipments represent international customers. Of the forecasted future 1 trillion dollar market over the next 20 years, the majority of this is for countries other than the United States.

2.5.2 Competitive Outlook:

BCAG currently faces an environment of increasing global competition. Airbus, a consortium of European aerospace companies, has as its stated goal a 50% market share of the international commercial jet airplane market by the year 2000. As Boeing currently has in excess of 60% of the market (in terms of dollar value), and Airbus and McDonnell Douglas the majority of the remainder, Airbus is not too subtly stating that they wish to replace Boeing as the leader in market share.

Airbus remains the number two commercial airplane supplier behind Boeing in terms of dollar value, with roughly 27 % of the market, followed by McDonnell Douglas in the third spot with approximately 10%. In 1995, a proposed merger between Boeing and McDonnell Douglas fell apart, in part due to disputes over the true market value for McDonnell Douglas. However, thought was also given to the notion that the combination of the number 1 and 3 suppliers for commercial aircraft would create a market with only two dominant suppliers. In such a market, the airlines might not want one firm to become overly dominant, and may want the market share split to become more even between the two firms. In such a case, the proposed merger may have actually assisted Airbus's goals of approaching 50% market share.

How is BCAG responding to this competitive threat? BCAG has embarked on an aggressive program of cutting costs and cycle times. Stated goals for cycle time reduction are in excess of 50% within the next 5 years. Coupled with this, BCAG intends to aggressively expand its product line as mentioned earlier. One element of its plan to cut costs and flow time is the HVC program, a program designed to attack and reduce the sources of hardware variation. Another element of the plan is for Boeing to focus its attention on those aspects of its design, manufacturing, and service programs where Boeing feels that it is either currently world class, or which are a core competency (such as the design and manufacture of airplane wings). Those areas which do not fall in the above two categories will then be studied to determine if Boeing should spin them off outside of Boeing, in the hopes of divesting those activities which add excessive cost and flow time to Boeing's products.

2.5.3 Make Buy Decisions being formulated

> *"Analysts have tended to define assets too narrowly, identifying only those that can be measured, such as plant and equipment. Yet the intangible assets, such as a particular technology, accumulated consumer information, brand name, reputation, and corporate culture are invaluable to the firm's competitive power. In fact these invisible assets are often the only really source of competitive edge that can be sustained over time"* [2]

BCAG has spent two years preparing a detailed procedure for determining which products, engineering, or services should be performed within BCAG (entitled "make"), and which should be acquired outside of BCAG (entitled "buy"). In 1995, BCAG released the internal procedure to be used in formulating these make / buy decisions. The procedure requires more than 10 different factors to be considered in making such

[2] Robert M. Grant, Contemporary Strategy Analysis (Cambridge: Blackwell Business, 1995) 113

decisions. Among these are whether BCAG is world class with respect to production of the product, whether the product constitutes a core competence, an analysis of Boeing's cost versus that of suppliers, and supplier capability. Essentially, the process is designed to address each of those issues which can easily be overlooked, as referenced in the quote at the beginning of this section. As a related example, in Boeing's recent decision to produce two modified versions of the 747 (one for greater passenger size, the other an extended range version), it was determined early on to maintain the characteristic hump of the 747, as Boeing felt that the silhouette of the 747 is one of the 5 most recognized symbols in the world. This ruled out any possibility of a full length double decker 747.

In mid 1995, the Owner of BCAG's Build Macro Process, announced that the total percentage of parts made outside of BCAG would be increased from 48% to 52% within the next two to three years.[3] The anticipated cost saving from such outsourcing has been estimated to be in excess of 500 million dollars in reoccurring costs per year.

One of the major decisions out of this offloading policy is that make / buy decisions would be made across the entire family of products, rather than on just individual airplane models. Therefore, if the decision was to transition a product from make to buy, it would be bought outside for every airplane product, and not just for the 747 and 767, for example. In addition, BCAG created product owners, where one individual would now assume responsibility for make or buy for a particular product, such as landing gear etc.

One of the products which was selected to be transitioned from make to buy was all airplane doors. As such, the DRC was to shift its focus from the production of doors, to transitioning its doors to make status over the next three years. The DRC manager was then selected to become the product owner for doors. Plans for the future of the DRC as an organization, with respect to its makeup and function, are currently being created.

[3] It should be noted that parts produced by Boeing Defense and Space Group for BCAG are included in those totals for parts produced by manufacturers external to BDSG. This reduces the total percentage of parts made for BCAG outside of The Boeing Company to under 50%.

2.5.4 Offsets required for Market Activity

> *"Selling airplanes is an international business. And just as selling airplanes is an international business, so too is manufacturing airplanes" Bob Dryden, BCAG Executive Vice President for Airplane Production* [4]

> *"Mr. Shrontz (CEO and Director of the Board of The Boeing Company) says Boeing won't be agreeing to any restrictions that ... "constrain our ability" to win foreign orders by putting some subcontracting work in factories in buyer countries"* [5]

Currently, almost 70% of BCAG's products are sold to international customers, which is one of the reasons behind Boeings position as the largest exporter for the United States. Several of these orders are in excess of 1 billion dollars, making them very visible to the economies of both countries.

As a result of its international sales, the Boeing company has been forced to use the methods of offsets as a means of obtaining and cementing these sale agreements. Offsets fall into two categories: Sales agreement, and market activity generation offsets.

Sales agreement offsets are those which are specified during the course of negotiations for a particular airplane order. In this case, in return for the sale of the airplanes to the foreign carrier, Boeing makes a commitment to purchase a specified amount of product from that particular country of origin over a specified time period. This product can be either goods or services. As several of BCAG's international customers are government owned, these customers are obviously very interested in balance of trade and current account issues, and the use of sales offsets helps address these issues.

Market activity generation offsets are similar, but are not as directly linked to current sales as they are future sales. Therefore, for a particular region which Boeing may view as a source of future airliner activity, Boeing is interested in helping secure its position for future airline sales. In this case, Boeing may pursue offsets such as placement of manufacturing work inside the company, some limited technology transfer, or training

[4] The Boeing News, November 10, 1996
[5] Wall Street Journal, October 5, 1995, Page A-6

of some of the local work force for manufacturing aerospace components. Again, these type of offsets are seen as a way of generating "good will" for Boeing for future sales, while concurrently providing a tangible benefit to the country receiving the offset.

As mentioned earlier, all airplane doors were targeted for transitioning from make to buy. However, several of the doors were considered as potential products to be used for satisfying offset requirements, which could fall into either of the above categories. Doors have long been viewed as an ideal product for offsets for several reasons:

1.) They fit in a box: Doors are fairly complex items, but are not very large. The are easily crated for shipment, and therefore appear ideal for manufacture overseas.

2.) They are detachable from the airplane: Unlike a component which is buried inside the plane, these products are primarily end addition items to the assembly process. As such, the major issue is how the door fits with the airplane frame, instead of worrying how several other parts mate to and attach to the door.

3.) Doors are highly visible: Everyone who comes on to a plane uses a door coming onboard, and for leaving the plane. Flight attendants point out the location of each door during the pre flight emergency procedure. As such, foreign countries like to be associated with a product easily visible to others, as compared to a part hidden behind some panels deep inside the aircraft.

4) Doors are apparently considered as a "simple" product by some within Boeing: While consisting of several different parts, doors are considered by many to be a fairly simple product to manufacture, and therefore a good product for offseting outside to a foreign supplier. Also, it is perhaps viewed as a product which does not require state of the art manufacturing skills, meaning it could be placed inside a low-tech manufacturing company inside a developing nation, for example. BCAG's experience with door suppliers, however, seems to be indicating that this opinion that doors are simple products may be greatly understated.

Currently, the DRC is making plans to transition all doors to outside suppliers within the next 3 years. What function or form the DRC will assume after all doors have been offloaded is still being studied and identified.

2.5.5 Labor Force / Union Issues

> *The truth is, working with foreign suppliers to secure international business creates jobs at Boeing. More than 85% of the jobs created by foreign sales stay in the United States" Bob Dryden, BCAG Executive Vice President for Airplane Production* [6]

> *Our membership wants to make sure that they will continue to be employed at Boeing in the future and are willing to go to any means to achieve that. The company is selling airplanes and making money, and we want the members to also share in the prosperity." Bill Johnson, president of IAM District lodge 751, representing the majority of IAM members in Washington* [7]

> *"By helping the Chinese ... one striking Boeing worker says, "we're cutting our own throats".* [8]

With the notification that the buy percentage was being increased from 48 to 52% over the next two to three years, the major concern of the hourly work force shifted to job security, and loss of jobs to oversees contractors. The union representing the majority of hourly workers, the International Association of Machinist (IAM), took the official position that they wanted to see an end to all offset activity, blaming it in part for the large decline in jobs forecast for the aerospace sector. The IAM often referred to a study by the Washington DC based Economic Policy Institute which reported that nearly 469,000 U.S. aerospace jobs could be eliminated by 2013 because of increased foreign competition and policies that allow Boeing and others to exchange jobs for new aircraft orders, i.e. offsets. This study went on to recommend that the U.S. government should negotiate a new civil aircraft agreement between all the major aerospace companies, both domestic and foreign, which prohibits any of these companies from exporting jobs and technologies as a means of gaining market access.

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[6] The Boeing News, November 10, 1996
[7] Valley Daily News, September 5, 1995 page C-1
[8] Wall Street Journal October 13, 1995 page A-2

Boeing countered by saying that only 1,910 jobs had been lost at Boeing as a direct result of subcontracting work to foreign contractors. Boeing's position has remained that the above proposal is too simplistic, in that it fails to address the complicated political, financial, and cultural issues involved in today's global market for civil transport aircraft. Boeing has also hinted that the job loss forecast above is unrealistic, and fails to properly account for the real sources of any lost jobs.

With this issue of job security and offsets remaining in clear focus, the IAM membership rejected Boeing's initial 3 year bargaining offer on October 5, 1996, and went on strike that same evening. They later rejected a second proposal on November 21 (which had been unanimously endorsed by local union management for approval), and finally ratified a 3rd offer on December 14th, ending a 69 day strike.

Although job security was only one of the issues involved in the strike, as mentioned previously, it was one of the most critical issues. The language of the first proposal contained this language in addressing the issue of offsets and subcontracting:

"In order to provide the Union with more information regarding subcontracting, briefings will increase to twice a year and will include the Company's Make/Buy plans. The union will be given advance notice of major Buy decisions and the opportunity to make proposals to keep work in-house. On-site subcontracting of production or tooling work will required approval of senior management and advance notice to the Union and employees"

The language of the third contract offer which was ratified, is included in the appendix as exhibit #1. It is obvious that the Union was able to negotiate a much stronger position on this issue of subcontracting as a direct result of its membership willing to remain on strike for 69 days.

2.5.6 DRC Employee Status

Prior to the strike, the main concern of the majority of the hourly employees at the DRC was what was going to happen to their jobs as a result of the decision to transition all of the doors from make to buy. The looming issue of how to accomplish this transition from make to buy was not as pressing an issue. After the strike was settled, and the workers knew that they would not become unemployed as a result of this decision to offload doors, the morale began to improve.

The morale of the work force was critical, in that the DRC management considered the involvement of the production work force as being critical for a successful transition of doors from make to buy. Their plans included not only sending hourly personnel to the subcontractors factory for training and on-site assistance, but also bringing in supplier employees into the DRC to allow training to occur concurrent with production efforts. Both of these efforts were considered vital, as the DRC realized that in it was critical to transfer the production knowledge contained in the Boeing work force, to the subcontractor's production force. Without this knowledge transfer, the transition would come at a greater cost of both lead-time and product quality. If the hourly workers were more focused on the loss of their jobs, than in aiding in this transition, the DRC realized that this knowledge transfer would become more difficult, if not impossible.

2.5.7 Chapter Summary

BCAG is facing a market characterized by vast demand for future product, but also an ever increasing supply of global competition. Boeing is responding by attempting to make its products faster, and at lower cost. By attempting to implement this by putting more work to be fabricated outside BCAG, they face the added obstacle of a work force concerned with the issue of job security. One subset of this whole scenario can be found at the Renton DRC, which will loose all of its products to the outside within 3 years. It is within this environment that an alternative methodology for the use of key characteristics will be studied.

3.0 Key Characteristics at Boeing

As mentioned previously, two programs at Boeing, AQS and HVC, make use of the concept of key characteristics. This was the beginning of the use of keys, and their use has spread throughout the company, as well as to several of its suppliers. The creation of keys was a direct response by Boeing to deal with hardware varitation, or as defined by Boeing, variation around the nominal value.

3.1 History of Efforts in Reduction of Hardware Variation at BCAG

The late 1980's characterized a time when Boeing began addressing earnestly the issue of rework existing in its manufacturing and assembly lines. One of the root causes of rework, hardware variation, was quickly targeted as a focus of attention. Concurrent, yet separate efforts were being made to address this issue at several of Boeing's different factories, as well as on different product lines at the same factory.

The issue of hardware variation was also identified as a source of concern for parts coming from suppliers external to BCAG. This issue was addressed head on by the Materiel organization, which is responsible for coordination of the specification, purchase, and buy-off of parts from outside suppliers. In 1991, Materiel began implementation of the Advanced Quality System, or AQS. AQS was developed through coordination with Ford Motor Company and General Motors as a means of assisting their supplier base with achieving product quality. This system referenced an internal spec, D1-9000, for suppliers to follow as a means of reducing hardware variation. AQS referenced the use of several different tools for use over the entire product life spectrum, from product design to product assembly. In addition to discussing items such as Statistical Process Control, the AQS program also introduced the suppliers to the concept of key characteristics.

With the release of the AQS program, the operations side of BCAG felt that it was now necessary to coordinate the different programs at each site or each product line that were addressing hardware variation. As such, in October of 1993, the Hardware Variability Control program (HVC) was formally introduced. HVC was released as a division wide program for BCAG. HVC came to be closely associated with the development of the 777 airplane, but this is somewhat of a misconception. The 777 design had been underway prior to the release of the HVC program. As such, the 777 program embodied some of the elements of HVC, but not the entire HVC methodology. The new 737-X program currently underway at Boeing, which represents the 737-600, -700, and -800 models, is the first new airplane program which was launched using the HVC methodology. Even on this program, however, the level of methodology of HVC has been inconsistent from one component to another.

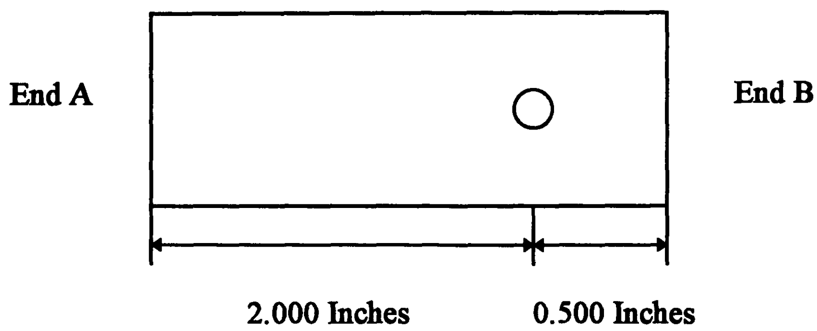
The current strategy at Boeing is to try to merge and combine both AQS and HVC, as well as the Hardware Variability Reduction (HVR) program practiced by Boeing Defense and Space Group, into one aligned methodology for practice by both Boeing and its suppliers for use in reducing hardware variation. This student was unable to reference any timetable or plan for this activity, however.

3.2 Overview of the HVC Program

HVC as a program teaches that the process for reducing hardware variation is one which stretches from collection of the voice of the customer, all the way through to the final quality inspection buy-off. It states emphatically that reduction in hardware variation cannot be accomplished solely on the factory floor. The main precepts of HVC are as follows:

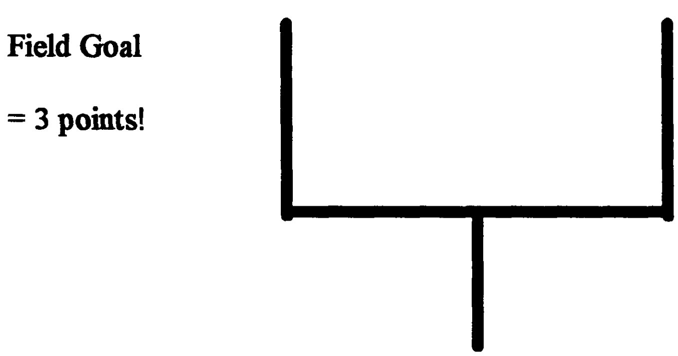
1) Coordination of indexes and datums: Without commonality of datums and indexes, errors can be made in the proper measurement of part or tool dimensions, which can act together with tolerance stackup, to create a large component of hardware variation.

A simple example of this is shown below:



Assume that the critical dimension is the location of the hole centerline 2 inches from end A. As such, one datum for this part is located parallel to end A. However, if the part is loaded into a tool such that it is indexed at end B, the dimension to be measured will likely be the .5 inch dimension. This measurement, however, does nothing to guarantee that the hole location is properly located with respect to end A, the critical dimension. This indexing or measurement step did not insure proper location of the hole, allowing possible variation in necessary hardware dimensions to be passed down the assembly line.

2) Implementation of continuous loss curve mentality: Prior to this adaptation, the image of tolerance measurement was viewed with a "Goal Posting" Mentality.



Consider the ends of the goal posts to be the range of the tolerance interval. Then just as in football, as long as a part's dimension fit in between the legs of this goalpost, the part was good (field goal =3 points!). It didn't matter if the part just barely cleared one of the upright legs, or split the middle; it was equally as good.

HVC implemented the idea of Taguchi loss curves, which says that deviation from nominal is a continuous function, with quality loss cost growing typically exponentially with increasing deviation from nominal. So unlike the goal post method, where one part just inside the upright is good, and another part just outside the upright is bad, the Taguchi loss function says that these parts are basically identical in terms of quality loss cost.

3) Implement HVC as part of a Plan-Do-Check-Act (PDCA) cycle: The PDCA cycle introduced by Dr. Edward Deeming has been chosen as HVC as the ideal implementation method. HVC prescribes two different PDCA cycles, one for existing programs, and one for new programs. Two different cycles were required, because HVC focuses a majority of attention during the product design process, which several different studies have shown can lock in up to 80% of the final product cost. On the existing program cycle, the continuous quality improvement aspect of the PDCA cycle is emphasized.

4.) Heavy use of Integrated Process Teams (IPTs): HVC made it clear that the proper format for this methodology was in a multi-team environment. The majority of the decisions, from design through final assembly, were to be formulated by IPTs. This decision was simply paralleling the mood within Boeing at the time, that the transition to IPTs from the traditional serial method of decision making was the proper step. As such, decisions over which datums and indexes to use would be done by an IPT involving design engineering, tooling, manufacturing engineering, manufacturing, and also quality inspection.

5.) Use of Key Characteristics for communicating customer requirements throughout the design and manufacture / assembly process: This concept of key characteristics is described in detail in the following section.

3.3 Key Characteristics as part of HVC

One of the critical elements within HVC is the identification and generation of key characteristics. HVC defines key characteristics as follows:

"Attributes or features of a material, part, assembly, installation or system in which variation from nominal has the most adverse affect upon fit, performance, or service life."

Key characteristics are specifically intended as a means for indentifying those attributes or product features which are critical to the customer at the finished product level, and then relaying these attributes down through the entire product assembly steps, including the detail part level. Keys therefore allow all organizations of a corporation to be able to understand and focus on those elements which are of primary importance to delivering promised product requirements, and hence delivering customer satisfaction. Keys essentially link product features to customer requirements.

Within the context of HVC, all key characteristics must be directly associated with ability to deliver a customer requirment. As defined above, for BCAG these fall under either the categories of fit, performance or service life. Fit deals how well the airplane joins together. Examples would be keel beam location, gap at mating surfaces etc. Performance is associated with how well the airplane will perform in the air, as well as dealing with structural and cosmetic issues. Examples would be contour of the airplane or wing sweep, as these items can have a negative contribution of the net effect factor, or in other words, aerodynamic drag. Boeing pays penalties to its customers for planes with excessive drag, as drag results in excessive service and operating costs. Service life deals with the performance of the plane with respect to maintainability, airplane life, corrosion, repair issues etc.

The above key characteristics are usually classified as Product Keys under HVC. Product key characteristics can apply to several different product requirements. While the majority of key characteristics apply to dimensional measurements, they can also include other physical properties such as weight or porosity, chemical properties such as surface roughness, anodizing quality etc., or even electrical properties, such as the level of allowable noise in the output of a power supply. Output of an engine in pounds thrust could be a key characteristic, as could air flow provided by a cooling fan in an electronics rack. One aspect that all key characteristics share in common is that they must be measurable.

Once keys have been identified, they are added to the engineering drawings, and highlighted by a flag note entitled KEY. In addition, each key is given its own specific numeric designator. Keys are intended to be added to drawings prior to DCN formal release of the drawings.

In addition to Product Keys, a second class of keys is defined under HVC, these being Key Process Parameters. These type of key characteristics refer to process parameters which are identified as being critical in order to meet upper level customer or product requirements. An example could be the drill bit speed of a CNC drill, or the temperature of a chemical milling solution etc.

HVC defines the procedure for generating product keys as follows:

1) Identify top level customer requirements: As mentioned above, these fall under one of the three previous categories. A partial listing of some these requirements is as follows:

Service ceiling	Speed	Crew Commonality	Range
Fuel Consumption	Gross Takeoff wght	Noise	Cost
Takeoff Distance	Engine Thrust	ETOPS	Reliability
Spares Commonality	Recurring Costs	Appearance	

These top level customer requirements are then used to generate the top level product keys. These upper level product keys refer to features associated with the final product, and are included on the drawing entitled "Airplane Integration Plan", or AIP drawing. An excerpt from this AIP drawing is included in the appendix as figure #2.

2) Flow down of upper level keys to detail part level: In this step, these upper level keys are "flowed down" to the next level of subassembly on the engineering tree. Essentially, the determination is made is which product features of this subassembly are critical for delivering the keys at the next higher level on the engineering tree. This same process is then repeated for the next level down on the engineering tree, until the upper level keys have essentially been flown down all the way to the detail part level. Again, each key identified on a sub assembly or a detail part, must be able to be linked to an upper level key and customer requirement. These lower level keys can be called sub keys. Concurrent with flowing down of the key characteristics, commonality of datums and indexes would also be flowed down.

Processes used for identifying which aspects are critical include risk assessment tools, fishbone diagrams, part rejection tag history, loss functions, use of part, or experience and intuition. Essentially, each potential key can be examined to see what the potential risks or effects would be on the upper level keys, should this potential key fall out of tolerance.

3) Generation of manufacturing, tooling and measurement plans: Once the keys have been identified, the above three elements, which comprise the build plan, can be finalized. The build plan essentially specifies the order of steps in which the particular product or subassembly will be built, specifies tooling methods and indexes, specifies plan and methodology to be used to measure the keys, and calls out any general or specific installation details. The measurement plan describes how and when each of the key characteristics are to be measured. As each key is measured at least once for each part; the measurement plan tells where in the build process to measure it, how to measure it, and what to do with the measurement. Several of the key characteristics need special fixtures or measuring devices in order to allow this measurement to be conducted. The preparation of the measurement plan is critical, as several keys if not measured early on in the process, may become impossible to measure later due to physical constraints, other parts blocking the item to be measured etc.

The identification and generation of Key Process Parameters can be done in a similar fashion, but rather than flowing down from upper level keys, these Key process parameters are identified by use of some of the same techniques used to define the Product Keys, including intuition and experience. In addition, the IPT can study the different sub keys and determine which process parameters are critical for delivering these sub keys.

3.4 Chapter Summary

HVC since the early 1990's has been the primary tool chosen to combat hardware variation, and its resulting loss in customer satisfaction. HVC prescribes several methods and tools to use as a means of reducing hardware variation. Chief among these of interest for this thesis are the tool identified as key characteristics. Keys within HVC are identified as either product keys, corresponding to measurable attributes of the detail part or the assembly, or Key process parameters, which are those which have been determined to be the critical parameters for achievement of the process.

In the next chapter, this HVC methodology will be contrasted to an alternate methodology for the generation and use of key characteristics.

4.0 Alternate Key Characteristic Methodology

The preceding chapter showed Boeing's current knowledge and implementation of keys. This format, however, is not state of the art when comparisons are made to other industries. This chapter introduces the reader to an alternate method for identification and classification of keys, which has as one of its potential applications the use for reduction of hardware variation.

4.1 Description of New Methodology

The use of key characteristics, which had its roots essentially in the automotive industry, has spread to other industries other than the aerospace industry. This allowed the use of key characteristics to be further studied and defined, so as to allow further improvements to be made in their application, as well as the process used to implement key characteristics.

Recently, research work being conducted at the Massachusetts Institute of Technology, has resulted in an improved methodology for the use of key characteristics. Several articles have been published relating to this new methodology, and are referenced in the bibliography.

The major advances put forth by this new methodology address two major issues:

1) Definitions and Classification of key characteristics,

2) Improved method for generating and identifying these key characteristics

This thesis will focus primarily on the first issue, an alternate methodology for the classification and use of key characteristics.

4.2 Key Characteristic Definitions:

This new methodology essentially recognizes four different categories of Key characteristics: Product Key Characteristics, Assembly Process Key Characteristics, Manufacturing Process Key Characteristics, and StatKC's. These four categories of key characteristics are identified and defined in an article by Don Lee and Anna Thorton of the Mechanical Engineering Department of MIT, written for a August 1996 ASME conference. Henceforth, the term "key" may be used interchangeable with the term "key characteristic"

4.2.1 Product Key Characteristics (PKC)

Product keys are defined as follows:

"These keys are a set of a product's features that are highly constrained or for which minute deviations from nominal specifications, regardless of manufacturing capability, have a significant impact on the product's performance, function, and form at each product assembly level. PKCs are permanent for a given product design decomposition and set of requirements"

The PKCs are linked to those product features which deliver the desired customer or performance characteristics. As per the definition above, the critical distinguishing feature of PKCs is where minute deviations from nominal can have large impacts on customer satisfaction or product performance.

The following example helps demonstrate this concept. Consider a simple cylinder of radius r and length L. Assume that the volume of the cylinder is of critical importance to the customer. As volume in this case would equal $3.14 \times (r^2) \times L$, it is obvious that variations in r will have a much greater impact on volume than would variations in L. As such, here r would be a PKC in comparison to dimension L.

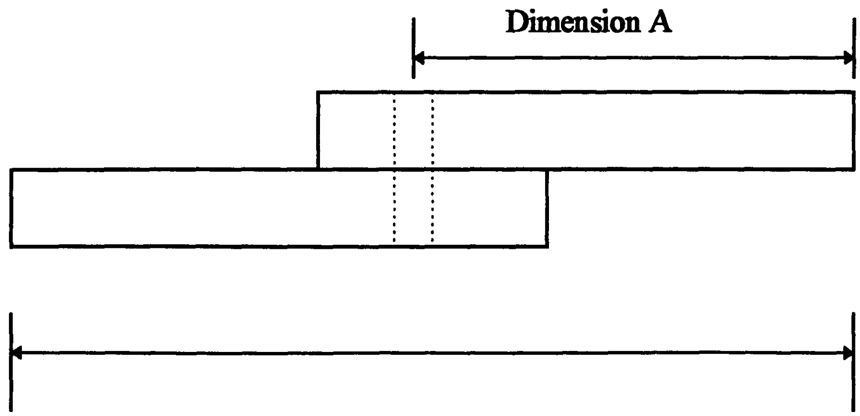
4.2.2 Assembly Key Characteristics (AKC)

Assembly Key Characteristics have the following definition:

"Assembly keys are the features during each assembly stage on the product, tool, fixture, or procedures that significantly effect the realization of a product KC at the next higher assembly process level. AKCs are permanent for a given assembly process and product design decomposition.

The critical factor to understand for AKCs is that the function or significance of these keys is only visible when viewed in light of the assembly process. These keys also must be viewed in light of their ability to affect the next level PKCs.

Consider an assembly made up of two plates as shown below:



Assume that the overall dimension of the finished assembly is of critical importance to the customer. In such a case, one would assign a PKC to this overall length. Also consider that the two pieces will be joined in the assembly process by means of bolting them together through their respective two holes. Here, the dimension of the holes in each plate, such as dimension A, could be considered as AKCs. This key characteristic depends entirely on the method of joining these two detail parts together. For example, if the decision was made to weld the parts together, and the bolt was eliminated, then dimension A would cease to be an AKC, as it no longer had any effect on the PKC, the overall length of the assembly. The importance of dimension A becomes apparent when viewing the assembly process; here it is possible to see how dimension A is involved in delivering the assembly level PKC. This would not be possible in viewing just the detail drawings for one of the separate plates. The importance of dimension A becomes apparent only when viewing the assembly, and this critical nature is dependent upon the method of assembly.

4.2.3 Manufacturing Process Key Characteristics (MKC)

Manufacturing Keys are defined as follows:

These keys are the manufacturing machine process parameters and/or fixturing features for machine tools and equipment that significantly effect the realization of a product or an assembly process key characteristic at the detailed part feature level. MKCs are permanent for a given manufacturing process and product.

Such a key characteristic applies here to the actual process used to create the detail part or the assembly. As mentioned, it can be either process parameters, fixturing features, or even perhaps a specified order in which to do certain assembly steps. Examples of process parameters which may be keys are spindle speed and feed rate for drilling a hole whose dimensional tolerance is a PKC. A tooling fixture may have a set of indexing points whose alignment may need to be carefully measured in order to be able to deliver the upper level PKCs for the assembly. And lastly, the specified placement of parts in a tooling jig could be a potential MKC.

4.2.4 StatKC

StatKCs have the following definition:

This is a subset of the above keys that add significant risk to the successful delivery of the product because the PKCs cannot be properly created at the required cost, quality, and/or schedule. StatKCs are eliminated when the PKC problems are permanently solved.

StatKCs are typically PKCs. The name was essentially derived from the term "stat" in a medical environment, which essentially means that it needs attention now. A StatKC would be a PKC which is in trouble of being delivered, and hence, a customer requirement is at risk. StatKC designation is a way for an organization to highlight those PKCs which currently pose a significant risk for customer satisfaction, and hence allow the organization to focus its attention on these particular keys.

4.3 Contrast of Alternate Methodology to Boeing Methodology

This alternate methodology, which henceforth shall be referred to as the "quadkey" methodology, has several characteristics which are similar to those of HVC. Both programs link keys to upper level customer or product requirements. They also are defined permanently for a given product assembly. These keys may only change if the assembly method, part design , tooling, tooling, manufacturing process, or customer requirement changes. Both programs realize the importance of manufacturing process parameters in the ability to deliver upper level keys.

The quadkey methodology of key characteristic classification, however, has two major areas of difference when compared to keys under BCAG's HVC:

1) No keys identified as AKCs under HVC

2) No prioritization of keys such as those identified as StatKC

For the purpose of this thesis, StatKCs will not be an item of focus. In order to determine or identify a key as a StatKC implies that some knowledge is available with respect to being able to achieve the PKCs which have been identified for the part or product. For the purpose of this thesis, no production data is available for the item of study; therefore there can be no identification or measurement of StatKCs currently.

4.4 Chapter Summary:

The quadkey methodology of classifying and identify key characteristics was formed out of research done in part at the Massachusetts Institute of Technology. This methodology defines a hierarchy of keys consisting of PKCs, AKCs, MKCs, and StatKCs. This broader classification of keys offers several advantages compared to the procedure espoused by HVC. In the next chapter, an assembly and installation operation will be studied in order to show an example of this new methodology at work, as well as allow some discussion to take place regarding the relative merits of this new methodology.

5.0 Example of New Methodology Applied to Forward Entry Door of 737-700

The 737-X is the designation for the new -600, -700, and -800 models of the 737 airliner. The 737 a few years ago became the most popular commercial airplane model ever, and Boeing anticipates that these three models will only serve to further advance that claim.

The 737 will incorporate several new technical advances compared to its older cousins. This applies not only to product features, but also assembly methods used to fabricate the product. This includes a brand new wing responsibility center tooling area, new flexible tooling for several manufacturing steps, additional automation, and some hole to hole assembly steps.

The Renton Door Center is also changing as a result of the 737- X program. Some doors will be fabricated with limited hole to hole assembly methods for the first time. Several door parts were redesigned using Design for Assembly (DFA) methodology, such as combining several sheet metal parts into one machined structure. Also, the DRC pursued heavily the use of a monolithic cast structure for the new over the wing exit hatches, but this design was recently rejected by the 737-X chief engineer for fear of possible crack propagation issues.

Because of the above reasons, the vast majority of doors for the 737-X were redesigned as compared to doors for the previous models. This decision to redesign the doors provided the DRC the opportunity to incorporate the use of HVC in support of a new product design. As such, this was the first real chance for several of the designers to utilize HVC and its methodologies and tools.

5.1 Forward Entry Door

The product which was chosen for study is the new Forward Entry Door (FED) for the 737-X. The FED is a pressurized door, and is the forward door used for loading and unloading of passengers. The design of the door is similar to other 737 doors, in that it still is a two hinge design, as compared to the 777 which introduced Boeing to the single hinge door. The door is essentially still a "plug" design, in that the door, even though it swings out, then swings back inside through the door opening and seals it from the inside, essentially forming a pressurized plug.

The design of the door is currently being finalized; the engineering drawing tree was still not completed, nor available for review. Detail part fabrication is still several months away for current production requirements. Design of the tooling fixtures has been completed, and some tooling is currently in production For the FED, prior to its transition to buy status, several of its detail parts will be manufactured within BCAG, but outside suppliers will also be heavily utilized.

Airplane doors are actually fairly complex items, consisting of well over 100 different parts. Like all airplane entry and exit doors, the door must be designed to withstand a crash, and still allow the door to open. The door operation must also be such that a 5% female (a woman in the bottom 5% of height and weight) can be able to open the door even when the fuselage is at a 10 degree tilt, in the event of a landing gear failure. Also, the door must be able to be opened by the same female when one quarter inch of ice is coating the door. In comparison to auto doors, which is often considered the toughest part of a car in terms of meeting fit and finish requirements, airplane doors are levels above in complexity. Unlike auto doors, which could fall off and still allow the car to drive properly, airplane door failure puts the plane at risk of not returning. The requirements on doors by the customer, as well as the FAA, are consequently very rigorous.

Another critical requirement placed on doors is the Interchangeability and Replaceability Requirement (I and R), which are listed on the Master Control Drawing for the FED. In a specification dating back to military customers, and spreading to the civil airliner industry, Boeing's airline customers require that all doors be I and R. This would mean that any door from stock would be able to be installed on any of the correct model airplane. This would be critical in allowing quick plane turnaround in situations where the door may be faulty or become damaged. Each of the DRC's products have I and R specifications attached to them. Unlike key characteristics, if the finished door does not meet the I and R requirements, the door is not shipped to the rigging assembly step. Keys are measured, but in the case of the FED, the door is not held back from shipment if a key is out of tolerance. However, several, but not all, of the I and R requirements are also key characteristics. These I and R requirements have been used by Boeing to insure customer requirements have been met long before the addition of key characteristics to Boeings tool box.

5.2 FED Gates

The FED door, as mentioned previously, is a plug design meaning that it seals from the inside surface. This means that the pressurized cabin assists the door in making the final seal. Because the door swings outside the plane for loading and unloading, this means that the door must twist somewhat sideways to allow the door to pass from the cabin side of the plane to the outside, or vice versa. In order to facilitate this motion, the FED is equipped with both an upper and lower gate assembly.

Both the upper and lower gate assemblies are attached to the top and bottom of the door by means of a hinge between the gate and one of the door's structural beams. As an indication of how similar the two gates are in operation, sections of the hinge assembly are identical for both gates. These hinges allow the upper and lower gates to fold in towards the cabin side of the door.

Figure 3 shows an older model FED with the lower and upper gates installed. The FED is designed to be opened by means of rotating a centrally located handle. When this handle is turned, it releases the door from its locking lugs. At the same time, another actuator folds in both gates. This greatly cuts down on the length of the door, and allows the door to be easily maneuvered through the door opening. Conversely, when the door is closed, the gates fold out when the door is locked in place, allowing an even tighter seal or plug to be created.

For the purpose of this thesis, only the lower gate assembly will be studied, The analysis for the upper gate assembly would be quite similar, as the design, function, and mounting of the two gates is quite similar.

The following figures are included in the appendix for reference during the discussion of key characteristics. For clarification sake, BCAG will typically have three levels of drawings for a sub-assembly which is mated to another unit during an installation or higher level assembly process. The first is a detail drawing for each of the parts in the sub assembly. The second level is an assembly drawing, showing all of the detail parts being joined. The third level is an installation drawing, showing the subassembly being joined to its mating part(s). Therefore, Figure 4 shows the detail drawing of the lower gate. This drawing actually functions as the assembly drawing for the gate also, as in the case of this casting, it can be a one piece casting. In this case, the decision is up to the supplier how to handle the required bushings; the supplier can either cast them in, or add them later. Therefore it is both a detail and assembly level drawing. This drawing is called the "Gate Assembly - Lower, Forward Entry Door". Figure 5 is the installation drawing for the lower gate with respect to attachment to the FED framework, and is entitled "Lower Gate Installation, Forward Entry Door.

Figure 4 shows the drawing of the lower gate assembly. The lower gate is a one piece part which is made by sand casting by an outside supplier. The drawing just specifies that the part be cast, allowing the supplier to make the decision whether the part be made via sand casting, die casting, or investment casting. The material of the lower gate is aluminum. Previously, all gates on 737 doors were made from magnesium. However, for the FED, the decision was made to go with aluminum for improved corrosion resistance. Also, the aluminum gate is only about half the thickness of the magnesium gate, but the weight savings is essentially null. As a sign of the magnitude that such decisions carry with respect to material, the other 3 loading doors on the airplane, designed by the Wichita Door Center, are still designed to use magnesium gates. The last major redesign included was enlarging the hole sizing in the lower gate webbing for easier maintenance access. This again was significant as it likely involved recalculating the stresses found in the entire gate assembly.

5.3 Product Keys for Door and Gate Assembly as defined by HVC

As this was the first use of the HVC methodology on a new product design by the Renton DRC, it was natural to expect that there would be a learning curve. Consequently, it took a little over 5 months for all parties involved in the IPT team to agree on the datums to be used for all the different doors, and finalize the coordination of all the different indexes with these datums.

An IPT was also formed to identify the key characteristics for the FED. Per the HVC procedure, the first step was to identify the top level customer requirements. These again were obtained from a drawing entitled the Airplane Integration Plan (AIP) drawing (For clarification sake, the methodology used to generate the keys at the AIP drawing level is likely viewed to be proprietary; therefore no mention will be made how the keys are selected to appear on the AIP).

5.3.1 Fair and Gap Key Characteristics

The only two key characteristics assigned to the FED on the AIP drawing are the keys of fair and gap. These would fit under both the categories of fit and performance in HVC's definition of key characteristics. Gap is concerned with the distance between adjoining elements, and is usually referenced with regards to the outer skin edges or surfaces.

Fair relates to the flushness of the outside of the door, especially at the interface point between different assemblies, skin panels etc. Figure 6 shows an example of some misfairings that are of particular concern to Boeing.

Both Fair and Gap were essentially identified as "dual" keys, important because they affected two critical product features or customer requirements. The first feature is the structural integrity of the airplane, as well as its cosmetic appearance. The same excessive gap which could look very unappealing to a customer is the same flaw that could represent a potential area of weakness in the structure.

The second feature or customer requirment concerns the Net Effect, or drag of the airplane surface. Drag is an item of paramount importance both to Boeing, as well as its customers. Boeing contracts often call for Boeing to pay drag penalties to airline customers where the airplane drag exceeds specified limits. Figure 6 is derived from a BCAG document showing yearly fuel tradeoffs caused by the shown misfairings; the numerical tradeoffs have been deleted for proprietary reasons. In simple terms, steps, gaps, and bumps cause drag losses.

In analyzing these upper level keys, the IPT at the DRC essentially created several other equivalent keys relating to gap and fair; these include the other key characteristics identified as contour, periphery, and flushness. Whenever these terms are seen on design drawings as key characteristics, they can be considered essentially as fair or gap key characteristics.

With respect to the gap key for the FED, the master control drawing when released will actually show two measurements for gap (dimensions not shown for proprietary reasons). One dimension is called the maintenance manual allowance, and is the maximum gap allowed up the customer. A second dimension is called the rigging documentation allowance, and has a smaller tolerance. The factory must meet the tighter rigging allowance, which will insure that the gap will fall within the customers acceptance limits.

5.3.2 Additional Upper Level Key Characteristics for the FED

Although the AIP drawing only specified fair and gap as keys, and these keys were used to generate the other keys of contour, periphery, and flushness, the DRC IPT decided that additional upper level keys were necessary to fully capture the critical product features and customer requirements.

Consequently, the DRC developed the following list of additional keys:

Weight	Door Opening Force	Corrosion
Torque Tube Alignment	Door Stop Location	

These additional upper level customer requirements were determined by the IPT. These keys evidently included customer requirements gained from discussion with airline representatives familiar with the FED, such as airline mechanics etc.

5.3.3 Flowdown

The next step for generation of keys as explained by HVC involves the flow down process of these customer requirements down through the assembly step levels, finally ending at the detail part level. The IPT began their flowdown process for the FED, but then subsequently ran into two obstacles:

1) Inadequate training of team members in conducting a flow down process

2) Schedule, schedule, schedule

These two items essentially resulted in a heavily truncated flow down process. Keys were identified for several detail parts with no benefit of flow down from upper level keys. This was necessary in order to meet DCN design drawing release dates. Designers stated that had they attempted to do a proper flow down with their level of training, that these drawing release dates, deemed critical for the production schedule, would likely have had to slide. Indications that the flow down process had indeed been truncated included detail parts drawings containing key characteristics, but no keys being identified at the next higher level of assembly drawings. Other examples were also found where the detail level keys were not associated with the keys found at the assembly level drawings.

As a result, keys were identified for several parts, including the lower gate assembly, without the benefit of a proper flowdown procedure. As a substitute for flowdown, the IPTs relied on a combination of engineering experience, intuitive linkage of detail part features to upper level customer requirements, and input from the factory floor. This input from the factory included a list of "problem areas" encountered with previous door design assemblies. Areas were identified that required excessive rework, or which often presented quality inspection concerns. A page from this document is included in the appendix as exhibit 7.

5.3.4 Current Product Keys for Lower Gate

The final result of the above efforts by the IPT resulted in the following keys being generated for the lower gate detail / assembly drawing:

1) Periphery

2) Contour

3) Centerline location of holes drilled in 3 pairs of actuator arm linkages.

4) Location of tooling indexing points

These keys are shown in figure 4 in the appendix. These 3 keys all applied to the finished cast part, and will therefore be dependent upon the supplier to provide.

In order to provide easy reference to features of the gate, the following names have been assigned to certain portions of the gate;

Hinged surface: Edge of Panel (EOP) of section of gate mating to hinge

Seal surface: EOP of outer edge of gate opposite the hinged surface

Prior to analyzing the keys, it is important to understand where the three datums are located. These are shown in figure 8. Datum A is parallel to the part, and will essentially be used as the main reference consequently for contour. Datum B is normal to horizontal portion of the seal surface. Datum C is parallel to the outer edge of one of the center actuator arm linkages.

Periphery, as shown in figure 4, applies to the location of the outer edge of the gate assembly. Detail drawings for the gate show the periphery key called out for all outer. The periphery is essentially defined by dimensioning the radius of the two rounded corners, and locating the two parallel flat edges with respect to the datums. No keys are attached to any of these dimensions, however. Only the location of the outer perimeter is assigned as a key for measuring. This decision was made after consultation with the casting supplier.

The periphery key as shown states that all outer edges must be within .04 inches from the respective datums. Machining of the seal surface outer edge is allowable for correcting periphery issues. The drawing, however, does not give the same permission for the vendor to be able to machine the outer edge of the hinged surface. Whether this is allowed by other documents is currently unclear.

Contour is defined by three points on the exterior surface of the gate. Because the gate has curvature in two dimensions, it complicates the measurement of the contour. Consequently, the three points where datum A intersects the outer surface of the gate were chosen as critical points. However, since two of these points contact the gate away from any relative surface or registering point, these two measurement points were moved to the inner edge of the sealing surface, as shown by K1 and K3 on the drawing. In order to help maintain this contour key, part specifications include limitations on the waviness of this surface, and a specified tolerance for the location of the surface with respect to each datum. In addition, this surface can be machined if necessary to meet the contour requirements.

The centerline location of the holes in the actuator linkages is specified with two tolerances as shown on figure 4. These holes are manufactured by bored through the actuator linkages. The first dimension specifies that the first hole location bored must be within .01 inches of the location specified by the datum. The second dimension indicates that the remaining holes must be within .02 inches relative to the location of the first hole.

The last key characteristic, the indexing point locations, are not currently shown on the detail part drawing for the lower gate. They are, however, mentioned on a document used to define the tooling configuration. There are a total of 6 indexing points, following the standard 3-2-1 rule of locating indexing points on the 3 datums so as to eliminate the 6 possible range of motions (movement along or rotation around any of the 3 axis's). Three of the indexing points are on datum A, and are located on the exterior surface contour of the gate. These are listed as A1, A2, and A3 on the drawings. Two additional index points are located on datum B on the periphery of the gates sealing surface, and are shown as B1 and B2. The last indexing point along datum C is located on the side of one of the actuator linkages.

The current contract with the gate supplier specifies that the supplier is to perform the measurement of the above keys prior to shipment of the gates. Currently, the vendor is still working on perfecting the casting of the part. The supplier has referred to problems with his gating design for the product, but more detailed information was not provided to DRC engineering.

5.3.5 Current Product Keys for Lower Gate Installation

When the lower gate assembly is attached to the door frame by means of the hinge, there is only one product key shown at this installation level drawing. This key is Flushness, and relates to how flush the outside of the gate is with respect to the outer skin of the door. The flushness tolerance at this mating surface is +/- .02 inches. Flushness can be considered as a key which addresses the issue of fairing. In this particular example, a bump is just as allowable as a valley at this transition from door to gate, but this is not always the case with respect to misfairing issues.

This key, unlike the detail part keys, will be measured at Boeing. It does not get measured when the gate is initially attached to the door, however. Flushness is measured in a measuring jig which occurs at the end of the door assembly method. A detail of this jig is shown in exhibit 9 of the appendix. This jig duplicates the installation of the FED into the airplane fuselage, and the flushness can be correctly measured in an as-installed state. In this tool, therefore, the door will be subject to all the loadings and proper weight distribution that it will encounter when it is actually rigged into the fuselage of the 737-x airplane.

Flushness from this point on will now be related to the underlying support framework of the door and gate. This of course is not the final outside surface of the door against which flushness is measured. The uppermost level PKC of flushness is measured with respect to the outside skin surfaces of the gate and door. However, the skin attaches directly to the door framework and lower gate. Thus the logic that will be used in this analysis is that if the lower beam and gate surfaces are flush, the final product will be flush once the door and gate skins have been added. This is somewhat simplistic in that it ignores other aspects of skin fastening which can cause a variation in flushness, but this is a whole new topic outside the scope of this thesis.

5.4 Lower Gate Assembly Build Plan

The build plan was again assembled by an IPT consisting of design engineering, tooling, manufacturing engineering, manufacturing, and also final inspection. The build plan is one of the major plans called for under the HVC program. The measurement plan segment of the build plan for the FED is still in preparation.

The build plan for attaching the lower hinge to the door frame structure is listed below. This build sequence takes place at Floor Assembly Jig #1 (FAJ1). This FAJ is the first tooling fixture utilized for the build process, and is the FAJ used for assembly and joining of the different door frame members and beams together. Consequently, prior to the following steps, the door framework structure has already been assembled on FAJ1. Exhibit 10 of the appendix shows the approximate appearance of the door framework at this point. This means that the lower door beam to which the gate is attached has already been located and assembled with the rest of the framework

1)Load lower gate assembly into the FAJ and locate per indexes provided in the tool. Secure in position with clamps

2) Locate lower hinge assembly to lower beam by aligning edge of hinge half with edge of beam, both ends, per Drawing

3) Secure in position for drilling

4) Drill full-size fastener locations common to hinge and lower beam per Drawing

5) Drill full-size fastener locations common to hinge and lower gate per drawing

6) Remove gate assembly and identify with airplane number

7) Remove, beam side, hinge half and identify with airplane number

8) Countersink, beam side, hinge half per Drawing

9) Deburr and touch-up countersunk holes per spec

10) At the workbench, countersink the lower gate at 32 full-size fastener locations per Drawing

The gate assemblies are then sent out for additional painting and sealing work, and are not reattached to the door frame until one of the final workstations. Not only is this done for painting and sealing operations, but until the door actuator arms are installed, the gates would essentially be free to move or flop around whenever the frame was moved from FAJ to FAJ. The gate is reattached to the door once all the necessary seals have also been added.

In order to more properly understand the build process, the method of indexing the gate was examined further. The six indexing points on FAJ1 are shown on exhibit 8. The method of indexing, in conversation with tool engineers, would be as follows:

1) Place gate assembly, exterior side of gate down, so that it rests on the 3 contour points located in the tool.

2) Slide the gate back into the tool until the gate contacts the two periphery tooling stops.

3) Slide gate over to the left until the gate center actuator linkage contacts the tool index button.

4) Clamp gate into place

Thus, all 6 index points are part to tool indexing. Looking at the design of the part and tooling, this is the only real feasible order in which to index the gate. If the tooling had been designed differently, the gate may be able to be indexed differently, but that currently is not the case.

For locating the hinge with respect to the gate and the lower beam, two different types of indexing are employed. Locating the hinge so that is common to both ends of the lower beam is employing Equal Spacing Indexing. Then by locating the one hinge half first to the lower beam, and then the other hinge half to the gate, Part to Part indexing is being used.

5.5 Application of Quadkey Methodology to Lower Gate Assembly

In the previous section, the keys as determined by the HVC process were analyzed. In this remaining portion of the chapter, the same parts will be analyzed for keys, this time applying the new quadkey methodology. This will allow direct comparisons to be made between the key characteristic generation and identification methods used by HVC and the Quadkey methodologies.

In applying the new quadkey methodology to the lower gate assembly, the focus will be on just the upper level customer requirements of gap and fair. This is appropriate as these are the only two keys included on the master AIP drawing. Regarding the list of other upper level keys for the FED, such as corrosion or door opening force that were mentioned earlier, the DRC felt that none of these were applicable to the lower gate, and this will be taken as correct for the point of this thesis research.

As the installation drawing refers to flushness as a dimension relative to both the lower beam and the gate, both of these parts need to be examined in order to determine potential keys.

5.5.1 Determination of PKCs for Lower Gate Detail / Assembly and Installation Drawings

The current drawing of the lower gate installation (exhibit 5) lists the measurement of flushness as the only key characteristic. However, the detail / assembly drawing of the lower gate itself includes periphery, contour, location of index points, and hole centerline location for the actuator linkages.

If these 4 keys are indeed correct for this lower gate, then by proper flow down standards, they must be related to keys at the installation drawing level. By this token, the contour key can be taken as flowing down from the flushness key, as contour and flushness are related. However, the contour of the gate, once it has been cast and machined by the supplier, is essentially fixed until attachment of the outer skin. Contour therefore need not also be shown as a key on the installation level drawing. However, periphery does not translate at all directly into flushness. Therefore, a periphery key must be added to the installation level.

Regarding the location of the 6 index points as a key, this is difficult to ascribe the status of a key as was done under the HVC process. These 6 points correspond only to locations in space which match up to points on the FAJ1, rather than actual locations on the part. They refer to only the indexing points where the FAJ1 contacts the lower gate. It is not possible to hand a mechanic the lower gate and request him / her to measure the six indexing points; there are no physical markings. These index points bear value only in relation to FAJ1. As such, this is not a key that should be assigned at the detail part drawing level.

The hole centerline locations are an item which is solely in the hands of the vendor. It can have limited effect on flushness of the gate with respect to the door, as the mounting of the hinge will wash away most of the uncertainty associated with flushness. However, these hole locations can affect the ease with which the door opens, so they should be linked to a key characteristic at a different level of installation detail, namely that of the actuator mechanism. They can affect the flushness of the gate with respect to the fuselage, however (namely by adjusting the length of the actuator rods), but this dimension of flushness has not been called out as a key. As such, no reference to the centerline location of these holes will be made at the installation drawing level for the lower gate.

Consequently, this results with the following key characteristic being identified using the quadkey methodology:

A) Detail / assembly level drawing: The keys which will be included on this drawing are periphery, contour, and hole centerline location. The key of the 6 index points will be deleted. These three keys are all classified as PKCs by definition. This is shown as exhibit 11.

B) Installation level drawing: The two keys of flushness and perimeter will both be shown at this drawing level. Both of these will be designated as PKCs. This is shown as exhibit # 12.

5.5.2 Determination of AKCs and MKCs

Having completed this truncated flowdown, the next step will be to determine which assembly keys, if any, are critical to delivering the above PKCs. It is important to note that it is not necessary to have assembly or manufacturing keys. Rather, manufacturing keys can flow directly to PKCs. However, in the case of large or complex assemblies, assembly keys can usually be identified. However, you cannot have MKCs and/or AKCs without these relating to or being flowed down from an upper level PKC.

5.5.2.1 Detail / Assembly Drawing AKC and MKC Analysis for Flushness PKC

As the lower gate is a one piece cast part, there are no AKCs for the lower gate itself. For the actual manufacturing of the cast lower gate assembly itself, conversations with the part supplier have indicated no major problems, other than designing the gating and riser system for the part. This is common to cast parts, and it appears that this is just a normal part of their development efforts. The fact that Boeing allows them to machine surfaces to obtain contour and periphery keys is also a great assistance in allowing them to deliver those PKCs. No AKCs, therefore, will be identified on this detail / assembly drawing.

Regarding the key for the location of the holes in the actuator linkages, this is just a fairly straightforward boring operation. Likely, there may be some process parameter for boring operations that is found to be a global key for all boring operations, such as drill speed etc. But for the purpose for this particular component, there appear to be no MKCs specific for just the lower gate detail part.

5.5.2.2 Installation Drawing AKC and MKC Analysis for Flushness PKC

At the lower gate installation level drawing, in order to determine the existence of manufacturing or build keys, the first place to begin was to analyze what was critical to delivering the PKCs of flushness..

After analyzing the drawings and the build plans, the following items were determined to have a potential effect on flushness.

1) Relative location of lower beam to lower gate when hinge halves are match drilled.

2) Match drilling hinge

3) Tolerance of the hinge assembly and the hinge pin

4) Variation in hole size when drilling lower beam and gate

5) Robustness of tooling

Each of the above items will be addressed in order in the following analysis.

Relative spacing of lower beam and lower gate

As the lower gate rests on three index points in the FAJ1 tool, its exterior surface location is fixed by the tooling. It is then clamped into place such that the gate continues to contact all of the index points. Likewise, the door frame superstructure is also clamped in place in the tool. However, the key of flushness is determined not so much by the absolute location of the outer surfaces of the lower beam and gate, as it is by their relative location. Their relative location will determine the relative attachment of the hinge halves to the lower beam and the lower gate, and hence flushness.

Once the gate is clamped into the FAJ1, a preliminary check should be possible to see how the lower bean and gate are aligning with each other with respect to flushness. Essentially, this would be determined by checking to where the outer, lower edge of the lower beam is resting relative to the gate. However, if the location of this outer edge of the lower beam is not flush with the gate at this step of the build plan, then the key characteristic of flushness could be jeopardized. Therefore, the location of this edge or line in space is a critical feature to deliver the key characteristic of flushness. See figure 13 in the appendix which shows the edge in question (this edge will be referred to as the "mounting edge" for clarity sake).

The dimension which is critical is the location of this mounting edge relative to the gate. Ideally, it would be preferable to locate this edge relative to the tool, but this appears difficult when looking at the drawing for FAJ1. In addition, it is not only the location of this mounting edge, but also its parallelism with respect to the gate that can affect flushness. As the gate is fairly rigid, if the door edge is not parallel to the gate in the tool, flushness problems can also result.

In order to embrace the above two critical aspects, that of the relative location of the mounting edge with respect to the exterior surface of the gate, as well as the parallelism of the mounting edge with respect to the tool, a new AKC will be created. This key should include two reference points on the beam, for example, one located 1/4 along the beam length, and the other at 3/4 of the beam length, and both situated on the beam edge. The key would be specified as follows:

> **Lower Beam flush with gate within +/- .02 inches at each of the two reference points.. In addition, each dimension must be within .0100 inches of the other dimension in order to insure parallelism of the lower beam to the gate.**

This above key, being critical to delivering an upper level PKC, is therefore an AKC. It is not itself a PKC, because it is a not of itself an ending goal or objective. It is rather an enabler of the upper PKC; it as an intermediate step critical to the realization and delivery of a PKC. It should also be noted that the importance of the mounting edge relative location in the tool was not apparent until the build plan and tooling fixtures were examined. Therefore, it arose out of analysis of the assembly process. It is not a key which the designer could have identified while the lower gate or lower beam was being designed, because at that time, no real knowledge of the assembly tool or assembly process was existing.

Match Drilling Hinge

The first step of the build plan specifies how to place the hinge with respect to the lower beam. This hinge is placed such that there is equal spacing on both sides. This is a critical step to insure that the hinge is located properly with respect to the door so as to allow proper fitting and sealing in the door opening. However, it does not affect the PKC of flushness.

The next step is to match drill the one of the hinge halves to the lower beam after clamping the hinge in place as above. The next step is to then match drill the other half of the hinge to the lower gate. According to some of the IPT members, they feel that this order of drilling is not critical, and could be reversed.

However, further discussions revealed that on previous door models, the hinge used to be shipped pre-attached to the lower gate. This practice was rejected, however, when it was found that significant rework could be eliminated by match drilling the hinge as specified in the above step.

When the gate is shipped with the hinge attached to the gate, it eliminates the possibility of match drilling both hinge halves relative to both the lower beam and lower gate. This pre attachment of the hinge to the gate resulted in problems with flushness between the gate and door. It therefore appears that this step is of significant importance to delivering the PKC of flushness. If the hinge halves are match drilled relative to both, the lower gate is constrained with the motion of the lower beam. Therefore, if the lower beam shifts when removed from the tool due to springback, etc. the lower gate will also move with it, therefore allowing relative flushness to be maintained.

Therefore, as this match drilling is critical to delivering the flushness key as proven by past history, this embodies an additional key characteristic. However, the definition of both MKCs and AKCs tend to point toward the usage of numerical quantities as keys, with the concept that keys can be measured. In this case, however, we have an method and order of assembly steps which has been shown to be critical to delivering flushness. This key can't be physically measured, but it can be physically checked and verified. This does, in a sense, fulfill the idea that keys can be measured.

This key characteristic can then be stated as follows:

Match drill hinge halves to lower beam and lower gate, with lower beam being drilled first

This key, in the author's opinion, belongs more in the realm of MKC rather than AKC. In this example, this MKC is linked to delivering a higher level PKC, rather than an intermediate level AKC.

Tolerance of the hinge pin and hinge assembly:

The tolerance of the hinge pin and the hinge assembly play somewhat into to the issue of flushness. If the hinge pin and the web of the hinge is designed and assembled with excessive slop, the PKC of flushness can be compromised. However, currently there is no key assigned to the hinge assembly.

The members of the IPT felt, and still feel, that the tolerance of the hinge has been found to be more than sufficient to prevent any possible problems with flushness. In addition, the gate actuators will help take out any play residing in the hinge. As such, this current assembly will not be assigned any AKCs. However, if this was a total new design or one which Boeing had no previous experience with, an AKC could be assigned to the hinge as it is one of the players in determining the flushness of the gate to door mating interface.

Variation in hole size when drilling lower beam and gate

As the current build plan specifies, after the hinge has been match drilled to the gate and the lower beam, the lower gate is again removed. One reason for this is that it allows the holes in the gate to be deburred and countersunk at a work bench rather than in the tool. If this drilling, deburring, or countersinking operation were to generate slightly oversize holes with respect to the fasteners, flushness could be jeopardized by allowing possible movement of the hinge relative to the lower beam or the gate.

However, hole variation would likely be in random direction, meaning that for a line of fasteners, such as it the case for the hinge, the net play in any direction could be canceled out. Essentially, all of the holes would have to be excessively large to allow this. As this is highly unlikely, there is no need to assign a key to this operation.

However, in conversations with factory mechanics about potential MKCs, the subject was raised regarding drill bits. Mechanics are finding that in order to achieve nominal size holes, that the condition of drill bits are a critical factor. The realization is being made that for several keys which are dependent upon drill and fill operations, that the quality of the drill bit is paramount to being able to deliver upper level keys. As such, mechanics admitted to more closely inspecting drill bits arriving from the reconditioning shop, and tending to reject a higher percentage of these reconditioned bits. One mechanic even admitted to hoarding certain bits.

This may be an indication that certain characteristics of drill bits may be critical to achieving upper level PKCs. These features could include factors relating to the sharpness of the bit, proper dimensioning of the tines etc. As this would be considered a process parameter in a sense, such characteristics would be MKCs.

Robustness of Tooling

The fabrication efforts for FAJ1 are currently underway. This tool was essentially designed in conjunction with the FED. It is similar to current tooling used in the shop, but contains some differences to accommodate the intricacies for hole to hole assembly.

Only one FAJ1 will be manufactured for the DRC. Future door suppliers will likely be responsible for manufacturing, as well as possibly designing, their own tooling.

The IPT felt that since only one FAJ1 was going to be built, that the concept of key characteristics did not apply, as keys applied to something which could be measured repeatedly. If only one tool was to be built, then the concept of keys would be worthless.

While this argument could be true for the fabrication of the tool, it does not mean that keys cannot be identified for the use of the tool. For example, the IPT identified the location of the 6 indexing points as a key characteristic on the lower gate detail / assembly level drawing. As mentioned earlier in this chapter, this is not an appropriate set of keys for that drawing level because it does not relate to something that can be physically measured. The location of the index points, however, can be measured on the tool FAJ1.

It is critical that these 6 index points are correct with respect to the door datums. The tooling calibration documents require that these index points are checked once every 6 months for proper location. This has been found by past experience to be a suitable timeframe for insuring accuracy of the FAJ1 indexing points.

However, as the IPT correctly realized, these 6 index points are critical for being able to deliver the PKCs of flushness and periphery. Thus, these index points on the tooling could be identified as AKCs. These are not keys which refer to the manufacture of the tool. Rather, they are keys referring to the proper use of the tool as a means of delivering the PKCs. They could be identified as AKCs keys on the tooling top level drawing. The measurement plan could indicate that these keys only need be measured on a 6 week basis, but this would document that these indexing point locations are critical to delivering the upper level key of flushness for the door and gate.

This accomplishes what the IPT was after when they identified these 6 points as keys on the gate detail drawing, but putting this key on the tooling drawing instead locates the keys in the proper location where their function and interface with the upper PKCs can be identified. Under HVC, this classification of keys would not have been possible. HVC led the IPT to believe that to list keys on the tooling drawing meant that the keys must apply to the manufacturing of the tooling. As shown here, the keys actually now refer to the use of the tool in the assembly process.

5.5.2.3 Detail / Assembly Drawing AKC and MKC Analysis for Periphery PKC

Similar to the analysis done for the flushness PKC, there are no AKCs at the detail part level for the periphery PKC from Boeing's perspective because this is a one piece cast assembly. The periphery PKC is the responsibility of the supplier, and is delivered through a combination of proper design of the casting mold, as well as the ability to machine the gate perimeter. Likewise, any MKCs at this level would be determined by the suppliers, and would apply to parameters associated with the casting of the machining operations. Therefore, there are no AKCs or MKCs relating to periphery at the detail drawing level for the gate.

An interesting point, however, is that the drawing revision block shows that a total of 9 keys were removed from the drawing, all of which related to periphery. After talking with the part design engineer, it was found out that originally the keys for periphery had been assigned to several different radiuses and other dimensions associated with the gate. It was through several discussions with the supplier that they eventually settled on the 2 keys for periphery included at this drawing level.

5.5.2.3 Detail / Assembly Drawing AKC and MKC Analysis for Periphery PKC

The analysis for the periphery PKC is much more straightforward then it was for the flushness PKC. This is primarily due to the fact that there are fewer factors which affect periphery than there are for flushness.

After studying the build plan and the installation drawings, the following items have been identified as affecting periphery of the gate installation:

1) Placement of gate into tool

2) Alignment of gate with respect to lower beam

These factors address the only parameters that can be addressed at this stage of the door fabrication effort. Periphery is a key associated with delivering the upper level PKC of gap. Even if periphery of the gate is built to absolute zero variation levels, there is still no guarantee that the upper level gap key will be delivered, as this depends on final skin attachment, skin trimming, and relative location of the fuselage door opening with respect to the door. Just as with flushness, the key of gap is measured at FAJ4, in the as installed position of the door, where the door is subject to the actual sags and deflections present in an actual installation due to weight distribution, the cantilevering of the door from the hinge etc.

Placement of Gate into Tool

The location of the six indexing points has been added as an AKC on the FAJ1 tooling drawing. These six indexing points as described earlier include 3 on the outer surface for contour, two on the lower edge of the gate for periphery, and one for relative indexing left and right (along station line of the airplane).

These two points on the periphery are the second step of loading the gate onto the tool. After first laying the tool on the three contour indexing points, the gate is then pulled back until it contacts the two periphery stop touch fixtures. After locating the final index point left to right, the gate is clamped into place. It is in this clamping operation that the gate could shift perhaps, and no longer contact the lower two periphery tooling stops. If this was the case, periphery could suffer, both with respect for the gate to the door, as well as the gate to the fuselage opening.

The temptation may be to add a MKC specifying that the gate should be checked again after clamping to insure that the gate is in contact with the two periphery stop touch fixtures. However, this is daily operating knowledge for mechanics, and thus is unlikely in an experienced door fabrication facility. However, in the transfer of work to a new offset supplier unfamiliar with doors, this may not be the case. In this situation, the checking of the gate to insure proper contact after clamping may be a MKC. For consistency sake, therefore, this checking method could be added to the O&IR documents (the instructions for the mechanics) for the purpose of assisting new suppliers without this level of knowledge or experience. However, in the interest of not creating excessive keys, this will not be used as an MKC at the installation drawing level.

With offset suppliers, the operating mandate, however, should be not to assume the obvious. For example, quality issues are now being resolved with one of the DRC's international vendors on fabrication of another pressurized cabin door. The vendor has evidently begun using oversize holes with the regulation size fasteners for attachment of door skins to the door. Not only does this pose a concern for the premature failing of the skin, but it also affects the stress analysis for the entire door. This mistake was made by a vendor with almost 6 years experience building doors for Boeing. The reason for the drilling oversize holes was apparently to allow easier attachment of the skin to the frame due to hardware variation issues. In other words, this helped them assemble the door "correctly", and was almost an MKC to them. Stronger implementation of HVC could have helped them avoid the need for this practice at this step. However, the point has been made that what designers may assume is common operating knowledge for an aerospace mechanic, is not so for a potential offload supplier.

This almost leads one to rationalize that in the course of design drawing efforts, as well as build plan creation efforts, designers and IPTs may need to take into account knowledge of the potential supply firm to fabricate the product. If this firm may be outside BCAG, extra precaution might be taken in indentifying those "obvious" MKCs such as insuring that the gate remained in position against the indexing points after being clamped into the tool. This may indicate that some MKCs are part of the learning curve experience, and could be potentially eliminated from a key characteristic list once this MKC knowledge becomes internalized.

Alignment of Gate With Respect to Lower Beam

When the beams of the door are placed into the tool, they are located properly by the use of two stop fittings, one on each side of the beam. These stop fittings mate into corresponding points on FAJ1 for proper placement and alignment of the beam.

After analyzing the FAJ1 tooling drawing, it is observed that there are two different type of tooling fixtures for the stop fixture. One of these involves the use of a hole, while the other involves the use of a slot (see figure 14). The mechanic first loads the beam in the tool such that the stop fitting on the left side of the door fits into the tooling locator with the hole. The right hand stop fitting is then placed so that it fits in the slot of the other tooling locator.

The existence of the slot is used as a means of being able to absorb, or "wash away" some of the hardware variation in a direction or manner in which it is not critical. If two holes were used, there would be no room for hardware variation in any dimension. However, the use of the slot allows a small acceptable allowance for variation in one dimension. The locating fixture is slotted in such a way for the beam to move slightly in the direction of the height of the door (waterline), but not across the depth of the door, or from side to side. This allows variation to be washed or directed in the one dimension for which it is not as critical as determined by the IPT.

However, this tooling design essentially allows the lower beam to shift so as to possibly loose its parallelness with respect to the lower gate. This could result in an gap between the frame and the gate which increases from one end of the beam to another.

Again, however, it must be remembered that gap is measured in the final build position FAJ4, or after all of the outer skin has been attached. If this gate is slightly uneven as described above, it can be corrected during a door skin trimming operation with no apparent major difficulties. A majority of the outer skin sections have the key of periphery included on their drawing, as the skin installation is the last opportunity to correct for any periphery issues. Therefore, such that this uneven gap possible between the door and the gate can be rectified by the outer skin trimming step, this is not an AKC. However, it bears repeating that the tooling locating assembly was slotted in the correct direction so as to wash the uncertainty and hardware variation away in a dimension which was non critical.

5.5.3 Tradeoffs Between Flushness and Periphery PKCs

One of the other benefits of this new methodology is assisting in determining the relationship between keys. In a typical HVC flowdown process, an upper level customer requirment is ideally flowed down through each assembly level and installation level drawing, all the way to the detail drawings themselves. This allows the map of causality to be traced for this key from its inception to its final state. However, once this has been established, there is no easy process to relate one key characteristic to another. How does the features or steps taken to achieve one key, affect the realization of another key?

As an oversimplified example, consider the top level customer requirements of weight and fuel burn. Obviously, these two top level requirements are in direct conflict with each other. As the weight increases, the rate of fuel burn also increases. These two keys are almost perfectly positively correlated with each other. As such, BCAG has tradeoff charts. These proprietary charts show information essentially relating to two different decisions regarding this tradeoff. The first involves balancing design or manufacturing efforts to reduce weight, against added increases in the cost of the plane. There is a threshold value that if this effort can be accomplished below a certain dollar value per pound, it adds value to the customer. The second regards adding weight while achieving a cost reduction for the airplane. Again, there is a threshold value that if the cost reduction is great enough, this adds sufficient value to the customer so as to offset the higher fuel burn costs created by the extra weight.

But what about in the case of keys where the relationship or correlation coefficient is not so perfectly clear? For example, what is the nature of the relationship between the upper PKCs of gap and fair for the FED? Do these conflict with each other in that a positive gain in one results in a loss for the other (negative correlation), or do they serve to amplify each other, in that if one improves, so does the other (positive correlation)? Or, is there very little or no complimentary or substitute relationship between the two key characteristics?

In order to analyze the relationship between gap and fair, one could attempt to analyze the nature of the relationship at this upper level, similar to what was done for weight and range. However, unlike our example, the relationship between gap and fair is not as clear. One method, then, to analyze the nature of such an unclear relationship would be to then to try understand the nature of the relationship at a root level. Or in the case of key characteristics, to move down the flow down for each key to see what relationships can be identified. So upper level PKCs can be studied by looking at the relationships between the other PKCs created at the installation, assembly, and detail level drawings that were created during the flow down process.

This is where the alternate methodology studied in this thesis has an advantage over HVC. Through the creation of AKCs, factors which are critical in delivering the PKCs have been identified. Therefore, a direct causality has been established between the AKC and the PKC. Improve the AKC, improve the PKC; suffer the AKC, suffer the PKC. Therefore, in order to study the nature of the relationship between two PKCs, one can move a level or function lower, and study the nature of this relationship by examining the relationship of their different AKCs. If a conflict exists between two AKCs, then a conflict will exist at the PKC level, although the magnitude of this conflict can range over a wide spectrum, and the magnitude of conflict is not just dependent upon the degree of correlation between the two different AKCs.

Therefore, a flow down process has essentially defined several other features, dimensions, or process parameters which have an effect on an upper level PKC. This can be stated as an upper level PKC is a f (Lower level PKCs, AKCs, MKCs). The assignment of an IPT, then is to attempt to define the relationship between these two functions, or alternatively, between the variables upon which these functions are dependent.

Therefore, for gap and fair, we can study one aspect of their relationship using the lower level PKCs of periphery and flushness which we have studied and analyzed for the lower gate. Specifically, primary attention would be focused upon the AKCs and MKCs which have been identified.

After performing such an analysis, it is found that for the case of gap and flushness for the lower gate, there is no tradeoff. The achievement of one does not come at the cost of the other. Concurrently, the achievement of one does not come at the guarantee of the other. A door can be in perfect flushness, but still have mis gap between the door and gate, or between the gate and the airplane fuselage. Or gap can be 100% at nominal, while still having flushness problems to correct.

However, in performing this analysis, a different tradeoff with an upper level PKC was identified. As was shown in this write-up earlier, the upper level key of fair relates to both the lower level PKCs of flushness and contour. However, conflicts can exist between these two PKCs, even if they support the same upper level PKC. For example, the supplier of the lower gate could cast a particular gate which met the contour requirements, but in which the mating surface is not located properly. In this example, when the gate is installed to the door, contour achieved would be at the cost of flushness. For this example, this tradeoff could perhaps have been eliminated by selecting different contour reference points, two of which may fall on the flushness surface. This would not have been apparent, however, without studying the flowdown and looking for potential tradeoffs between the different keys.

5.6 Chapter Summary

Application of the new quadkey methodology to the lower gate assembly of the FED resulted in the definition of the following key characteristics:

PKCs

1) Detail / Assembly drawing:

Periphery
Contour
Centerline location of holes in linkage actuators

2) Installation Drawing

Flushness

Periphery

AKCs

1) Detail / Assembly drawing

Not Applicable

2) Installation Drawing

Location of mounting edge relative to gate

MKCs

1) Detail / Assembly drawing

Not Applicable

2) Installation Drawing

Match drilling of hinge to gate and beam, with beam being drilled first

Under the HVC methodology, a separate classification of AKCs would not have been established. In addition, without identification of the AKCs, the same MKCs may not have been identified, even though HVC recognizes the use of process parameters as key characteristics. Again, this is due to the foundation of the quadkey methodology, in that the MKCs and AKCs act together to deliver the lower level PKCs, and together, these flow up through the assembly and installation process to deliver the upper level PKCs or customer requirements.

In addition, through identification of AKCs and MKCs, the nature of the relationship between two different keys becomes easier to be determined. Classification of the relationship, as to whether there is a tradeoff, mutual benefit, or no correlation at all, becomes more visible with the use of AKCs. As was seen for the PKCs of flushness and gap, there is no relationship between these for the lower gate assembly.

6.0 Advantages of Quadkey Methodology

The quadkey methodology proposes the use of an expanded method for the classification and generation of key characteristics, as compared to the current key characteristic procedure under HVC. The main difference is the addition of the classifications of AKC and StatKCs. As was seen from the previous chapter where the quadkey methodology was applied to the lower gate for the FED, the AKCs and MKCs were directly identified with their ability to influence upper level PKCs, allowing an even further causal map to be defined with regards to ability to achieve upper level PKCs than that currently espoused by HVC. The addition of AKCs adds a tool to the method of key characteristic identification by allowing keys to be identified from the assembly process, a segment of the build plan hidden from most design efforts, the traditional breeding ground for most PKCs.

As was seen from the previous chapter, a hierarchical relationship was established between the different keys, as follows:

Upper Level Customer Requirements

↑

Upper level PKCs

↑

AKCs

↑

MKCs

This hierarchical chain sets up and defines the cause and effect relationship between the keys. The upper level PKCs are derived directly from customer level or product requirements. Once these are defined, they are then flowed down to the other assembly levels, culminating at the detail parts. During the course of this flowdown, other PKCs are identified at these other levels which support those PKCs located at higher levels in the engineering tree.

Once these PKCs have been identified, the assembly process can be studied to determine what aspects of this process, or the associated tooling, play a major role in achieving the PKCs. Then, certain of these elements can be selected as AKCs, based directly on their ability to deliver the PKCs. AKCs are then selected based on their ability to deliver PKCs. This allows the assembly process to become an integrated participant in the deliverance of PKCs, rather than just a mute stepping stone.

In a similar relationship, MKCs are selected by examining the process parameters of the fabrication or assembly steps. These process parameters are also selected by their ability to influence or deliver the associated AKCs, as well as PKCs. This again brings the chain of influence full circle, in that the very critical elements which start the fabrication process in motion, are now linked to the final product at the end of the chain.

6.1 HVC Issues at the DRC

One avenue to explore the advantages of the quadkey methodology was to research the use of HVC at the DRC, determine any areas or issues where difficulty was encountered, and then determine if the use of quadkey methodology would have tempered some of these issues.

As mentioned previously, the 737-X is the first use by the DRC of HVC on a major new program. Prior to this opportunity, the DRC oscillated between implementing AQS, or following the HVC program, on their existing products. ISO 9000 was also being discussed as an potential option.

When the decision was reached to implement HVC, the predominant issue was "How to measure, and Where?". The main point of controversy was regarding tooling. Tooling wanted to redesign all tools to accommodate a fixed Allen Bradley Datamyte measurement gathering probe; engineering felt that this was excessively expensive for benefits which weren't exactly clear. Engineering favored the use of the current tooling. However, this would require the parts to be removed from the tool in order to perform some of the measurements. This would introduce additional uncertainty and other variables into the measurement process, and it could prove unclear whether the actual assembly process was stabilized and in control.

The decision was finally made to go with the dedicated tool. However, by the time this had been finalized, and the tool fabricated, it was too late to embed it in the current process. As such the fixture was rarely used.

After observing manufacturing operations at the DRC, and speaking with employees associated with the effort, the following issues were identified as potential issues regarding the successful implementation and use of HVC at the DRC. Again, in order to see what additional benefits could result from the use of the quadkey methodology, each of these will now be examined to determine if these issues could be mitigated through use of the quadkey philosophy.

1) Predominance of existing versus new designs

This seems to reflect the intuition that it is often easier to start from a clean sheet of paper, or the greenfield effect. It is unlikely that the quadkey methodology would have any major significance here

2) Too much effort required in construction of build plan

A build plan or similar document would be essential for any organization to create if hardware variation was going to be significantly studied and reduced. The quadkey methodology, through the use of AKCs, however, would allow cause and effect relationships to be identified further through the assembly process. This may allow an easier "line of sight" during the fabrication of the build plan.

3) Insufficient training:

Often, managers were only able to allow their engineers to partake in a 4 hour HVC overview class. These same engineers were then tasked to implement HVC. While the principles of goals of HVC may sound fairly simple and achievable, implementation of these principles in a product as complex as an airplane door turned out to be much more difficult than most visualized. Often times, engineers would hit a barrier early on, and there HVC would come to a grinding halt. In this situation, it is also unlikely that the quadkey methodology could prove of additional assistance.

4) Schedule pressure

Schedule is king at Boeing, and the quadkey methodology would have to be implemented in such an environment. The pressure to meet schedule caused designers to tend to focus on completing the design, rather than the proper implementation and use of all of HVC's steps. The implementation of the quadkey philosophy would also come under such pressures.

5) Detail parts last component analyzed during flowdown

The last part to analyzed during the flow down process is the detail part level. Unfortunately, in order to meet schedule, these are the first parts whose design needs to be finalized first, and which need to be produced first. Therefore, the very part which forms the foundation for the elimination of actors contributing to variation are the last analyzed, but the first needing to be manufactured. Due to the ongoing pressure et meet schedule, detail part drawing realize could not be jeopardized. This seems to have resulted in keys being assigned to detail parts just for the sake of attempting to identify keys, rather than the result of a proper flow down to the detail part level. The quadkey methodology can not help this systems dynamics case study referred to above, in that the very parts in which proper key identification is necessary, are the very parts for which the system favors termination of the flow down methodology.

6) Too many keys:

This issue was heard from members from all the different organizations of the IPT, yet was the end result of their own process. The final list of keys for the FED included over 250 different product keys. This was still viewed by some to be excessive, and several of these keys felt to be improperly identified as keys.

The quadkey methodology may prove to be of assistance in this issue. Through the use of a proper flowdown and identification of AKCs and MKCs, the proper causality for hardware variation through the web of parts and assemblies would be identified. This web of causality may make it simpler to eliminate a potential PKC which may be added just out of intuitive sake. As such, the quadkey methodology may allow some PKCs to be eliminated after the flowdown process, when it is seen that they are already being addressed by other AKCs or MKCs. This however is still conjecture, and would need to be studied further.

7) Too much measurement time:

This complaint was heard primarily from mechanics on the factory floor, and goes hand in hand with the previous issue; are there too many keys, or are there too many measurements? Some mechanics felt that measurement of the keys could increase the amount of work for them in excess of 10%. Even though they realized that reduction of hardware variation in upstream manufacturing steps prior to their work station could make their own job easier, it was difficult to seize the value of this when they could compare it to the instantaneous time added due to implementation of the measurement plan. One is a long term benefit, hard to visualize, while the other is a short term cost, altogether too easy to visualize.

This is one area where the quadkey methodology may prove to be of benefit. The quadkey methodology, as was shown for our flowdown for the FED lower gate, actually resulted in more keys than was the result from HVC. Again, however, this is the critical benefit of also identifying the AKCs and MKCs, as well as StatKCs. This additional keys are the critical keys to delivering each of the PKCs, which then flow up the engineering tree to deliver the required customer requirment. If these AKCs and MKCs are more properly understood and captured, then it should result in an assembly process which is more in control with respect to delivering the upper level PKCs. Then, perhaps once the process is known to be in control, a reduction in the need to measure the PKCs perhaps could be implemented, the logic being that if the AKCs and MKCs are verified to be in control, then so will the PKCs. It is often these higher level PKCs which are the most tedious to measure, and perhaps the quadkey methodology could reduce the frequency required to perform these measurements, as they are currently measured on every assembly.

7) Unable to measure certain keys

Certain points which have been selected as keys are the source of great consternation in the creation of the measurement plan. Issues such as not only which method is the best way to actually make the measurement, but can an person even physically reach the point to be measured arise frequently. On the FED, the IPT encountered this same difficulty. The decision was made to make an actual mockup of the door, and to try different measurement techniques first on this mockup. The notion of trying different measurement techniques on a digital mockup was discarded because to model the motion of a human arm capable of an infinite different number of motions, attempting to manipulate itself around numerous physical barriers, was deemed to be much more difficult.

The quadkey methodology, coupled with a proper flow down methodology, could aid in this problem area. Most of these difficult to measure PKCs are at higher levels of assembly. If the proper AKCs and MKCs have been established down to the detail part level, the ability to deliver these upper level PKCs would be enhanced, and these measurements perhaps eliminated from the measurement plan. The measurement of the proper AKCs and MKCs would be utilized to insure proper delivery of the PKCs.

8) Difficulties in implementing the principles of HVC

Use of the quadkey methodology would only supplement the definition of key characteristics under HVC. It would not replace the other main precepts of HVC, such as commonality and flowdown of indexes and datums. These other areas are often times where other issues or difficulties can arise. For example, on the lower gate assembly drawing, the two lower contour index points A2 and A3 were selected by the designer to be towards the middle of the exterior surface. However, the tooling engineer located these same index points towards the ends of the lower gate assembly (see figure 15), due to design issues surrounding the fabrication of the tooling. The part designer was unable to modify his index points to accomplish this, as his points were chosen on the plane of intersection of datum A with the exterior surface. If his index points were to have been shifted to where the tooling designer had located them, datum A would have had to rotate, and it would have lost its 90 degree alignment with the other two datums. So in this example. tool fabrication difficulties coupled with an earlier datum definition made it difficult to insure commonality of index and datum. The use of the quadkey methodology would have no impact on this example of practical implementation difficulties.

9) Lack of involvement with suppliers

The HVC program encourages use of suppliers in the IPT environment. However, other issues, such as schedule, or the fact that the part is designed well ahead of a supplier even being identified, make this difficult. However, the benefit of this is obvious, as was seen by the elimination of 9 keys from the lower gate detail drawing after discussions were held with the final supplier.

Here the use of the quadkey methodology would pose no additional advantage. In order to obtain the maximum utilization of either the quadkey or HVC methodologies, the involvement of the supplier is critical. Once this relationship has been established, then the identification of keys can take place in a much more knowledge rich environment. The supplier, like Boeings own factory, brings with it its own inherent knowledge of potential AKCs and MKCs, and these are critical to the use of the quadkey methodology. In such discussions between Boeing and the suppliers, as well as during the actual fabrication efforts, these AKCs and MKCs could "bubble up" to the surface and be documented as soon as their role and function become understood.

In conclusion, the above study of issues of HVC implementation difficulty at the DRC point out additional benefits for the use of the quadkey methodology. Specifically, these were regarding the identification of the real PKCs from apparent PKCs, establishment of the causality web between the PKCs, AKCs, and MKCs, and the possible reduction in need or frequency of measurement for upper level PKCs due to assembly processes being in tighter control with regards to delivering upper level PKCs.

6.2 Proposed process for conversion to New Methodology

The incorporation of the quadkey methodology into the HVC program would have several benefits to Boeing, including those referenced above and earlier in the philosophy. The primary advantage is the hierarchical relationship between the different classifications of keys, acting together to form a web of causality to deliver the important upper level customer requirements.

One of the first steps to take, regardless if whether the quadkey methodology will be implemented, is to properly define hardware variation. As HVC sees it, hardware variation is variation around the mean, rather than variation within the mean. This is an important concept, and should be properly defined in this context.

The process to incorporate the quadkey methodology into HVC would require additional effort on the parts of all members of the IPT, as well as the corporate HVC staff. Issues which would need to be addressed include the following:

1) Documentation of AKCs and MKCs

Under HVC, all keys are to reside on the engineering drawings. In conversations with several individuals at Boeing, it is still uncertain if this is the best format for the AKCs and MKCs. By their nature and definition, AKCs and MKCs could change as the assembly process changes. These classifications of keys need to be easily changed from a documentation point of view in order to allow improvements to be studied in assembly methods. As such, the best location for AKCs and MKCs would not be on the engineering drawings, as this would require a formal drawing release each time a change is made in an AKC or MKC.

2) Easy addition or deletion of AKCs, MKCs

As assembly processes change or improved, the related keys specific to the assembly process or method must be allowed to be modified as necessary. In addition, any member of the IPT, including the supplier, need to be able to request such a modification. Therefore, a streamlined "change board" procedure needs to be established.

3) Ownership of Keys

Once a key is accepted or removed from an existing build plan, a party will need to be identified to insure that the key is referenced properly in the measurement plans, O and IR documents as required, etc. Some standard must be established to insure the proper dissemination of information to the necessary departments within Boeing, as well as outside Boeing.

4) Identification of StatKCs. Once all keys have been identified, each key would have to be analyzed to determine if it was a StatKC. Once all the StatKCs have been identified, they would need to be published in some fashion for all the affected departments. As StatKCs are keys which are potentially out of control temporarily, keys must be easily added or deleted from this StatKC database. In addition, procedures must be established for proper timeframe and review of data in order to determine if any additional keys need to be added to the StatKC database.

5) Determine additional methodology for generation of MKCs.

Currently under HVC the concept of Key process parameters and their selection method would need to be expanded, to incorporate additional activities at the factory level. As manufacturing keys have an implicit association to the factory, additional mechanisms need to be established to allow identification of these keys at the factory floor level.

One potential application which was considered during the research for this thesis was the use of Value Engineering as one possible means for determining manufacturing keys. Value Engineering is a concept which has been around for several years, and is practiced more in the Defense side of Boeing than on the Commercial side. Specifically, use of the Function Analysis System Technique (FAST) would prove the tool of Value Engineering with the most potential for the identification of MKCs. Marlo Stebner of BCAG is the current expert in Boeing on value engineering, and is willing to pursue its application in the arena of MKC identification for future study.

6) Drafting Standards:

Additional engineering and drawing standards need to be defined, such that each classification of key is readily identifiable from each other. A MKC should be distinguishable from an AKC in some fashion, even if it is just the simple addition of AKC, for example, after the numeric indicator assigned to the key. In addition, creation of an identification system to allow keys to be linked to the other keys associated with them as identified during the flow down process would be of great assistance. In such a system, an AKC would be possible to be studied, and determine which upper level PKCs it is associated with, as well as which MKCs its deliverance is dependent upon.

7) Supplier Base: In addition to allowing implementation within Boeing, the system must allow for easy transfer and introduction into Boeing's external base of suppliers.

6.3 Chapter Summary

After studying the history of HVC at the Door Responsibility Center, areas have been identified where use of the quadkey methodology, in conjunction with those tools already developed by HVC, could promote increased use of key characteristics within Boeing and its supplier base.

Any attempt to implement the use of the quadkey methodology at Boeing would require several elements to be addressed, some of which were listed in the preceding section. A more thorough study of this topic would be required, and would be an ideal topic for a future related thesis.

7.0 Additional uses for Key Characteristics

In studying and observing how keys characteristics are utilized at Boeing, other applications other than their use for pure hardware variation began to be realized. Especially when the quadkey methodology is implemented, key characteristics create a causal web down through the engineering tree, identifying those features or attributes which are critical for delivering customer satisfaction. By being able to identify those items during the manufacturing process responsible for delivering customer satisfaction, we have identified those fulcrum points where we can exert leverage not only on reducing hardware variation, but also other arenas which can add value to Boeing. Some of these potential applications include the following applications:

1) Support Total Productive Maintenance (TPM) activities

2) Improve Standard Operations

3) Capturing of Tribal Knowledge

4) Focus for Kaizen or CQI activities

5) Improvement of Transfer of Work Packages Outside Boeing

6) Support Assembly Modeling Attempts

Each of the above will be discussed in more detail in the following section.

7.1 Support Total Productive Maintenance (TPM) activities

TPM is a philosophy which Boeing feels is a major component of its move toward a lean production system. TPM involves an attitude of ownership of the part of the machine operator toward the maintenance of the equipment. One of the critical issues behind TPM is when to alert the operator or other maintenance employees of the need for major routine maintenance.

Currently, heavy emphasis is placed on the use of diagnostic equipment (i.e. accelerometers to warn of impending bearing failure for a rotating shaft) to determine when maintenance will be required. However, the use of keys pose an alternative trigger point for this determination. The performance of the equipment in delivering any keys directly associated with the operation of the machine could be used as one determination that maintenance may be required. For example, consider a CNC lathe which is used to machine the diameter of a shaft, and that this shaft diameter has been established as a key characteristic. This key would be measured and recorded for each shaft. Assume that this key begins to show a definite trend away from nominal but still within control limits as defined by SPC. Due to the quality loss curve, we know that this deviation is coming at an increasing cost to Boeing and the customer. As such, since this machine is having difficulty in delivering a particular key characteristic, this could be a signal to schedule the machine for a maintenance inspection. This is being done as almost a cost avoidance step. Had this dimension not been a key, and the output was still within control limits, this same decision would likely need not have been made. Essentially, costs associated with maintenance are justified easier by the costs avoidance associated with the nominal delivery of keys.

7.2 Improve Standard Operations

Standard Operations is a element of manufacturing operations derived from study of several of the Japanese "lean" manufacturing companies. Standard operations are one element of the DRC's planned transition towards a lean manufacturing system.

Standard operations are defined as "effective combination of workers, material, and machines for the sake of making high-quality products cheaply, quickly, and safely". In the automotive factories such as Toyota, standard operations detail in explicit detail what the optimum process is to perform a manufacturing operation. They often go into such detail as to show the operator where to stand, and how to walk from station to station. The purpose of the standard operation is to cut out all unnecessary waste from the process, where waste is anything unnecessary that doesn't add value. For example, not walking the most direct path between work stations doesn't add value to the process and can be eliminated. Changing a drill bit is a necessary but non value added step, and should be minimized in duration. The actual drilling of the part is a value added process, and the standard operation must be defined to focus on these value added steps.

In the course of eliminating waste from standard operations, how can the issue be addressed of whether the output of the value added steps is being compromised? This is where key characteristics can be utilized. The use of key characteristics will show those outputs of the manufacturing process which cannot be compromised by the deletion of apparent waste in the name of process improvement. If a process cycle time is cut by 50%, but the delivery of the associated keys is compromised, a decision needs to be made which presents the greater opportunity for cost avoidance. The use of keys, therefore, can be used as a means of improving standard operations, to insure that any process improvements don't come at the expense of customer satisfaction. They form a quality map to insure that the waste reduction operations stay on the proper track.

In addition, there is a possibility that synergy can be found between the creation of standard operations, and the identification of MKCs. As standard operations are created, there will be certain steps or procedures which will be found that cannot be compromised in order to deliver the output of the process, which may include delivering some key characteristics. As these certain steps cannot be compromised, there is something associated with them that is key to delivering the output. As such, these steps may contain some the MKCs for this particular operation. Some of these MKCs can likely be determined in advance of creating the standard operation. However, others may not become apparent or realized until the standard operations themselves identify those particular steps or operations which cannot be compromised. In this case, the creation of the standard operations may allow previously unrecognized MKCs to "bubble up" during the process. This currently is only conjecture, but would prove a valuable area for future research in the author's opinion.

7.3 Capturing of Tribal Knowledge

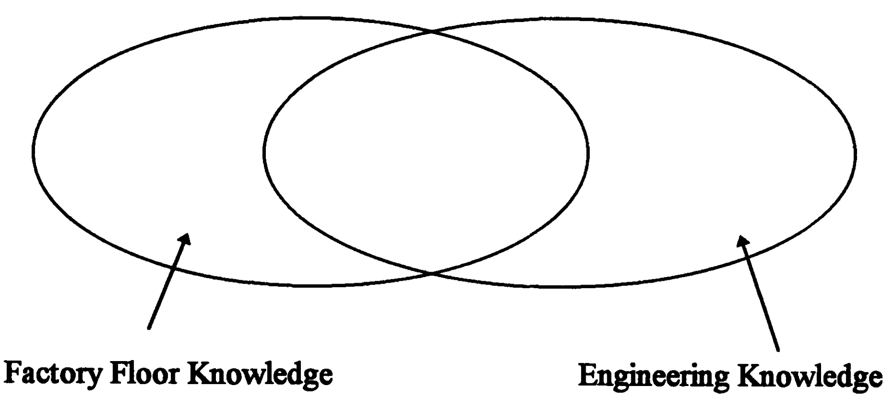
Boeing has often referred to the existence of "tribal knowledge" in referring to internalized knowledge within its work force. The term is usually directed more towards production workers than engineering disciplines, although it applies in both arenas. Tribal knowledge is considered to be the critical knowledge to allow an individual to do a job correctly. It could be conjectured that the accumulation of tribal knowledge is what leads to falling cycle time associated with the learning curve effect. Tribal knowledge is the key knowledge to perform a task; take away the knowledge, and the task doesn't get done.

The difficulty lies in capturing tribal knowledge. As this usually is knowledge which tends to be gained through hands on experience, it is often unable to be documented in build plans. A build plan may specify the correct order to perform an operation, but this is not the same as knowing how to perform the operation. This is where tribal knowledge lies.

As the image of a "tribe" suggests, this knowledge is usually transferred from one worker to another through performing the same operation together, and by verbally passing the knowledge from one tribe member to another. This knowledge does not get documented; rather it remains an unwritten body of knowledge.

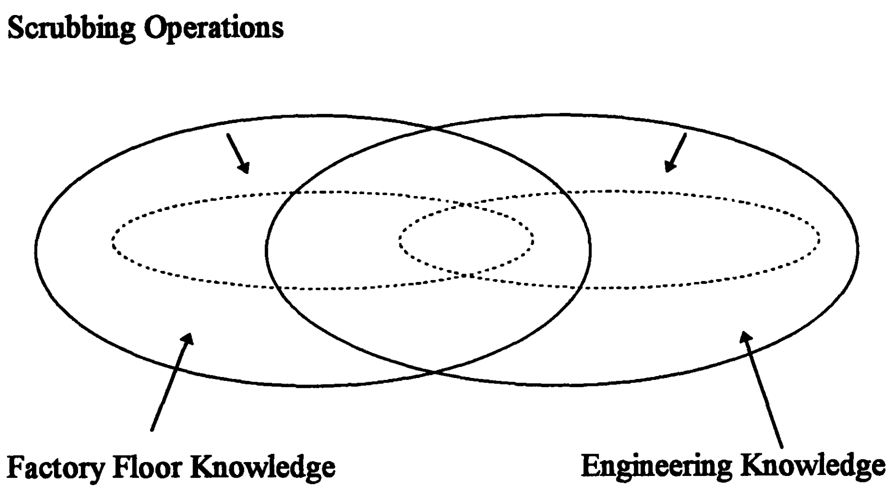
Boeing realizes that in order to capitalize on this tribal knowledge, that this knowledge must be documented. This is where the author believes the tool of key characteristics, especially manufacturing keys can be applied.

Consider the following pictorial:



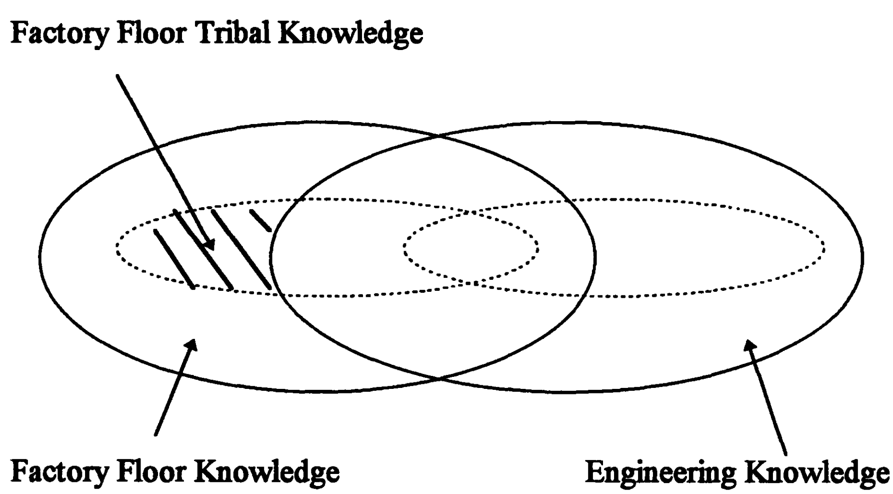
The two ovals represent two different bodies of knowledge. The factory floor body contains the knowledge of the manufacturing arena, including not only production workers, but also manufacturing engineering, quality assurance etc. The engineering knowledge body contains that of design engineering, tooling design etc. These bodies of knowledge include both written as well as non written aspects of knowledge.

Not all of this knowledge, however, is critical to the performance of a certain manufacturing operations. Essentially, “scrubbing” actions can be done to each body of knowledge to find out which knowledge is critical to achieving the goals of the process, and which isn’t. These scrubbing operations could consist of standard operations such as mentioned previously for the factory floor, or Design of Experiments for the engineering arena. As such scrubbing actions take place, the volumes of critical knowledge begin to emerge within the larger bodies of knowledge



As these scrubbing operations continue, the critical bodies of knowledge for the particular process grow smaller. As these areas contain the critical knowledge to successfully deliver the process, then the associated MKCs must also be contained within this critical region. Eventually, they assume a final configuration with three distinct areas as shown above. One is knowledge contained only within the engineering ranks, one is a body of knowledge common to both the factory and engineering, and third is contained only within the factory floor. Dispersed within this area are contained the MKCs for the process. And therefore, in the process of defining the MKCs, a body of knowledge has been identified which spans the factory and engineering volumes of knowledge. The MKCs can then be seen as a bridge or link between the two different bodies of knowledge. Or as expressed in broader terms of BCAG's macro processes, it is a bridge between the "Define" world, and the "Build" world. This is a critical link which is difficult to forge in any manufacturing operation, but especially one in an environment such as Boeing. Due to the sheer size of BCAG's product, as well as the actual facilities and plant locations, forging this common link between the two arenas has been made even more difficult. It is this identification of the MKCs that can help bridge this gap, and assist in the linkage of the build world to the define world.

The third area of knowledge, that common only to the factory floor, which is of also particular interest. It is within this arena that the majority of the MKCs lie in the authors opinion, and it is this body of critical knowledge not shared with engineering that represents factory floor tribal knowledge.



It is within this area of knowledge common only to the factory floor that the majority of the MKCs lie, as well as the factory floor tribal knowledge. In a majority of cases, these two may found to be equivalent, in that an activity which would have been considered as tribal knowledge is actually now identified as a MKC. In the course of identifying and documenting MKCs, what will actually be occurring is the capturing and transfer of unwritten tribal knowledge, into documented knowledge that can be transferred from employee to employee, or outside the company as necessary to support "buy" decisions. This is one use of keys which needs to be strongly considered, is that by identifying MKCs, the tribal knowledge so long felt to be a critical part of Boeings production processes can begun to be captured.

7.4 Focus for Kaizen or Continuous Quality Improvement (CQI) activities

This is somewhat related to standard operations, in that some of the key cornerstones for any process can be found in the MKCs. As MKCs have been identified as critical to delivering the upper level PKCs, and PKCs are those areas of potential high quality loss to the customer, then MKCs are ideal target candidates for continuous quality improvement initiatives. The goal, therefore, of such a Kaizen or CQI improvement activity would switch from improving the output of the process, to improving upon the MKCs. If two MKCs could be combined to form one MKC which is more controllable, or easier to monitor, then that would be a form of process improvement. By focusing improvement upon the MKCs, the process improvement can be achieved, and not at the expense of delivering the PKCs.

7.5 Improvement of Transfer of Work Packages Outside Boeing

The AKCs and MKCs as defined are critical to delivering the upper level PKCs. As in any transfer or work package outside Boeing (or even within Boeing between different factories), one of the deliverables will be the PKCs. Unlike traditional HVC, the inclusion of the AKCs and MKCs will tell the supplier not only what is important to Boeing, but how to achieve it.

Traditionally, in reviewing past offloading at work at the DRC, too much emphasis is placed on what the final product requirements are, rather than on the process to achieve the final product. The supplier at times appears uncertain at times of what can or can't be done to achieve the final product. A typical offload usually starts by shipping door kits to the supplier, and then having them assemble the door from the kit. A gradual transition is then planned until the supplier can manufacture or procure their own parts as necessary to fabricate the door. However, this transition from kits to manufacturing doors on their own also requires the transition of the AKCs and MKCs unique to the manufacturing process. The supplier will not likely have identified all these during the kit assembly process, and therefore problems will likely still be encountered at this transition, as shown by past offloading experiences.

Therefore, inclusion of AKCs and MKCs along with the PKCs will assist the new supplier in identifying not only what to build, but how to build it. The added keys represented by the addition of the AKCs and MKCs serve to transfer the data contained within Boeings drawings and process specification, from just information to true knowledge.

7.6 Visible levers for cost Reduction Activities

One of the common complaints heard on the factory floor concerns trying to understand how their actions on the shop floor impacts the bottom line. It is hard for a drill press operator to see how their local improvement activities improves the bottom line for a new 747 standing out on the flight line. This is where an additional use for keys becomes manifested. Often times, an operators activity may not be associated with a PKC, so that in performing their operation, they have no need to be aware of the PKC. However, the addition of AKCs and MKCs lowers the level of the PKC attainment down to more of the lower level assembly steps, and hence to a greater population of factory workers. By identifying these AKCs and MKCs, the operators will begin to see how their actions, or items under their control, affect these intermediate keys. Then, by understanding how these intermediate level AKCs and MKCs are linked to upper level PKCs, a "line of sight" will be established from their vantage point to the upper level of the product assembly, or in other words, closer to the bottom line. If workers can see how their actions are linked to cost and profit, this provides additional incentive over and above the normal incentives and metrics in place.

7.7 Support Variation Simulation Analysis (VSA) and Assembly Modeling Efforts

VSA is an analytical method to study different possible assembly methods, and determine how variation might increase or decrease with each different assembly method. Assembly modeling is looking at the different possible paths or order of steps for the assembly to occur, and looking at the relative benefits of each. In either situation, keys provide the roadmap to insure that the assembly process is staying on track. The end goal of the assembly studying techniques would then be to deliver the optimum process which is still capable of delivering the associated PKCs. This use of keys provides a quantitative measure on which to judge and compare the different assembly methods.

7.8 Assist in Supplier Selection

With the decision to increase the amount of components bought outside Boeing, keys present a tool at the disposal of the purchasing or Materiel organization within Boeing. As one method of quantitatively ranking the suppliers, performance against delivery of comparable keys could be compared. Or for a supplier new to Boeing, keys could be identified by the IPT which would be the most difficult to obtain. The capability of the vendor to then deliver on these specific keys could be studied and tested, rather than just relying on a tour of the manufacturer's facility, and their response to a bid specification. If the supplier's capabilities appear such that these critical keys will instantly become StatKCs, then that vendor will need closer re-examination in comparison to other potential sources.

7.9 Chapter Summary

Key characteristics were created at Boeing as a tool for use in addressing the issue of hardware variation. However, as this chapter has shown, limiting keys to the use of just attacking hardware variation is ignoring several other potential benefits of key characteristics, especially when adapting the expanded quadkey methodology of identifying and classifying keys. Keys should exist at Boeing not just because of the AQS and HVC programs, but rather because this is one of their potential applications. By linking customer requirements explicitly to fabrication and assembly steps deep in the build plan, a host of other opportunities emerge outside the traditional realm of hardware variation reduction.

8.0 Conclusion

Key characteristics have proven themselves at The Boeing Company to be a valuable tool towards the strategic goal of reducing hardware variation. The quadkey methodology is the next evolution in the use of key characteristics, and its inherent advantages would only further improve Boeing's efforts to reduce hardware variation, and insure a built-in commitment to the deliverance of customer requirements;

8.1 Summary of Findings

The research conducted during the internship at the Renton Door Responsibility Center, as well as during the writing of this thesis, has resulted in the following findings:

1) *The HVC methodology is difficult to implement, even on new programs verses existing programs*. Even basic concepts, such as commonality of datums and flow down of key characteristics, become exponentially complex as one moves further down the engineering build tree

2) *Key Characteristic flow down as prescribed under HVC is not being done in several areas within BCAG*. Several elements contribute to this finding, among them that drawing schedule release dates are currently to aggressive to allow adoption of the HVC principles. A second major issue is that several members of the IPT's assigned to carry out the implementation of HVC have not received the proper training. The proper training is available, but apparently due to schedule or budget reasons is not being administered to all of the IPT members.

3) *The quadkey methodology poses several advantages for incorporation within Boeing*. Chief among them are the following:

a) Use of Assembly Keys to force realization that aspects of the assembly process are critical to delivering customer requirements

b) Concept that it is important to recognize whether a key is currently not being realized, or that is likely to be difficult to deliver. Such keys demand increased attention relative to other keys. This is embodied in the concept of StatKCs.

c) The identification of MKCs (although somewhat paralleled in HVC) and the realization that they are not just critical process parameters, but that they are intimately connected in a web of causality for delivering the upper level PKCs.

d) Establishment of a discipline and hierarchy between keys over and above that established through a flow down procedure

e) Identification of MKCs and AKCs related to delivery of specific PKCs allows easier tradeoff comparisons to be made between different PKCs in order to determine if the successful deliverance of one PKC is coming at the expense of another PKC. This is important to allow global optimization, rather than localized sub optimization.

4) *Key characteristic utilization should not be limited to just use for reduction of hardware variation.* Several other potential benefits for the use of keys are feasible and highly advantageous, such as their use in TPM, assembly modeling studies, or improving the transfer of work within or outside of Boeing.

8.2 Recommendations:

In the context of the above summarized findings, the following recommendations are made by the author.

1) *Incorporate the quadkey methodology for the generation and use of key characteristics:* As the current plan within Boeing is to attempt to merge and combine the precepts of the AQS program, the HVC program, and possibly Boeing Defense and Space Group's Hardware Variability Reduction (HVR) programs into one combined program, this would pose a significant opportunity for the inclusion of the quadkey philosophy.

2) *Insure that all members of the IPTs implementing HVC have sufficient training on the implementation and practice of HVC*: Four hour overview courses are insufficient to allow team members to fully implement the concepts of key characteristics and commonality of index and datums, much less the finer concepts embodied in HVC.

3) *Increased upper management support, especially at the lower and intermediate levels, must be generated to successfully implement HVC*: Although this is too easy of a recommendation to always suggest, it is in this case a real issue. Management needs to provide design and drawing release dates that allow for the successful inclusion of HVC principles. As up to 80% of the total cost of an airplane is determined solely within the design portion, this design segment is the proper time to insure that the precepts of HVC are being fully and accurately implemented. Metrics currently being utilized do not appear to communicate this requirment to management.

4*) Stress additional uses for key characteristics outside of HVC*: Keys, as was shown in this thesis, have several benefits outside the realm of hardware variation reduction. These additional benefits need to be communicated to all parts of the "Big M" value chain so that ability to deliver improved customer satisfaction is enhanced not just on the factory floor, but in the several other areas which also have a direct effect on attainment of customer satisfaction.

5) *Benchmark the automotive industry, as well as other potential industries which would need to be identified, as to the proper practice of key characteristics, specifically the quadkey methodology*: Boeing needs to study companies which are world class in the use of key characteristics. The automotive industry appears to have advanced the concept and implementation of key characteristics beyond that implemented by Boeing. While AQS and HVC were developed in conjunction with the automotive industry, this partnership needs to be continued to insure that the advances in the generation and use of key characteristics generated by others are also captured by Boeing. This involvement should not only include the corporate HVC group, but also several members from the different organizations in the manfuacturing value chain, so that these real world practices become more visible to them.

8.3 Recommended Areas for Further Research

To further benefit from the research conducted from this thesis, additional effort in the following areas would be suggested:

1) *Implementation process for adoption of quadkey methodology*: The incorporation of the quadkey methodology, while proving useful to Boeing, will not be without its difficulties. The adoption on new programs will not pose as much difficulty as will how to address its use on existing programs which utilized the key characteristic definitions under HVC. A method to allow identification of AKCs and MKCs for these products, while not requiring the prohibitive drawing change costs, needs to be determined. In addition, training materials would need to be revised to incorporate the methodology. The very infrastructure which made the adoption of HVC a success at Boeing now becomes in a way the largest impediment to further change.

2) *Methodology for the Identification of MKCs*: While PKCs and AKCs can be derived more from study of build plans or engineering drawings, as was done in this thesis, MKCs rely more on data than intuition. A machine tool may have tens of different parameters, each of which is being tracked by control monitors, but which of these are MKCs, if any, is difficult to qualify. A well performed Design of Experiments would be one method to allow this determination, but this would require the assistance of engineering. Methods to allow the factory operators themselves to determine the potential MKCs would generated additional benefits (process ownership etc.) beyond just the identification of the MKCs.

3) *Methodology to quantify relationship between different keys*: As was mentioned in this thesis, the quadkey methodology makes it easier to determine the relationship between keys. However, methods to allow this relationship to be defined in numerical or other qualitative terms, such as BCAG currently does with weight and fuel burn tradeoffs, would be a significant advancement.

4) *Continue to study ways in which practice of the use of keys can support Boeing's transition to an Agile company*: Key characteristics are often linked to companies that are agile. By being able to capture the customer's requirements throughout the manufacturing process, the ability for mass customization, and ability to maintain costs independent of volume levels, are increasingly able to be realized. The generation and use of keys will assist in the attainment of these end states, and Boeing needs to continue to research how the use of keys can help them obtain these end states.

5) *Identify metrics or incentives to allow increased acceptance of key characteristics at the factory floor level*: During this internship, the finding was made that keys are relatively misunderstood on the factory floor, and their measurement and use not considered as value adding steps. This appears not to be so much as a lack of training, but

inherent work force issues, perhaps linked to current metrics or incentives. These two items should be studied and modified as necessary to insure proper adoption of key characteristics on the factory floor level.

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Appendix

Exhibit 1: New Contract Language on subcontracting

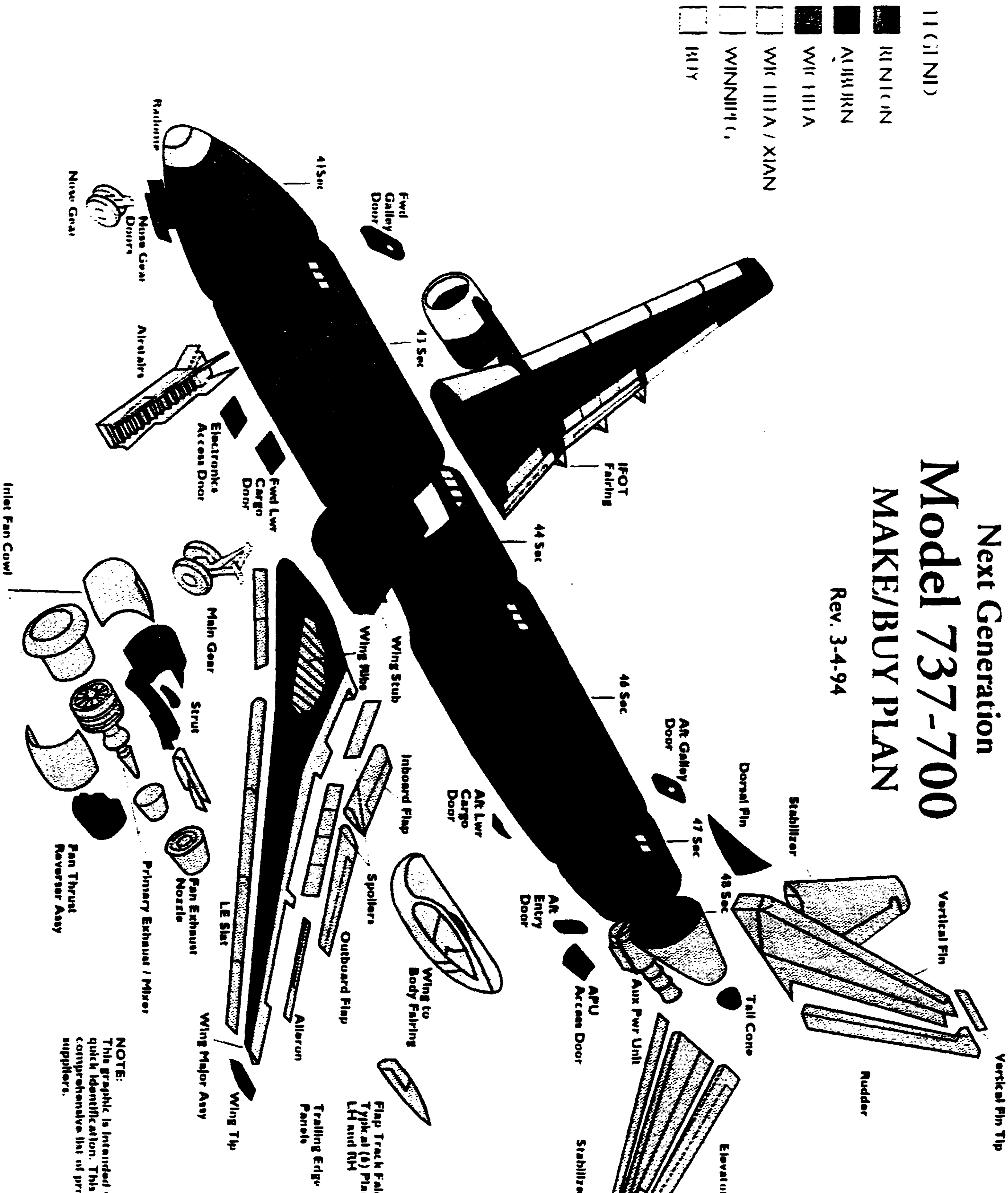
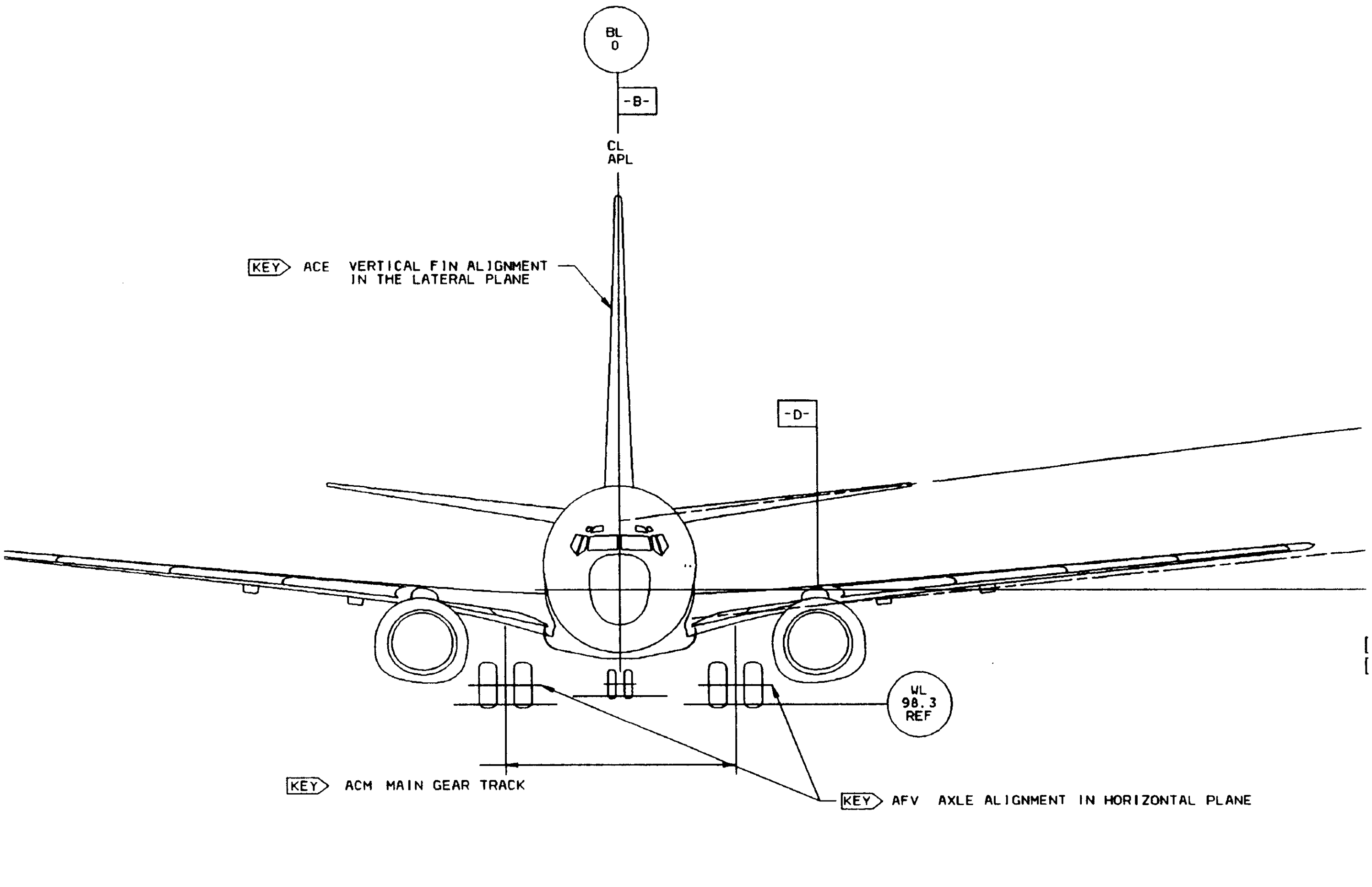


Exhibit 2: Example of AIP drawing



FRONT VIEW

Exhibit 3: Door with gates

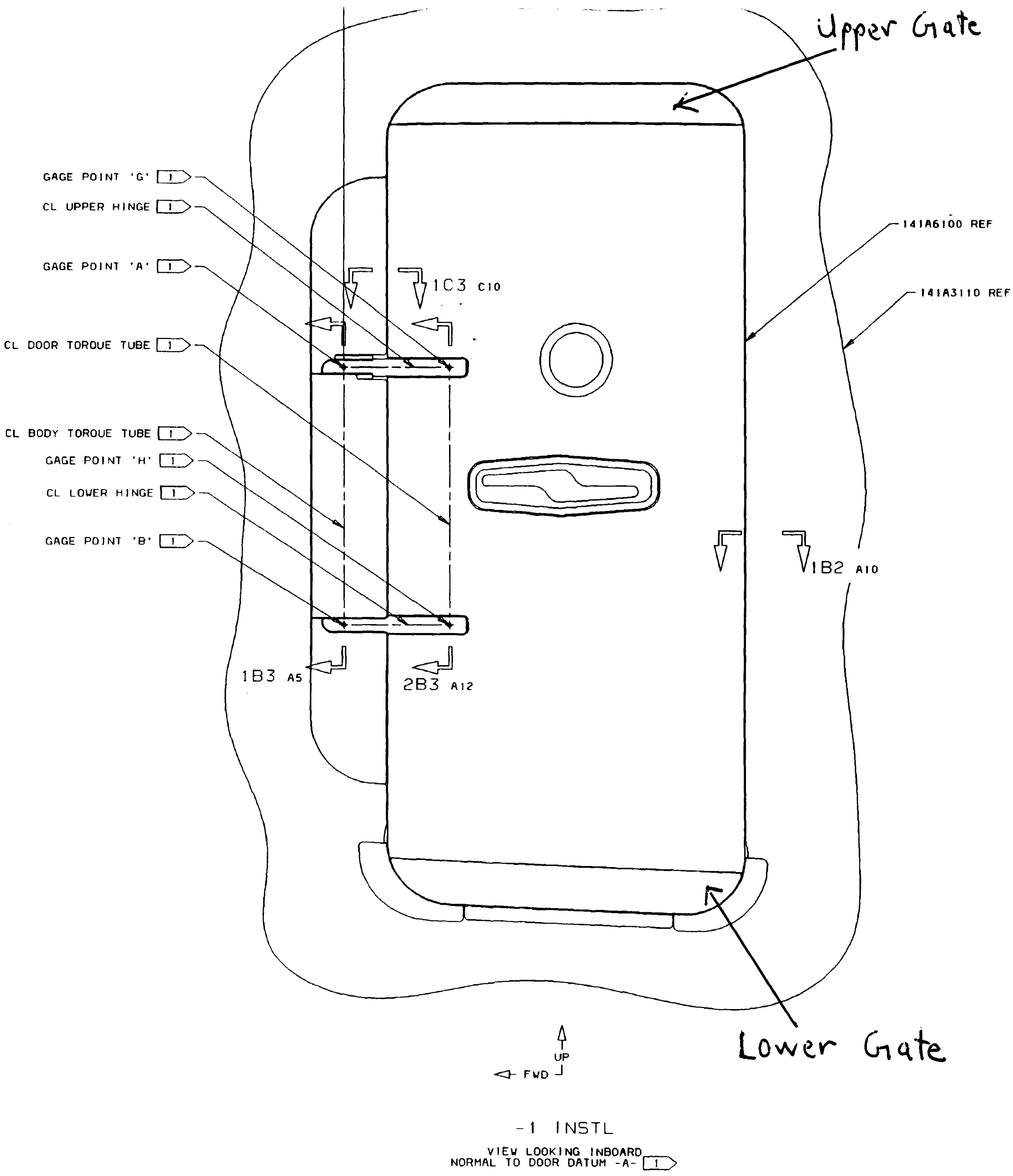


Exhibit 4: Lower Gate Detail Drawing

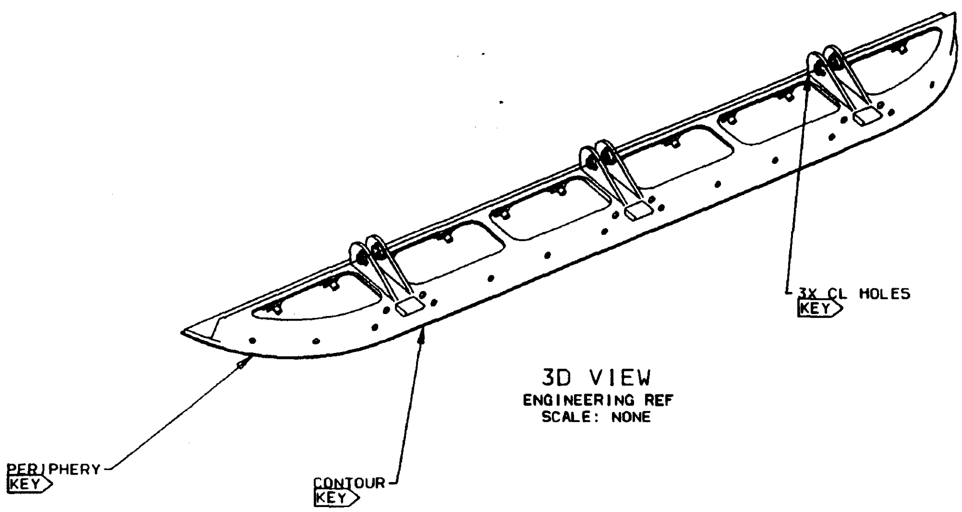


Exhibit 4 Continued

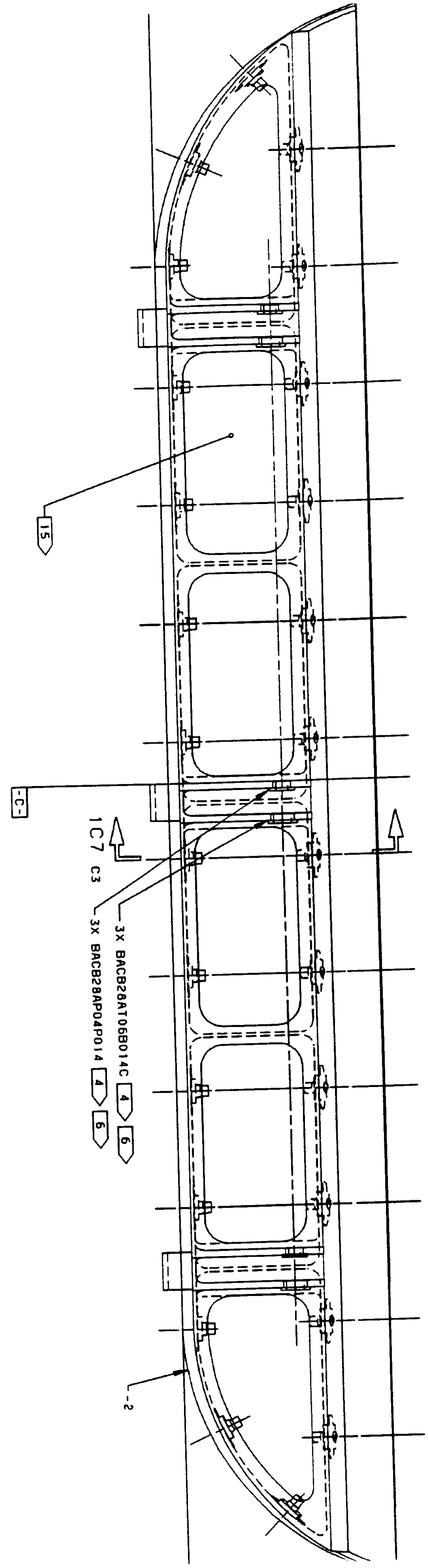


Exhibit 4 Continued

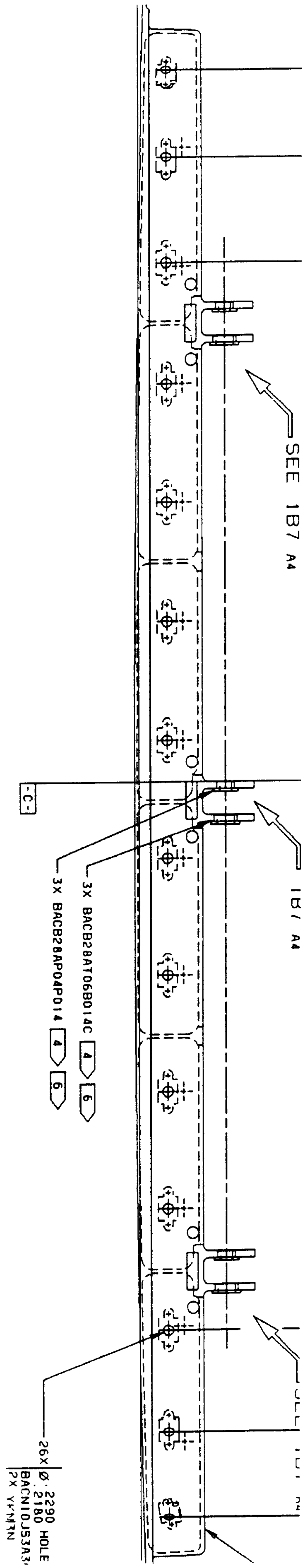


Exhibit 5: Lower Gate Installation Drawing

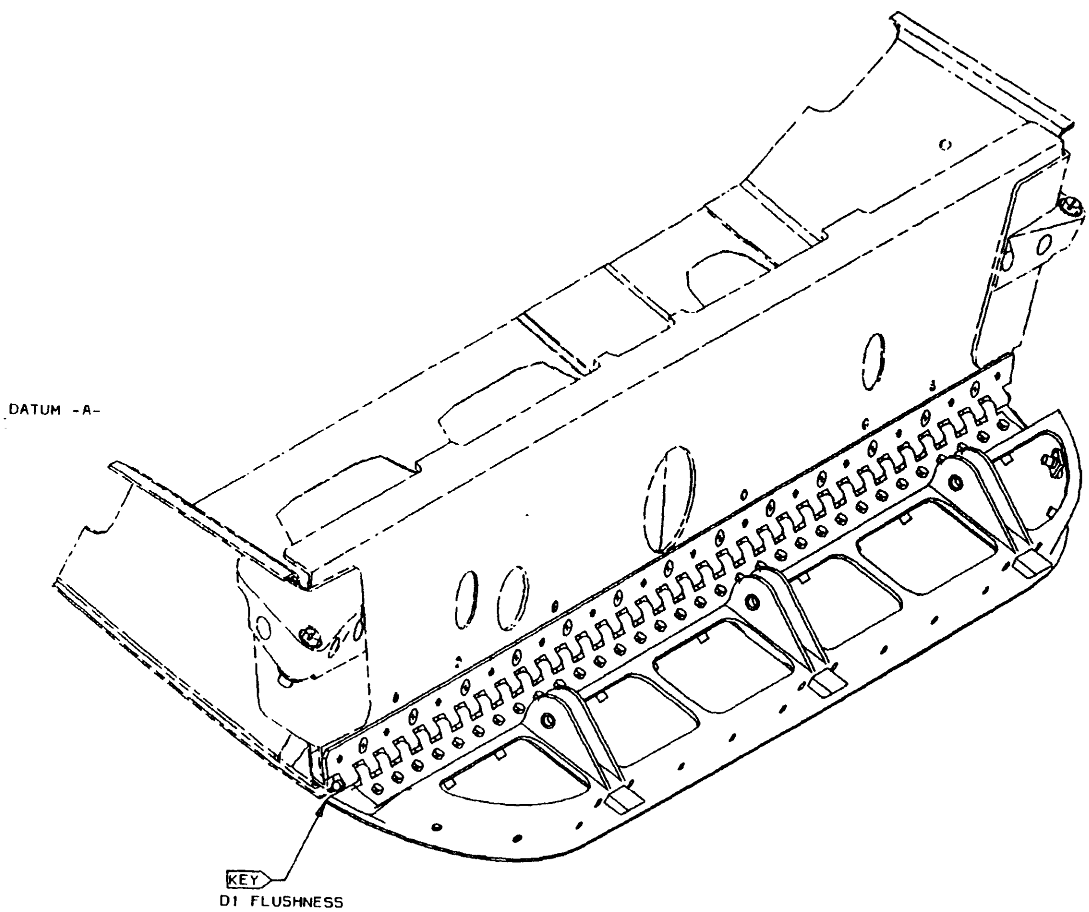


Exhibit 5 Continued

TOOL INDEXING POINT DEFINITION			
POINT IDENT	DIST. FROM DATUM -A-	DIST. FROM DATUM -B-	DIST. FROM DATUM -C-
POINT A1	6.2212	10.3789	-34.5380
POINT A2	5.6056	-5.2234	-30.9638
POINT A3	5.0036	26.2410	-32.1520
POINT B1	6.4382	20.4500	-35.6518
POINT B2	6.8249	0.2681	-34.8896
POINT C1	7.6966	10.8682	-32.9325

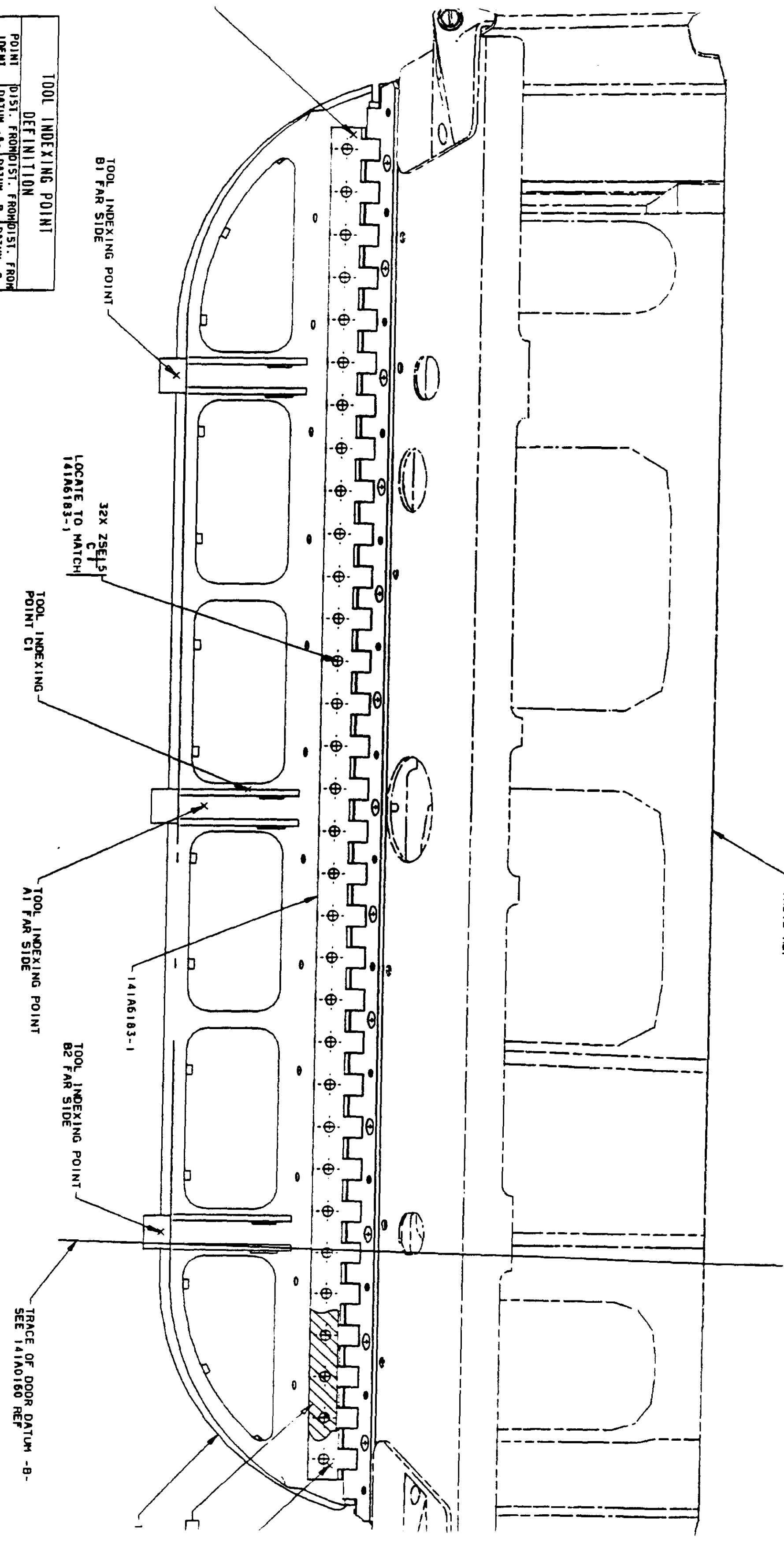


Exhibit 5 Continued

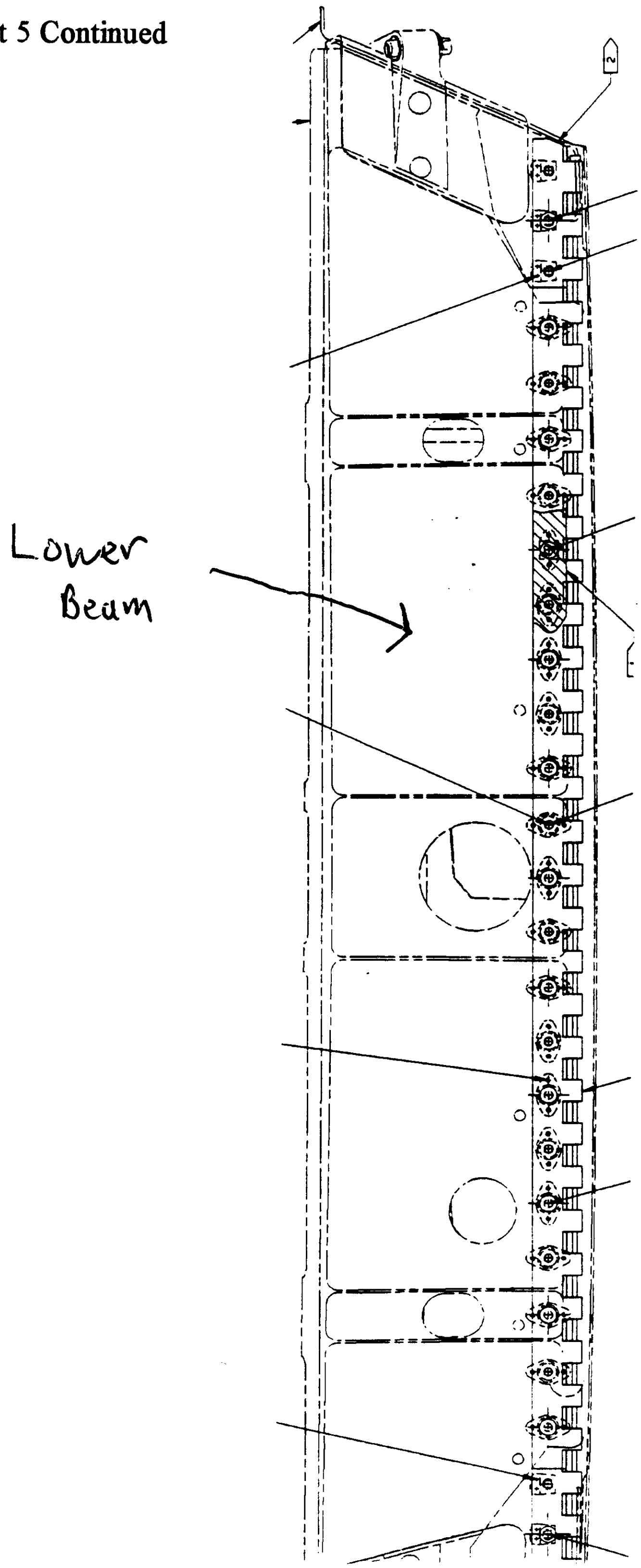


Exhibit 6: Misfairings Example

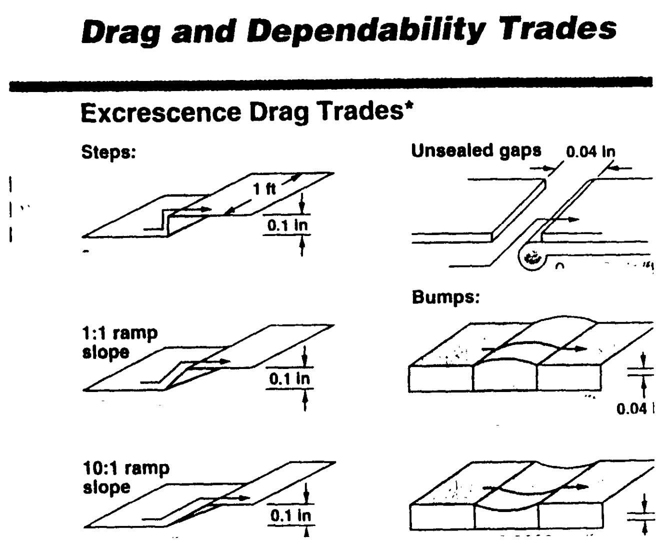


Exhibit 7: Previous Shop Problems Document

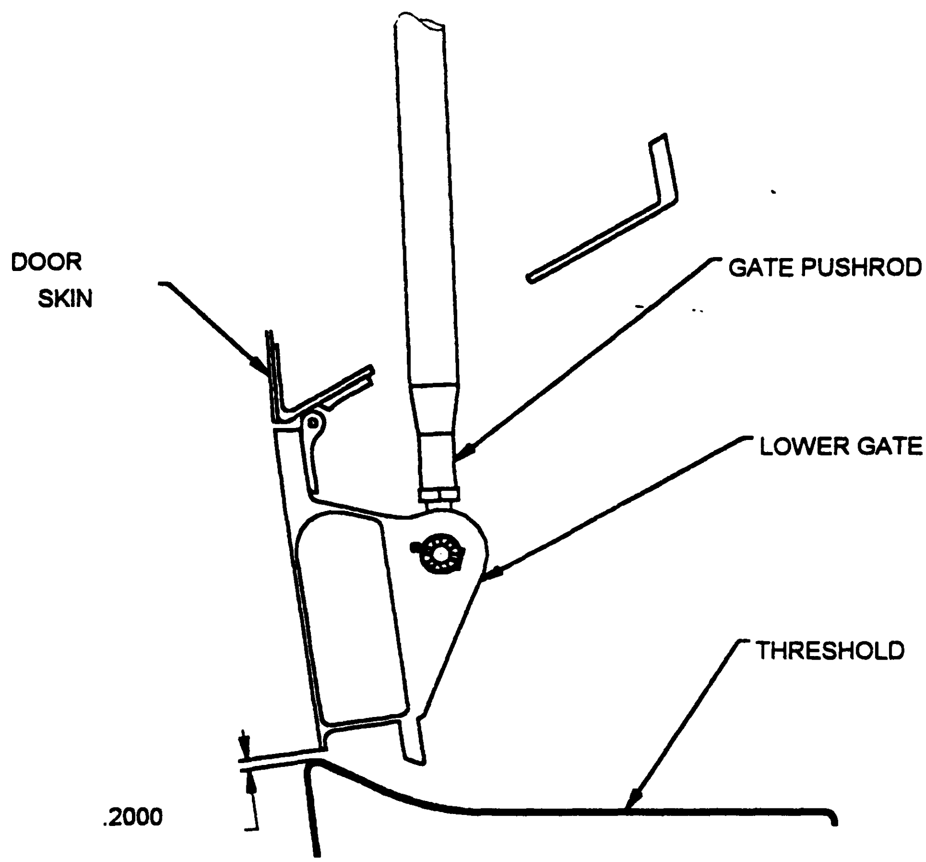


Fig. 2-9

Lower Gate Gaps

Once door height adjustments are complete, check that the door is bottomed on the lower nut, bring the upper nut down to contact the upper bearing snugly, and back off to the nearest cotter pin hole. Avoid overtightening the nuts.

Install cotter pins in both nuts.

Exhibit 8: Datums

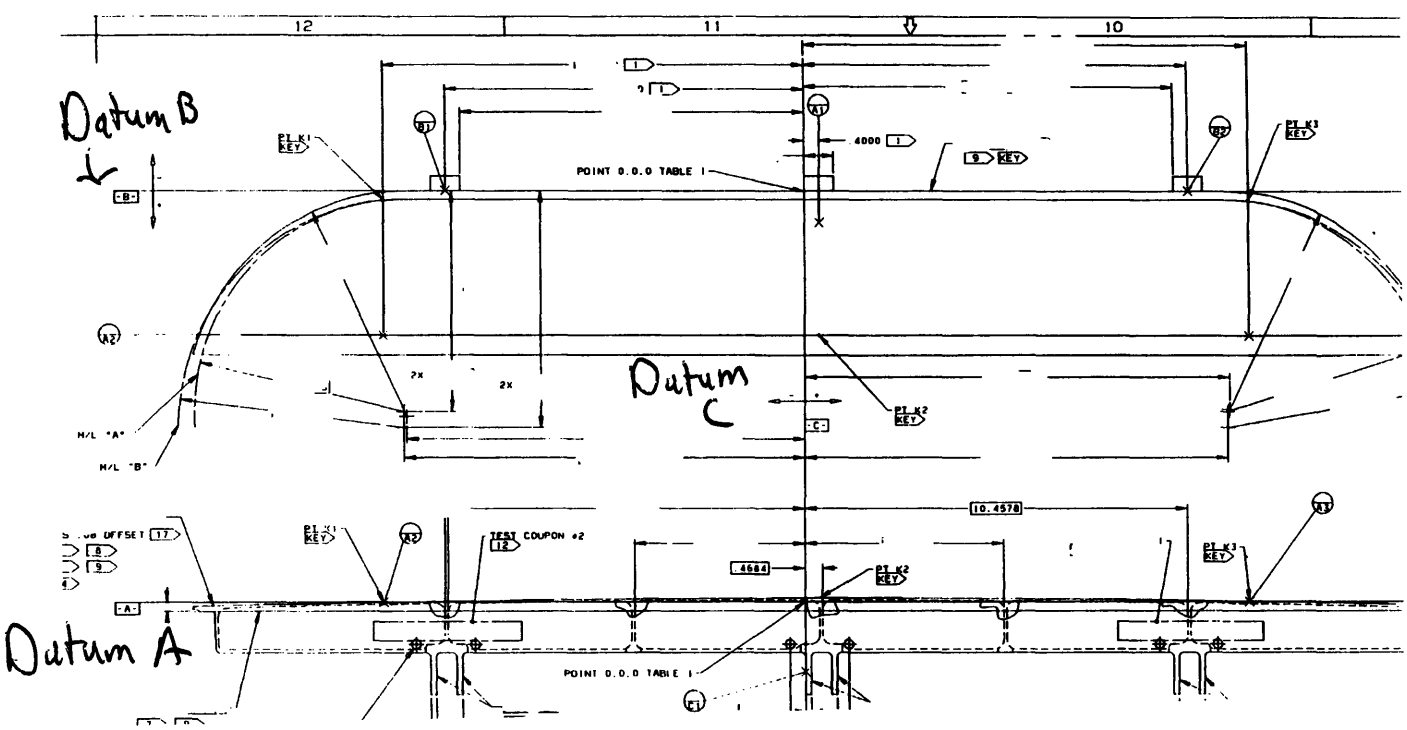


Exhibit 9: FAJ4 inspection tool

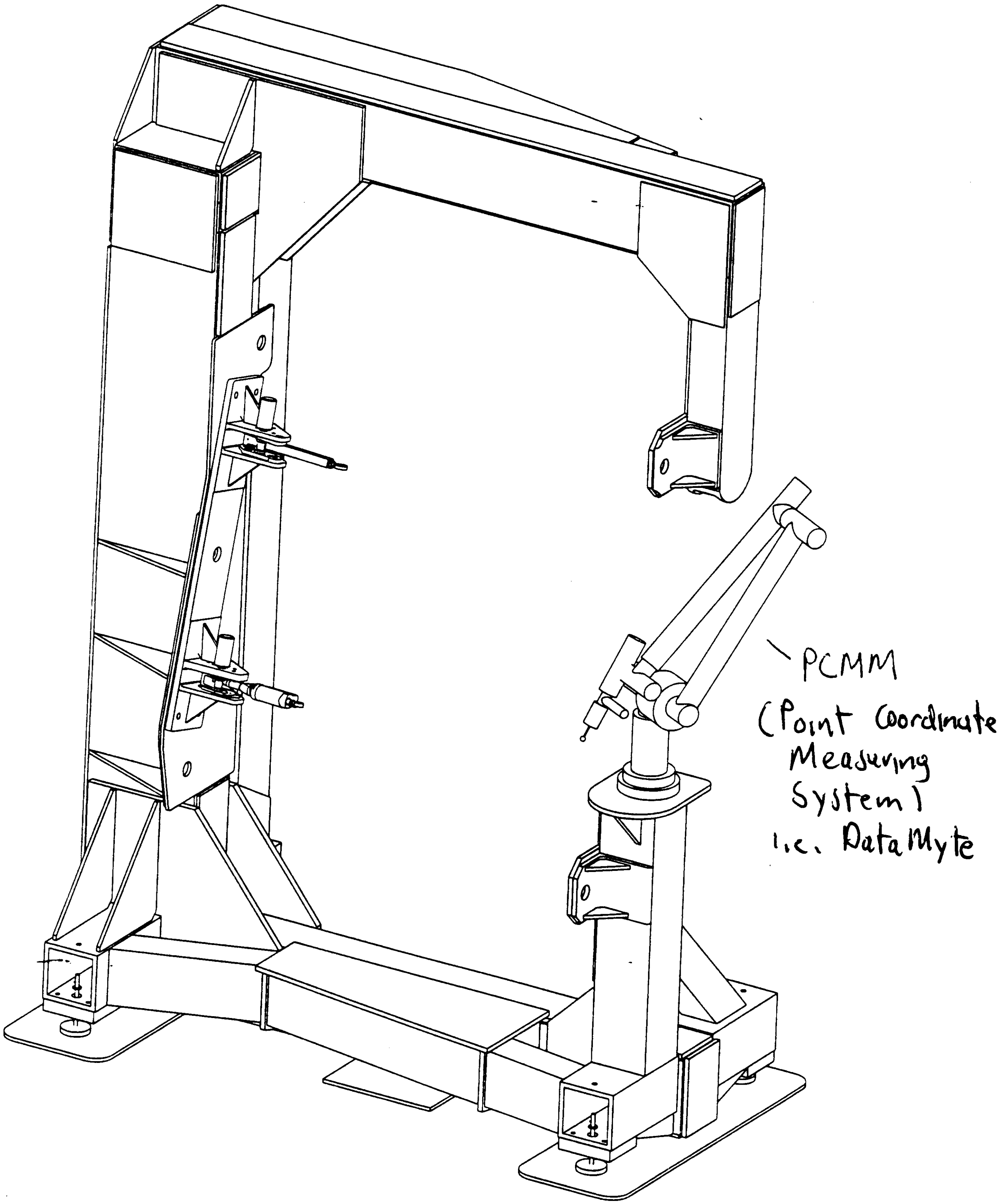


Exhibit 10: Door Frame

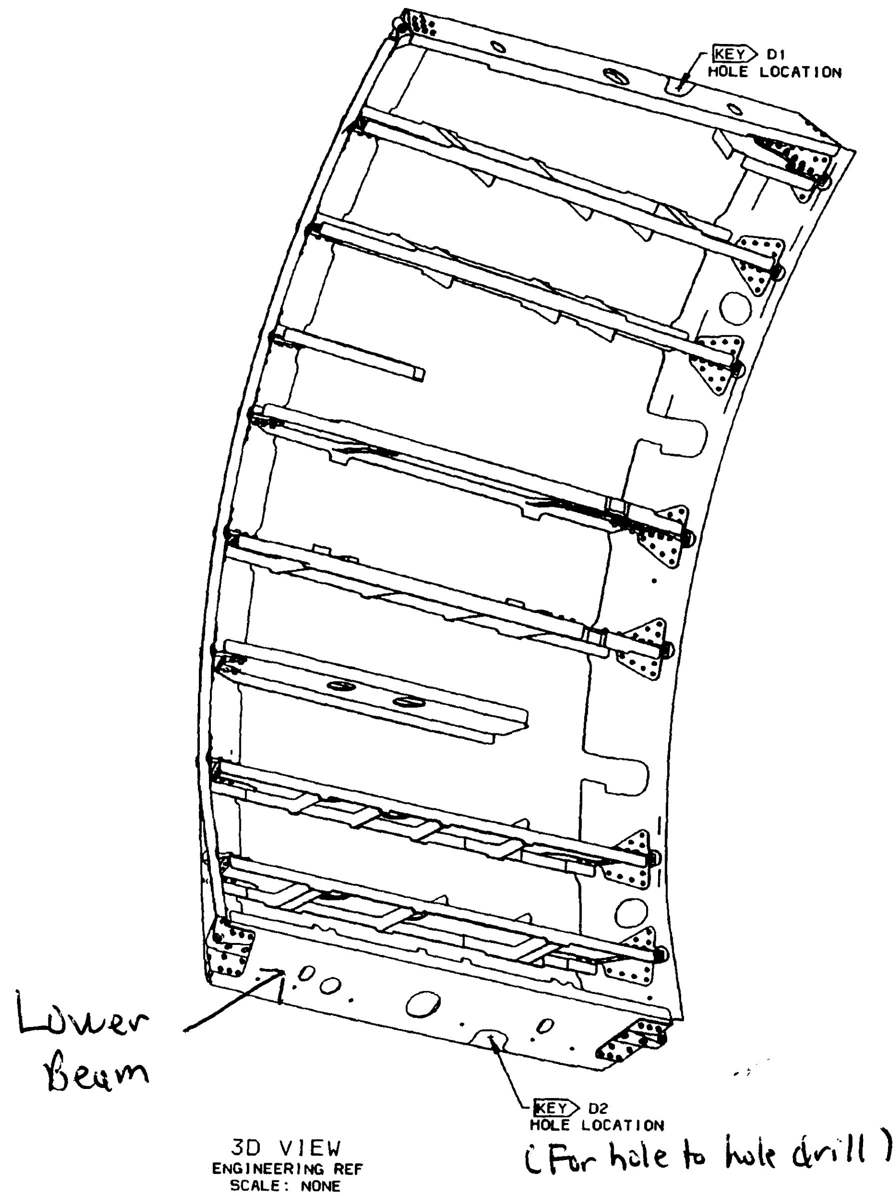


Exhibit 11: Assembly Level Quadkeys

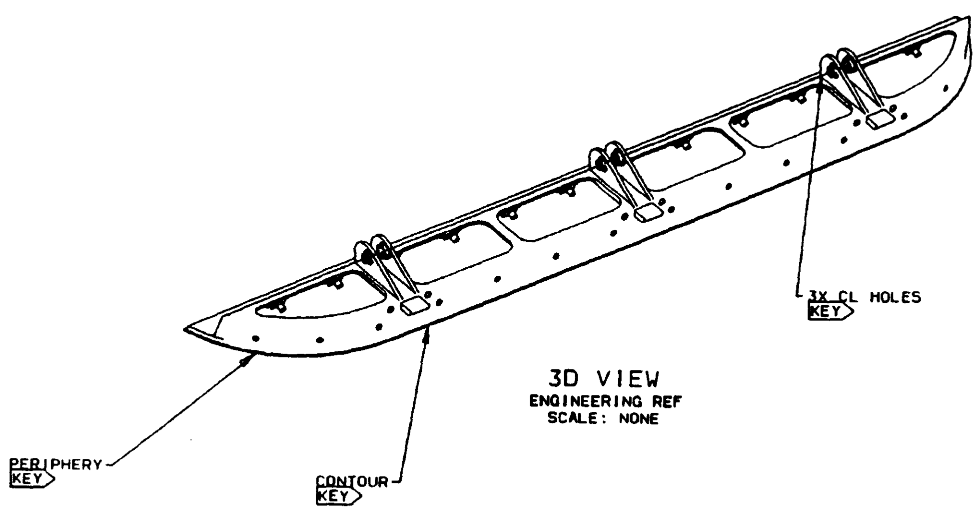


Exhibit 12: Installation Drawing Quadkeys

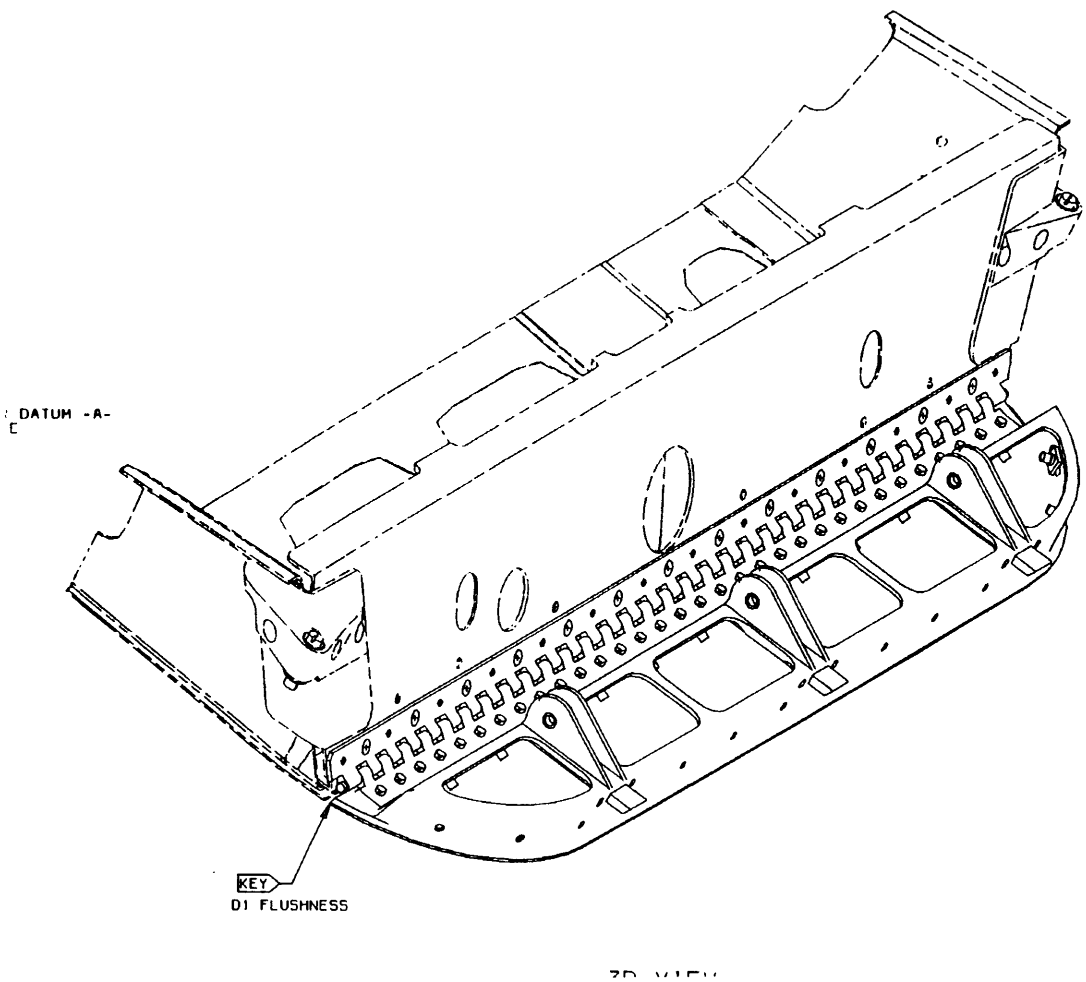


Exhibit 13: Mounting edge

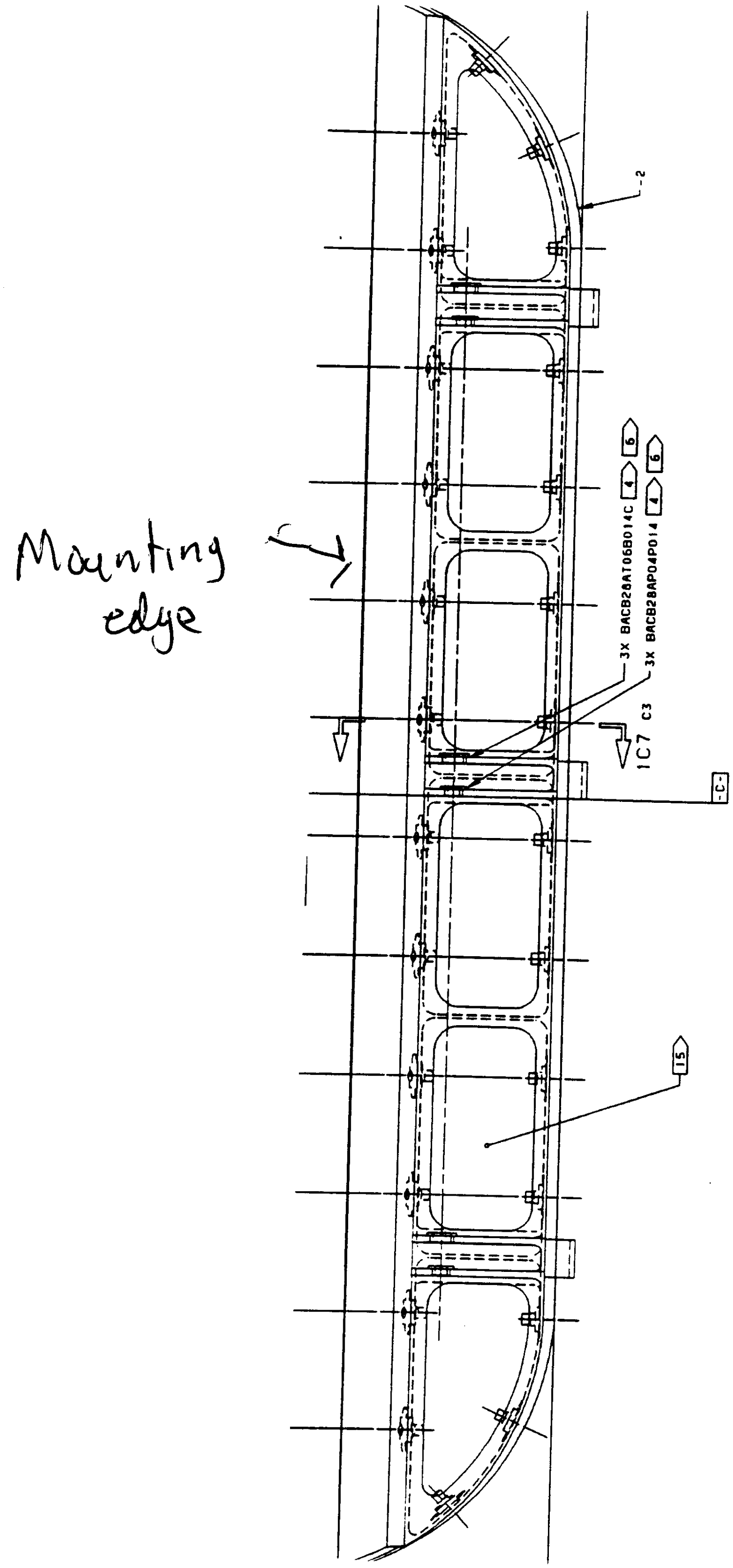
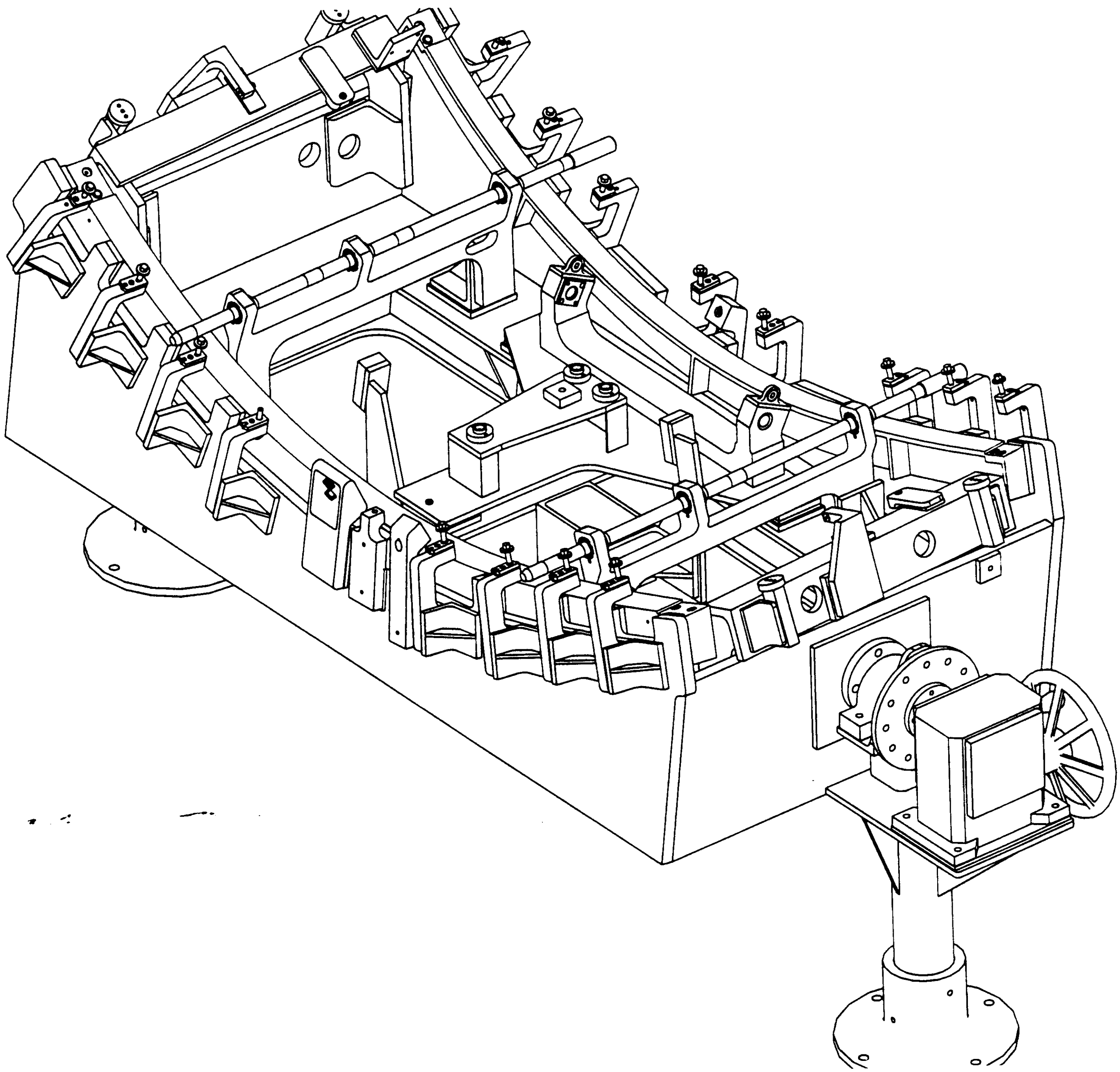


Exhibit 14: Door Beam tooling Fixture



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