An Optimized Product Development Process For Aircraft Gas Turbine Engines

by

Maurice Weinberg

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Signature of Author _____

Maurice Weinberg
System Design and Management Program
February 2002

Certified by _____

Warren P. Seering
Thesis Supervisor
Professor of Mechanical Engineering

Certified by _____

Dr. John Saabas
Industrial Thesis Supervisor
Vice President Engineering Pratt & Whitney Canada

Accepted by _____

Steven D. Eppinger
Co-Director, LFM/SDM
GM LFM Professor of Management Science and Engineering Systems

Accepted by _____

Paul A. Lagace
Co-Director, LFM/SDM
Professor of Aeronautics & Astronautics and Engineering Systems

BARKER

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1.0 Chapter 1 – Abstract and Introduction

The eventual success or failure of a project is often determined by how the program was managed from initiation until it is finally certified and introduced into the field. This Thesis will concentrate on projects that are large in nature and the success or failure of the project has a real impact on the financial well being of the company involved.

Steve Eppinger and Karl Ulrich, in their book, "Product Design and Development"(1), defines Project Management as the activity of planning and co-ordinating resources and tasks to produce products that meet their goals. Project execution involves co-ordinating and facilitating the myriad of tasks required to complete a project in the face of inevitable unanticipated events and the arrival of new information. This thesis will propose and evaluate an optimum methodology to accomplish this.

All projects start by a concept being sold to someone – either to an end customer or to a board of executives for approval. There is a limited time frame coupled with limited resources for the Project Management Team to fully understand all the unknowns before the Project is presented. All funds used have to be internal risk money, which is lost if the Project is not given a go ahead. At the point where the Project is sold, commitments, that must be kept in the future, are made. The Project Manager does not want to invest a lot of resources into a Program, which he doesn't know for sure will move forward. On the other hand once he makes the commitments he has to deliver on them. The Project Manager is faced with these types of dilemmas throughout the entire Project at least until the product is delivered and usually after that.

To address these dilemmas Project Managers have developed many processes such as Best Practices, Standard Work, and Design Reviews etc. This thesis will look at the processes used and develop some key steps that minimise the long-term risk in an efficient manner. Because of the background of the author the type of projects this thesis applies are large, technically complicated projects, whose success, or lack of, has a direct impact on the financial health of the company.

The development of these types of programs really can be broken down into the following five phases:

1. Pre-launch – All the activity that is done from the time a Project is conceived until it is sold to either an outside customer or investor, or an internal board of directors.
2. Concept Design – The phase when the concept is firmed up into a real design and the Product is defined.
3. Detail Design – The phase when the Product becomes defined to the point where it can be produced, developed and validated.
4. Development and Validation – The phase in which the Product is developed and made ready for the market.
5. Production – The Phase where the company reaps the rewards of its effort. If the Product meets or exceeds the original promises made in Phase 1 then the rewards to the company are positive. If the product falls short of the promises made in Phase 1 the warranty costs, coupled with lost sales can be very costly to the company.

In European companies there is actually a phase between phase (2) as shown above and phase (3). This phase is the Embodiment Phase – in which the high-risk items in the design are addressed.

This Thesis concentrates on the Aerospace Industry and the first three phases listed above. I will delve into some of the different Management techniques currently being used, and an understanding of them by presenting case studies and interviews that were held with Senior Program Directors in my company Pratt and Whitney Canada. I will present the major policies being used, why they were developed, to whom do they give the most benefit, and their positive and negative aspects. I will then present the notion of "Full Upfront Knowledge" coupled with using an "annealing process" to arrive at an optimum definition, and relate to how these methods enhances the design and development of Aerospace Products. These notions are incorporated into the Embodiment phase used by many European companies.

The Product that I use in this study is the Aircraft Gas Turbine Engine, which represents a high development cost, high technical challenge, and very competitive performance product in the Aerospace industry. I will bring in concepts from other industries, such as the "Toyota Set Based Design System, and the "IDEO Product Development Concepts". I will show the benefits of the "Full Knowledge" approach and how it is best applied to the design and development of new and innovative Aircraft Gas Turbine engines.

In order to successfully bring a new Aircraft Gas Turbine Engine into the market it must either fit a niche in which there are no other competing products, or bring in benefits that make it superior to anything in the market now or in the near future. Both scenarios by their very nature contain unknowns. The product must be innovative and have features that are not currently on existing products. These features have risk associated with them and these risks must be mitigated. That is where the concept of full knowledge and product definition annealing come in.

Full Knowledge refers to understanding the product fully at a component level early on in the program. It requires putting in a massive effort up front in a program to really understand all the potential issues and risk that can arise during the program. Arriving at Full Knowledge early in the program requires that the Project Management team really understand what knowledge is needed, and the best and most effective manner to gather that knowledge. There are basically three ways to gather the knowledge:

- Learn from previous programs and the existing knowledge base. Many companies enforce a "Rules Based Design" in which only technology that has previously been developed and validated in the Research community can be used on a new product. This then forms a firm base for understanding the new product.
- For concepts where "Rules Based Designs" don't apply or must be enhanced by new and innovative approaches, there are basically two methods used for gathering the required "Full Knowledge", analysis and testing.

A critical decision on any full knowledge program is to understand what knowledge can be obtained with a high level of confidence using analytical tools, what requires testing, and what is best served with a combination of both. It really requires the weighing and balancing of the cost, level of certainty and time required to achieve a confident answer of each of the methods used.

The issue with the "Full Knowledge" approach is that the information, which has to be collected early on in the program, isn't perfect. The data is collected on prototype or boundary objects that don't exactly represent the real product. Many in the Design/Analytical community are perfectionists especially if the results do not match prediction and therefore ignore all the data and knowledge collected.

Product annealing refers to the method of not firming up a design too early in the process. Once a design is frozen the "solution space" becomes very limited and the opportunity to arrive at an optimum solution is compromised. Product annealing coupled with concepts of the Toyota Set Based design methodology allow the solution space to remain large during the early phase of the program, and then follow a controlled convergence to an optimum solution.

As mentioned above the focus of this thesis is the design and development of Aircraft Gas Turbine engines. This activity has been ongoing since World War 2 and the Aircraft Gas Turbine engine has evolved into a technical marvel. Over the past 2 decades the life span of a particular product has been reduced from approximately 40 years of new production to approximately 15 years of new production. At the same time the development cost of a new product has risen dramatically. Very few companies have the financial strength to develop an Aircraft Gas Turbine engine by itself. Partnerships have flourished to share in the cost risk and eventual rewards. Due to the high risks involved many different Product Development methods have been developed.

In Chapter 2 of this document I will review several Project Management processes as they are currently practised in companies outside of United Technologies and for products other than Aircraft Gas Turbines. The main focus in this chapter is to have an in depth look at the automobile industry, as well

as other innovative organisations, and determine how products are developed and understand the methodology used. In Chapter 3 I will review several recent engine development programs at Pratt and Whitney Canada, a division of Pratt and Whitney Aircraft. The thesis uses historical data coupled with program success to establish best practise aircraft gas turbine engine development procedures. In Chapter 4 I will present an alternative method and discuss where it is applicable and how it is an improvement over the systems currently being used to develop aircraft gas turbine engines. The methodology developed is being utilised on a current development program the PW600 family of engines. The development of this family of engines is being used to case study the methods proposed in this thesis.

2.0 Chapter 2 - A Study of Program Management and Product Development outside of Pratt & Whitney Canada

The automobile industry has experienced vast changes to how their products are developed and how programs are managed over the last century. Henry Ford at Ford and Alfred Sloan at General Motors established the methodology that allowed the automobile industry to evolve from making a luxury item for the few to making a essential product that can be enjoyed by the masses. In the last 30 years lean manufacturers, led by the Japanese, have revolutionised the automobile industry, which has brought that industry new levels of efficiency and quality. Below I have summarised several books and papers that describe the history and evolution of the Automobile industry emphasising product development in that industry.

The book, "My Years with General Motors" (2) outlines Alfred Sloan's tenure at General Motors. He developed a management system that allowed General Motors to dominate the automobile market until a new wave of Japanese carmakers entered the market in the 1970's. The management systems and the development processes used by these Japanese car makers is outlined in the book "The Machine that Changed the World" (3) and the papers "Principles from Toyota's Set-Based Concurrent Engineering Process", (4) and "Product Development in the World Auto Industry"(5). In this chapter, I have summarised this literature and then outlined the different product development management systems used. The objective of this chapter is to understand the differences between the two competing product development systems, the strengths and weaknesses of each system, what each system does well, to whom does each system cater to and in what environment does each system flourish.

2.1 My Years with General Motors

After World War I, Henry Ford and General Motors' Alfred Sloan moved world manufacturers from centuries of craft production - led by European firms – into the age of mass production. It is important to note that the key to mass production wasn't – as many people then and now believe – the moving, or continuous, assembly line. **Rather, it was the complete and consistent interchangeability of parts and the simplicity of attaching them to each other. ***

Alfred Sloan led the management of General Motors for over 30 years from the 1920's to the 1950's. In that period he established General Motors as the premier automobile development and manufacturing company in the world and earned a reputation for management excellence. In this chapter we will review Sloan's methodology in an effort to understand what he did and establish (in chapter 4) which of Sloan techniques should or perhaps should not be used in the product development of high technology items such as an aircraft gas turbine engine.

Sloan believed in focus, knowing the product and working from facts. He stated that the strategic aim of a business is to earn a return on capital. " The primary object of the corporation was to make money, not just motorcars". Sloan insisted that managers be focused on the bottom line and manage by the numbers. He claimed, "I happen to be one of the old school who thinks that a knowledge of the business is essential to a successful administration". He believed that managers must be technically competent and know the product as opposed to some who believe that management is a science onto itself and one can go from managing a light bulb factory to managing an aircraft engine company.

To manage such a large and diversified company Sloan advocated decentralisation of management. General Motors Management philosophy was and still is **decentralisation to the divisions with co-ordinated control from the corporation through executive committees.** This is designed to give a very large corporation the advantages that smaller companies enjoy such as lower levels of bureaucracy and speed of decision making while still maintaining the advantages of big companies such as huge resources, and political clout.

2.1.1 Research and technical development

All great managers build their management philosophies around their experience usually learning from their previous mistakes. Sloan was no exception. The defining project that showed that GM really needed a procedure for defining and developing technically advanced programs was their attempt, in the 1920's to develop a new type of automotive engine the "copper-cooled" engine. General Motor's experience with the "copper cooled engine" is summarised below.

The copper cooled engine was a great theoretical concept that on paper offered many important advantages.

- It got rid of the cumbersome radiator and plumbing system of the water-cooled engine
- It reduced the number of parts in the engine, its weight and its cost.

It was designed and developed by scientists rather than engineers and in isolation by a remote Advanced Design Team (later called the General Motors Research Corporation at Dayton). No attempt was made to get buy in from the divisions. The copper cooled project was established by decree and shoved down the throats of the division engineers with a fixed incorporation date. There no backup plan or as Sloan later said " a second line of defence". The timetable was set based on success. No buffer was put in for reworks, or things learned during the test phase.

The initial testing phase was not rigorous enough so when the product finally went into production, all the cars produced had to be recalled. Once the initial cars were recalled the project was doomed. It could never recover, especially since there was no buy in from the Producers. The Producers (divisions) were only too happy to let it fail.

The significant influence of the copper cooled engine was in what it taught General Motors the value of the organised co-operation and co-ordination in engineering and other matters. It showed the need to make effective distinction between divisional and corporate functions in engineering, and between advanced product engineering and long-range research. The following lessons were learned:

- There is a distinct need for Advanced Engineering to define long-range technical improvements.
- The engineering concepts proposed must be demonstrated in such a way that **the facts** must be accepted rather than theories.

- Advanced engineering should have waited until they had a car that **demonstrated** a reasonably satisfactory performance before proposing it to the divisions.
- Risk mitigation techniques should have been used. A back up design should have been developed.
- Advanced Engineering should have sold the concept to the Producers and involved them in the project early in its development.

After the "copper-cooled" engine fiasco, and as a result of the lessons learned, General Motors created the General Technical Committee to address some of the shortcomings that are listed above. The basic structure followed GM's management philosophy of decentralisation that is co-ordinated by committees.

The General Technical Committee included the Chief Engineers of each Car Division; Staff engineers from the Research Corporation (the central Advanced Engineering Organisation) and a number of very high-level officers of the General Motors. This was an attempt to bring all relevant parties into the technical discussion and decision-making process. The mandate of the committee was to deal in problems, which would be of interest to all Divisions and would, by dealing with such matters largely formulate the general engineering policies of the Corporation. The committee accomplished the following:

- **It established the importance of product integrity as the basic requirement for any new innovation incorporated into the product.** The General Technical Committee developed a Proving Ground to thoroughly test vehicles, using standardised test procedures and measuring equipment. The Proving Ground became the corporation's center for making independent comparisons of division products as well as competitors products. The Technical committee laid out 4 principles that had to be satisfied before Appropriations for Capital expenditure could be approved. One of the principles that had to be satisfied was – Has the Project been properly developed **technically?**
- It set up the General Motors Research Corporation at Dayton that would be devoted to long – range investigations. Those that showed promise would then be further developed by the GM

general engineering staff. The general engineering staff assigned to the task would consist of special "product study group" that was formed and placed inside a manufacturing division. When they worked out the technical bugs it would be handed over to the Division and commercialised by the Division engineering staff.

The philosophy for such an arrangement is that a division, charged with bringing out a new model every year, constantly brings out new problems, which are its primary responsibility. When you inject a piece of long-range research and development into this situation you are superimposing on an already loaded organisation something to which it cannot properly give its attention. Recognition of this led to the **formation of the Engineering Staff**, which reports to the central office. The Engineering Staff engineers the science from the Research Corporation into a practical state so that the Division engineering departments can incorporate it into cars

A good example of how this system functioned is illustrated by the development of the Automatic Transmission. Work started in the early 1920's. The General Motors Research Corporation at Dayton studied a wide variety of candidate automatic transmissions. By 1928 the Research Laboratories had reached a consensus on an automatic-transmission form that might be satisfactory. This was an infinitely variable type using a steel-on steel friction drive employing a mechanical principle like that of a ball bearing.

The job of developing that transmission was then given over to the Buick Division since GM had no general engineering staff at the time. Many units were built and tested out on test cars, but despite a great deal of effort they never managed to solve all the problems involved, and this transmission was never put in any GM car sold to the public. The effort then went back to the Research and corporate staff engineers and in 1934 this group became the Transmission Development Group.

By 1937 the Research and corporate staff engineers perfected a fluid torque converter design that they successfully incorporated on their busses. During the WWII this design was adapted for use in Tanks. After the war the Engineering Staff working together with Buick and Chevrolet engineers adapted the fluid torque converter design to passenger cars. In 1948 after many years of

research and engineering, General Motors offered automatic transmissions that could be produced economically and efficiently even for low priced cars.

By creating the General Technical Committee GM accomplished the following:

- Established the importance of long-range research (the concept of creating technology) as something different than product development. Product development was done in the divisions while primarily General Motors Research Corporation at Dayton handled long-range research. Once the basic research was done and proven the Division engineers took on the task of developing the technology into a product.
- Brought Division Engineering much closer to the work being done by Research Corp (Advanced Engineering)
- The General Motors Research Corporation at Dayton would continue to push the science but it became the task of the Division to commercialise and develop the concept. It became their product and they had an interest in making it work.
- Product integrity became important and a standardised testing and substantiation system was created to confirm the product integrity.
- Product uniformity was established across the General Motors.
- Competitor products were investigated and learned from.

2.1.2 Product Development

Sloan subscribed to the importance of a full product line even when the intermediate products take market share away from other products the company is producing. In the 1920's the General Motors product line was - Chevrolet $510; Olds $750; Oakland (Pontiac) $945; Buick "4 cylinder" $965; Buick "6 cylinder" $1295; and Cadillac $2985. Sloan determined that there was a gap between the Buick "6 cylinder" and the Cadillac at the top and the Chevrolet and the Olds at the bottom. He insisted that a car be developed between the Chevrolet and Olds to fill the market gap. He overruled the opposition to this product who felt that the new car would diminish the sales of the existing product. He felt that although the new car would probably take business from both Olds and Chevrolet, it was be better that we take business from their own Divisions than have competitors do so. Sloan then decided that the new car would be designed by Chevrolet; He determined that development should be undertaken by the Chevrolet Engineering organisation because in so doing there will be every tendency for them to use what they could of existing Chevrolet products and to capitalise Chevrolet components, plants and assembly plants. He also felt that there would be less tendency to introduce this or that difference simply because the engineer wishes very naturally and properly to inject his own personality into the picture.

Sloan laid out the product development process that hasn't changed greatly at General Motors over the years. The entire new-model automobile program has three phases. *Styling* dominates the first year of the program; engineering *design* is continuous almost throughout the entire two-year period, with work ending just before mass production begins; equipment *and tooling* begin before Styling completes its work, and cover the multifarious and elaborate processes required to actually make a car. Overall engineering work fall into two areas: one centers on the **product** and the other on the **process of making it.** Engineering and styling define the product. The Manufacturing engineers are responsible for the process of making the product. Their general aim is to improve product quality, increase productivity and reduce the cost of manufacture.

During development, boundary objects are used extensively. During the initial design review meetings the Styling Staff display full size drawings as well as "**seating bucks**" which are constructed to

simulate the proposed car interior. Over the months the Styling Staff refines the design and continuously build, **first clay and then plastic models** of the proposed new cars. After the Engineering Policy Group, Fisher Body, and the car divisions approve the clay and initial plastic models- often with some modification- the Styling Staff set to work building new, much **more elaborate plastic models**, which are identical, inside and out, with the models that will come off the production. The engineering departments of the car divisions and of Fisher Body work continuously with the Styling Staff in order to reach agreement on the chassis dimensions. The car divisions build **handmade experimental chassis** for testing and evaluation.

2.1.3 Management characteristics of A. P. Sloan JR. and General Motors under his leadership

Sloan believed in managing objectively "by the numbers" from a small corporate headquarters. He set up an excellent system of checks and balances and insisted that people work from facts. * Sloan and his executive group demanded detailed reports at frequent intervals on sales, market share, inventories, and profit and loss and reviewed capital budgets when the divisions required funds from the central corporate coffers. New professions of financial management and marketing specialists were created to complement the engineering profession, so that every functional area of the firm now had its dedicated experts.

Sloan thought it both unnecessary and inappropriate for senior manages at the corporate level to know much about the details of operating each division. If the numbers showed that performance was poor, it was time to change the general manager. General managers that showed consistently good numbers were candidates for promotion to the vice presidential level at headquarters

Sloan was always planning for the future. – In 1942 during the heat of World War II General Motors had an active Post-war Planning Group. He was able to master change, unlike his competitor Henry Ford, or the US automobile industry today. Sloan was able to understand how the business was changing and what he had to do to compete. Sloan was an innovative thinker who resolved the basic mass production need for standardisation and the model diversity required by the huge range of customer demand. He achieved both goals by standardising many mechanical items, such as pumps and generators, across the company's entire product range and by producing these over many years

with dedicated production tools. At the same time, he annually altered the external appearance of each car and introduced an endless series of "hang-on features," such as automatic transmissions, air conditioning, and radios, which could be installed in existing body designs to sustain consumer interest. *

Sloan required that products sold to customers be fully tested before being shipped to the customer. While this might seem obvious today, one must realise that GM's competitor Ford rarely inspected finished automobiles. No one ran an engine until the car was ready to drive away from the end of the assembly line, and no Model T was ever road tested. *

Sloan had vision. He understood the need to bring in a car between the Chevrolet product and the Olds product even if the resulting product would take away business from the existing General Motors Product. He understood that it is better to take business from GM's own divisions than have the competitors do so.

He understood how to combat the Ford Model T's unstoppable advantage of low cost. General Motor's was able to offer a more modern product for only a little more money. *

He foresaw a rapid acceleration of transportation by air, not only for passengers but for **freight as well.** He added foreign (European) designers into GM as early as 1927. As with every visionary his forward predictions were not 20/20. He made a mistake by feeling that by the 1980's the car was a fully technically mature product and that the engineers would spend their efforts solving the problems created by the stylists. He did not feel that General Motors' cars had to be technically superior to the competition's car. I feel that the Japanese manufacturers proved this wrong.

Sloan used logic as well as business methods. When the Assistant Secretary of War approached GM with a request to produce V-1710 Allison engines for airplanes the Secretary could only give a firm order for 836 engines. Building a factory to produce 836 engines seemed a bad risk. Sloan made a decision on the **feeling** that the V-1710 engine would probably be in great demand. In addition he felt that one does not lightly turn down any government request having to do with national security. In the end GM produced 70,000 V1710 engines.

Sloan fully understood the three distinct phases of technology development and the interaction between the phases.

- Phase 1 – Long-term research and homework. The General Motors Research Corporation handled this.
- Phase 2 – Converting the science and technology into engineering terms that relate to the product. Corporate Staff engineers handled this.
- Phase 3 - Taking relevant fully tested and developed technology and incorporating it into a specific product. This was handled at the division level responsible for creating the car model.

Sloan first brought all the top management of all the parties together at the General Technical Committee. He eventually brought all of the corporation's technical staff together in one place by creating The General Motors Technical Center Northeast of Detroit.

Items with an * denotes that the information was take from the book " The Machine that Changed the World" (3)

2.1.4 Summary of Project Management at General Motors during Alfred Sloan's tenure.

Product development was characterised by slow innovation and introduction of technology. This was a direct result of Sloan's bad experience with the copper cooled engine. Sloan insisted that Product Development be focused and insisted that people work from facts. He insisted that in order to be a Manager at General Motors one had to know the product. He established a system where technology was developed outside the product, then brought into the product only when it was thoroughly tested. A rigorous system was established to take the science that was developed up front in the General Motors Research Corporation to a proven technology that a division can incorporate into a new car.

General Motors made extensive use of testing and up-front prototypes. They developed the concept of platforms, building new on top of established old.

The emphasis during development is on minimising risk. An effort was made not to lock into a design too early. The development system at GM did not seem to emphasise reduced development cycle time.

Sloan's management system was built around the concept of "work by the numbers". He demanded the facts and worked from those facts. He however never felt that top management needed to understand the micro details. If the numbers showed that the top-level commitments were not met then

the General Manager in charge was replaced. The emphasis however was always to quantify the situation rather than fix problems quickly. The emphasis was always on knowing what the problems are or could be in the future rather than fixing the problems or creating new innovation. Sloan however spent a lot of time thinking and planning for the future and looking at the big picture.

Sloan understood why things happened not just how they happened. An example of this is he understood that the essence of the mass production system was not a moving assembly line. That was just a how. The essence was the complete and consistent interchangeability of parts and the simplicity of attaching them to each other that made the system work.

2.2 The Machine that Changed the World

This book discusses in detail the differences between the product development methodology of what they call the mass-production firms and what they term lean product development firms.

2.2.1 Program Management Structure

2.2.1.2 Mass Production Firm –General Motors

Senior executives designate a Program Manager to take the lead, but only give him very limited power. He is a high profile co-ordinator, who through his power of persuasion, co-ordinates the different functional departments, as well as the different Divisions into developing a new product. The management process used was one of absolute democracy (or anarchy) in which the Program Manager has to reason with people in order to co-ordinate efforts. The Program Manager isn't allowed to be a leader who gives orders and expects to be obeyed. Many company executives view the job of Program Manager as a dead end in which success leads to little reward and failure is highly visible.

Except for a small core group, everyone working on the Development Program reports to his or her own functional department boss in addition to the Program Manager. In reality the assignment to a particular program is only short term. The functional departments' boss has the real impact on the employees' long-term career and pay structure.

The functional groups work on many different programs, and don't feel a particular alliance to any one program. Their real concern is to develop designs that satisfy as many different car models as possible rather than optimise a design for any product.

2.2.1.3 Lean Product Development - Honda

Senior executives appoint a *shusa* or as Honda call it a "large project leader" (LPL). The *shusa* is simply **the boss**, the leader of the team whose job it is to design and engineer a new product and get it fully into production. The *shusa's* task is clearly to manage not co-ordinate. The position of *shusa* carries great power and is, perhaps, the most coveted in the company.

At the commencement a new large project, the *shusa* borrows all the appropriate people from each of the relevant departments and **transfer's** them to the project for its life. The *shusa* can move the project along rapidly, because all the necessary resources are under his direct control.

2.2.2 Focus

2.2.2.1 Mass Production Firm –General Motors

There is a distinct lack of focus on the end product. The development project consists of **individuals,** including the team leader, who are on short-term loan from a functional department or a specific Division. Moreover, the project itself is moved from department to department along a sort of production line from one end of the company to the other. Totally different people in each area work on it. Clearly the focus on the program gets quite blurred and this makes communication to solve problems very difficult. In addition problems are past down the line till they become obvious at the end. In a mass production firm **the maximum amount of people working on a project is near the end of program,** very close to the time of launch of the product. It is at that time when all the hidden problems become visible and a massive effort is undertaken to clean up the mess.

The members of the team know that their success depends on moving up through their functional speciality, and therefore work very hard in the team to **advance the interest of their department.**

In a mass production firm tasks are done sequentially. The design and fabrication of a tool to make a part, for example is commenced only after the part is fully defined. Since the toolmaker is brought in very late in the process there is very little communication between the toolmaker and the component designer.

2.2.2.2 Lean Product Development – Honda

The *shusa* leads a very tight knit and **focused team**. As mentioned before the core team stays intact for the life of the program. **The total number of people involved in the project is highest at the very outset of the program** (I plan to discuss this aspect when I present the Toyota set based concurrent engineering system later in this Thesis). All the relevant specialities are present, and the *shusa's* job is to force the group to **confront all the difficult trade-offs** they will have to make to agree on the project. The *shusa* ensures that the functional group is working toward what the product needs rather than what is best for the individual function. Conflicts about resources and priorities occur at the beginning rather than the end of the process. The essential knowledge of the development team lies in the shared viewpoints and experiences of the team members who remain together over an extended period.

The career path of everyone on the team is dependent of how well the project turns out and his or her contribution to the project. The *shusa* has a real impact on ones career.

Simultaneous development is used extensively. Using the example above in a lean production development firm the toolmaker is involved at the start of component design. The toolmaker and the component designer is in direct, face to face contact and have probably worked together in previous product development teams. The toolmaker starts making rough-cuts to the dies early in the program when he has a feel of where the designer is heading. He continuously firms_up his tool as the designer firms up his or her design.

2.2.3 Research and Innovation

2.2.3.1 Mass Production Firm –General Motors

General Motors (as I discussed in detail in my review of the book My Years at General Motors by A. Sloan) has a huge research center. The authors of the book, the Machine that Changed the World, point out, however, that under Alfred Sloan, **General Motors shied away from leading edge technical design.** The authors felt that the reason for this was that in the 1960's General Motors had such a large market share, that if they brought in any truly epochal innovation, they could have bankrupted Ford and Chrysler and attracted the attention of the anti thrust enforcers of the U.S. government. Another explanation of this phenomenon based on Alfred Sloan's book is that after Mr. Sloan's disastrous experience with the copper cooled engine that he had supported in the 1920's he lost his appetite for untried innovation.

In reality however the General Motor's Technical Center has, over the years developed a large proportion of the technology that is in both the American and Japanese cars. The trouble is that at GM it just isn't **focused** toward a product. New ideas percolate from the research center to the market very slowly. When new ideas are introduced, the lack of day-to-day contact between the thinkers in the research center and the implementers in product development often results in the implementation of the technology not living up to the original technical targets.

In summary we can conclude that General Motors' research is not focused, isolated from the product and is generally not encouraged.

2.2.3.2 Lean Product Development – Honda

Japanese lean producers exercise extreme care not to isolate their advanced technologies from the day-to-day workings of the company and the incessant demands of the marketplace. Engineering, even of the most advanced sort, must be tied into the key market-driven activities of the company. The activity is very **focused.** Even longer term and more advanced projects have a very specific objective – to remedy some weakness in the company's products identified by the product or major-component development teams. The research is tied tightly to the needs and timetable of specific development projects, and engineers who thoroughly understand the practicalities of product development and production do the work.

When one examines carefully the advanced engineering done by the Japanese carmakers during the 1980's one can see that very the lean producers originally discovered little of the innovation that they incorporated. What they did do is carefully study and understand the weaknesses in the product they manufactured which was basically small cars powered by small 4 cylinder engines. They then compensated for these weaknesses by incorporating innovations, such as double overhead cams, and 4 valves per cylinder that had been previously discovered previously in the Detroit research centers. What they did do well was **focus** on the smallest details of the design as well as paying endless attention to manufacturability. The end result was a bigger and better engine than their competitors who had been the original inventors, but hadn't been able, or had the desire, to implement the technologies that they had discovered.

2.2.4 Supplier Assembler Relationship

2.2.4.1 Mass Production Firm –General Motors

The design process in a mass production company is one step at a time. After the component is fully defined, then the producer, whether he is an in-house parts manufacturer or an independent company, is called in, shown the drawings and asked for a bid. The winning bid is usually the lowest bid. The supplier is brought in late in the design process and can do little to improve the design. Since all suppliers are constantly in the bidding game, they are reluctant to share ideas on how to improve their product while it is in production.

2.2.4.2 Lean Product Development Firm

At the very outset of product development, the lean producer selects all the necessary suppliers. They are not selected on bids, but rather on the basis of past relationships and a proven record. The first tier suppliers, then, have full responsibility for designing and making component systems that perform to the agreed upon performance specification in the finished car. A target price for the component is derived in the following manner. The lean assembler establishes a target price for the car or truck and then, with the suppliers, works backward, figuring how the vehicle can be made for this price, while allowing a reasonable profit for both the assembler and the suppliers.

2.3 Principles from Toyota's Set-Based Concurrent Engineering Process

D.K. Sobek II and A.C. Ward

This paper details the salient principles that form the foundation of Toyota's use of "Set-Based Concurrent Engineering" (SBCE) for product design and development.

1. Toyota develops deep technical expertise in both its engineering and management ranks. Managers are always good, experienced engineers.
2. Toyota's three vehicle development centers have a matrix structure with general managers heading functional organisations and chief engineers (CE's) leading vehicle programs.
3. **CE's are totally responsible for their vehicle, from early concept stages through launch and into the initial marketing campaign. The CE creates the product vision and he creates the product for the customer. (The position of CE is described in my summary of the book, The Machine that Changed the World when I describe the position of *shusa*)**
4. **The basic design and development process used by Toyota is referred to as set-based concurrent engineering (SBCE).**
5. SBCE assumes that reasoning and communicating about sets of ideas is preferable to working with one idea at a time. A basic aim of Toyota's entire set-based development process is to ensure that a chosen design is feasible before committing to it. By exploring multiple designs in parallel, and gradually converging to a single optimum one, Toyota aims at identifying issues up front and thereby avoiding late problems.
6. The design process starts by looking at the total solution space, filled with all the feasible solutions for each function in isolation, but based on the constraints on its subsystem derived from past experience and information from the CE. As a starting point the engineer starts with the current checklists, which contain the history and lessons learned from previous programs. Defining feasible solution regions requires experimentation and analysis **(facts)** not just ideas or sketches on paper.
7. The next step is communication. Each function must then communicate the feasible boundaries of their solution space so that everyone understands the feasible region of others. They tell each

other "these are the things we can (or cannot) do," and, "these are the costs and benefits from our perspective" **(focused)**.

8. Having communicated the possibilities, teams can look for the intersections where feasible regions overlap. If an intersection is found then a solution that is acceptable to all has been identified. Organisations that do not communicate sets and look for their intersections wind up trying to marry independently optimised components. Toyota looks for solutions that **optimise total system performance.**
9. Within the acceptable solution space there can be many alternate solutions. Toyota engineers explore the trade-offs by designing and prototyping (boundary objects) or simulating alternate systems or sub-systems. An intense trade off study based on quantifiable test data **(facts)** in then carried out to fully understand the pros and cons of each alternative. A trade-off curve that establishes a relationship between two or more parameters is used to choose a solution that is really the best.
10. Conventional US practice calls for making as many decisions as possible as early as possible, thereby imposing as many constraints as possible in order to simplify the interactions among subsystems. At Toyota they specify only the minimum amount of constraints and allow the maximum acceptable tolerance. This policy even extends to outside suppliers. Toyota believes in allowing as many degrees of freedom to exist so that they can gather data **(facts)** by allowing maximum variability to know what parameters really need to be controlled and which other ones do not really have an appreciable effect on the end product. This builds in robustness into Toyota products.
11. Countering all this however is the need to narrow the solution set space down so that a decision can be made and a design frozen. A decision process that gradually eliminates possibilities until the final solution remains is used, rather than just picking the best from a set. As the set grows smaller, and more knowledge is collected at the boundary conditions the resolution of each idea or design grows sharper. This process is **orchestrated by the chief engineer** who decides to either delay a decision in order to collect more data, or presses for a decision to keep the program on schedule.

12. Toyota will often pursue a potentially high pay-off but risky solution, but when doing so will always prepare a back-up solution that it knows will work. When pursuing a high-risk high pay-off solution, Toyota's engineers first break up the problem into manageable pieces. For each sub-problem, the engineering team develops multiple alternatives, one of which must be a conservative solution. The elements are modularised so that they will work with any combination of the other elements. At a pre-specified cut-off date, a determination is made as to whether the radical solution is feasible, or whether they must go with the conservative alternative.
13. Once a set is chosen and communicated to all the other functions, a commitment is made to stay in that set. For communication to be trustworthy, participants must stay in the narrowing funnel. It is therefore paramount to establish that a solution is feasible before committing to that solution set.
14. The controlling mechanism, of SBCE is a series of gates, each of which is tied to an integrating event that brings all the pieces together. The CE controls the uncertainty at these gates, reducing it with each successive gate.
15. Toyota's set-based concurrent engineering process is designed to provide robustness against physical, market and design variations. A robust design means the design works over a wide range of variability. By forcing the design to work with only the minimum amount of constraints, over the largest possible tolerance band, ensures that the design can function with a lot of variability in the unconstrained areas. In addition SBCE provides for short development cycles, manufacturing flexibility and standardisation that can help get a product idea to market faster and thereby decrease design susceptibility to changes in market demand or competition.

2.4 Product Development in the World Auto Industry

By Kim B. Clark, W. Bruce Chew and Takahiro Fujimoto

Professor Kim Clark at the Harvard Business School together with Takahiro Fujimoto, a PhD candidate at the Business School surveyed practically every auto assembler in North America, Japan and Western Europe in an attempt to ascertain how many hours of engineering effort were needed and how much time it had taken to produce recent new products. What they discovered was that Japanese projects were completed in two-thirds the time and with one-third the engineering hours of the non-Japanese projects. In absolute terms the Japanese typically completed a project more than a year and a half earlier than their non-Japanese competitors. These differences have significant implications in an industry in which engineers are a constrained resource, a model's life may be only four to five years, and market demands are continually changing. This paper attempts to outline the differences in Product Development structure between Japanese and non-Japanese auto assemblers to give an understanding of where the advantage comes from.

Below is a summary of the researches findings:

1. The Japanese make extensive use of propriety and/or black box parts, which are supplied by outside suppliers. This implies that the Japanese draw more engineering resources from suppliers. The researchers charged the hours put in by the supplier engineers to the Japanese auto assembler, so as not to bias the results. The researchers however concluded that since these supplier engineers were experts in the technology in which their own company competes, they bring a higher level of efficiency to the task as compared to the auto assemblers own engineers.
2. The researchers found three types of management structure in the automobile industry.
   - **Functional structure** – Development is organised into functional departments, and activities are co-ordinated through the functional hierarchy. There is no project manager or matrix structure.

Historically the functional structure was the dominant management mode and remains prevalent in Western European automobile manufacturers.

- **Lightweight project manager** – Work is organised into functional departments. A project manager is in charge of co-ordinating activities but has little influence over the content of the project. The project manager has relatively low status within the organisation. *This management mode is prevalent in North American automobile manufacturers and is being adapted by some Western European companies.*
- **Heavyweight project manager** – The project manager has direct responsibility for all aspects of the project. He or she has a strong influence outside the development group, works directly with the engineers and has high status within the organisation. *Japanese companies use heavyweight project managers.*

The researchers found that projects that used heavyweight management used far fewer hours than those that used a functional structure, with the ones using lightweight management in the middle. When the researchers looked at lead-time they found that the heavyweight group had an advantage of 9 months over the lightweight group, which in turn was 8.5 months faster than the functional projects.

3. The researchers found a profound relationship between the level of specialisation in a development organisation and program lead-time. They claim that the relationship is U-shaped. If the degree of specialisation is very small then more specialisation will expand expertise, permit parallel processing of critical path activities, and reduce hours and lead-time. On the other hand when there too much specialisation, the division of work into clear-cut subtasks becomes more difficult. Time and resources grow as specialisation increases and beyond a certain point adds to the overall hours and lead-time of a project. The researchers found that the Japanese heavyweight management system often used relatively small multifunctional teams with broader assignments given to each participating engineer.

4. Because solving problems is the central activity in product development, the way problem-solving tasks are linked is an important factor in project performance. The timing of the activities and the nature of information transfer and communication between them determine the linkage between a given pair of tasks. The research showed a positive relationship that the extent of overlap between the upstream problem solving cycle and the downstream process engineering cycle has on product development lead-time and cost. With shorter lead-time comes the ability for these producers to outperform the other automobile producers in design quality and product development effectiveness.

The research showed this benefit was a function of the quality of communication and information transfer among activities. They distinguished between two general approaches; the batch model and the dialog model. In batch communication all data are transmitted in one shot at the end of the activity. When this happens then overlap of activity is a liability since the early start of the downstream activities will be based on faulty assumptions concerning the upstream activity out put and will have to be redone. In the dialog model the upstream group transmits preliminary information little by little, and the downstream unit sends its own information back upstream in a continual give and take. The probability of having to repeat work is greatly reduced. With this effective lead-time reduction comes more accurate forecasts of customer tastes or competitor moves.

The researchers found that Japanese projects are highly overlapping in activities coupled with intensive information transfer. U.S. projects have a high degree of overlap, however information transfer was not intense enough to support it efficiently. European projects tended to be the least overlapped, that is, by far the most sequential accompanied by a mix of batch and dialog information transmission. The Japanese released preliminary information more frequently than either the U.S. or European companies.

In summary the researchers found that the Japanese firms seem to be able to develop a product of competitive quality in much less time and with fewer engineering resources than their U.S. or

European competitors. They attribute this success to the Japanese Project organization structure and operating methods; a heavyweight project manager who leads a dedicated multifunctional integrated team, in which problem-solving cycles are overlapped and closely linked through intensive dialog. The producers with shorter lead-time tend to outperform the other automobile producers in design quality and product development effectiveness.

2.5 Organisations for Effective Product Development

A thesis presented by Takahiro Fujimoto

In his thesis Fujimoto outlines the following key attributes of an optimum development process:

1. Direct and continual flows of information from market to concept generation units, which creates product concepts proactively, rather than reactively.
2. Continual elaboration and revision of product concepts throughout the project period, which allows for flexible adaptation of the concepts to the changing market needs.
3. Direct and continual internal flows of information among the concept generation units, product planning units and the product engineering units throughout the entire period of product development.
4. Early information exchange to bring up downstream experience to the upstream effectively and to make conflicts revealed at the early stages.
5. Overlapping problem solving. Downstream problem solving cycles starts before upstream cycles complete. In order to implement this overlapping effectively, upstream and downstream have to be integrated by early release of preliminary results in both directions.

Fujimoto's research found that effective companies have strong overall internal integration mechanism. This requires:

1. A strong Product Manager exists those co-ordinates project activities for all related areas (including production and Marketing) as well as all stages (including process engineering).

2. Product manager has close contact with the working engineers. Project managers walk around engineering.
3. Project liaison teams (IPTs) with the project manager as leader. The project liaison team includes key functions in engineering as well as functions outside of product engineering such as production and marketing.
4. Close and continual information flows from market to product design. The product manager must be in close contact with the customer.

In addition Fujimoto found that the effective companies:

1. Use many prototypes during the development of the product. Quick prototype building is key.
2. Have early feedback from manufacturing. Process engineering is part of IPT right from the word go. However manufacturing does not have veto power over product design.
3. Have a large degree of overlapping development between product and process.
4. Product managers in effective producers tend to emphasise imagination as a critical ability.
5. Give broader task assignments to working engineers.

2.6 The basis of the IDEO Product Development and how it can relate to Full Knowledge and Simulated Annealing (Based on HBS case study 9-600-143)

The IDEO development philosophy is "Fail often to succeed sooner". This is also one of the basis of Full Knowledge described in chapter 4 of this thesis. Know where the feasibility boundary is. Fail, and then tighten parameters till you succeed.

Also central to IDEO's design philosophy is the role of prototyping (boundary objects).

- Prototypes ensure that everyone is imagining the same design during discussions about a product.
- Follow the three "R's" – " Rough, Rapid, and Right". The final R "Right", referring to building several models focused on getting specific aspects of the product right. Do not try to build a complete model of the product you are creating. Just focus on a small section of it. Again another aspect of full knowledge. Understand the engine at a component level. When one understands the components well he can then really understand how the entire engine functions.

IDEO believes in generating as many ideas as possible ***early in the design*** process. The design process should resemble a funnel, with many ideas at the top, three or four at the base and only one making it all the way through. This process is close to the Toyota set based concurrent engineering system using simulated annealing.

- Close customer contact is paramount. Very frequent customer meetings are needed so as to really understand the customer's business.

2.7 Project Management and Product Development

In this portion of the thesis I will explain the differences between the Product development methods used by traditional companies such as General Motors, and compare those methods to those of progressive companies such as the Japanese car manufacturers, and IDEO outlined above.

The emphasis at a Lean Manufacturing company is at understanding how to fix situations. The mass production companies want to know and quantify the issues. Sloan's effort to work from the numbers was aimed at a no surprise atmosphere rather than a fix it atmosphere. Sloan's management style works very well in a relatively stable and homogeneous customer expectation environment.

First I would like to point out two factors that both types of companies had in common.

1. Both believe that technical expertise is needed in both the management and engineering ranks.
2. Both believe in extensive and through prototype testing.

To understand the differences between these companies one must understand the basic motivation inherent in the companies. General Motors is focused on production. General Motors was driven by a real desire not to make an error. Throughout its long history General Motors did not really have strong innovative competition. The principle theory was that as long as no major mistakes are done they could continue to lead the pack and be an invincible prey for any predator. The emphasis is on developing the maximum amount of product at the minimum cost and risk. The structure of General Motors is designed to support this philosophy.

The progressive companies discussed above are predators. They could not live with the status quo. They are focused on the product. While they too would suffer if major errors were done, this need is tempered by the need for innovation to overcome the strength of their preys. These companies address the issue of mistakes by giving a strong ownership of the project to its team and trust the team to overcome all issues. The emphasis is to maximise success and innovation and minimise errors.

2.7.1 General Motors

- Product development is governed by a process, which, because it is so well defined, it requires little central leadership. The theory is that if one follows the well-developed process one will never make mistakes. Because of this, the Project Management job is not a coveted position, nor one that has any real power. A real powerful innovative Project Manager will lead to challenges to the process. Obviously General Motors do not want their processes challenged.
- A Project Manager is a high profile coordinator, who through his power of persuasion, co-ordinates the different functional departments, as well as the different Divisions into developing a new product. The management process used was one of absolute democracy (or anarchy) in which the Program Manager has to reason with people in order to co-ordinate efforts. The Program Manager isn't allowed to be a leader who gives orders and expects to be obeyed. Many company executives view the job of Program Manager as a dead end in which success leads to little reward and failure is highly visible.

  Except for a small core group, everyone working on the Development Program reports to his or her own functional department boss in addition to the Program Manager. In reality the assignment to a particular program is only short term. The functional departments' boss has the real impact on the employees' long-term career and pay structure.
- The functional groups work on many different programs, and don't feel a particular alliance to any one program. Their real concern is to develop designs that satisfy as many different car models as possible, (minimise overall development cost) rather than optimise any design for any product.
- GM Management philosophy is one of decentralization to the divisions with co-coordinated control from the corporation through executive committees. Sloan created a system that allowed GM to be at the same time a huge company as well as a collection of smaller companies. Committees form the glue that connects the various divisions.
- Strong emphasis on facts – work from data. If one has all the facts one can't ever err.

- Very slow, very deliberate change ability- very risk averse as a result of bad experience in the 1920's with copper cooled engine.
    - Long-range technology development is kept out of the divisions, whose prime development activity is to come out with a new car every year.
        - Long-range research (the concept of creating technology) is treated as something different than product development. Product development was done in the divisions while primarily General Motors Research Corporation at Dayton handled long-range research. Once the basic research was done and proven the Division engineers took on the task of developing the technology into a product.
        - Lately a step has been added where a central Engineering Staff, which reports to the central office, does long range technology development. The Engineering Staff engineers the science from the Research Corporation into a practical state so that the Division engineering departments can incorporate it into cars.
    - Development is backed up by rigorous testing using standardised test procedures and measuring equipment
    - Product integrity is given a lot of importance and a standardised testing and substantiation system was created to confirm the product integrity.
- Strong efforts to get buy in from divisions before incorporating designs
- A real effort to achieve co-operation and co-ordination in engineering and other matters. An understanding of the distinction between divisional and corporate functions in engineering, and between advanced product engineering and long range research.

All this is designed to satisfy the following two basic needs of the incumbent prey companies:

1. Mistakes are not made.
2. Management is never surprised.

2.7.2 Honda, Toyota and IDEO

These companies are driven by the fact that they are the predators. By their very nature they live in a more risky environment where they have to bring in product that demarcates itself from the established leaders (the prey). However they too must succeed without running out of time, money and good reputation. Strong ownership of the product by its development team characterizes their organizations. Pride rather than process drives these organizations.

There however is a process used. The Toyota set-based concurrent engineering process outlines the guiding principles for the development of the program. It however is not a cookbook but rather a guidebook. It doesn't tell you how to run the program rather gives the principles needed.

A strong Program Manager leads the programs. There is never any doubt as to who is the leader and who is responsible for the program. He works with a committed team that stays with the product.

There is always risk taking but it has to be well managed. The total number of people working in the project is highest at the very onset of the program. Work is done concurrently on sets of ideas not just one at a time. All the designs are evaluated for feasibility using either experimentation and/or analysis. The technical expertise of suppliers is used extensively to ensure that the best ideas are proposed.

Simultaneous development is used extensively. They overlap the upstream problem solving activity with the downstream process engineering cycle. By its very nature this introduces risk. Rather than shy away from this risk the predator companies use intensive information transfer to mitigate the risk.

As pointed out by in the summary of the book " The Machine that Changed the World" the Japanese carmakers have not discovered a lot of their own unique innovation. What they did

successfully was use the innovation discovered by the Detroit company labs, fully understand it (achieve full knowledge) and adapt it to their needs. The end result was a better car than their competitors who had been the original inventors, but hadn't been able, nor had the desire, to implement the technologies that they had discovered.

All this is designed to satisfy the following two basic needs of the progressive predator companies:

1. The need to come into the market with a better product than the prey.
2. The need to remove risk from the product prior to it reaching its initial market.

3.0 Chapter (3) – A Study of Project Management at Pratt & Whitney Canada.

3.1 Program Structure

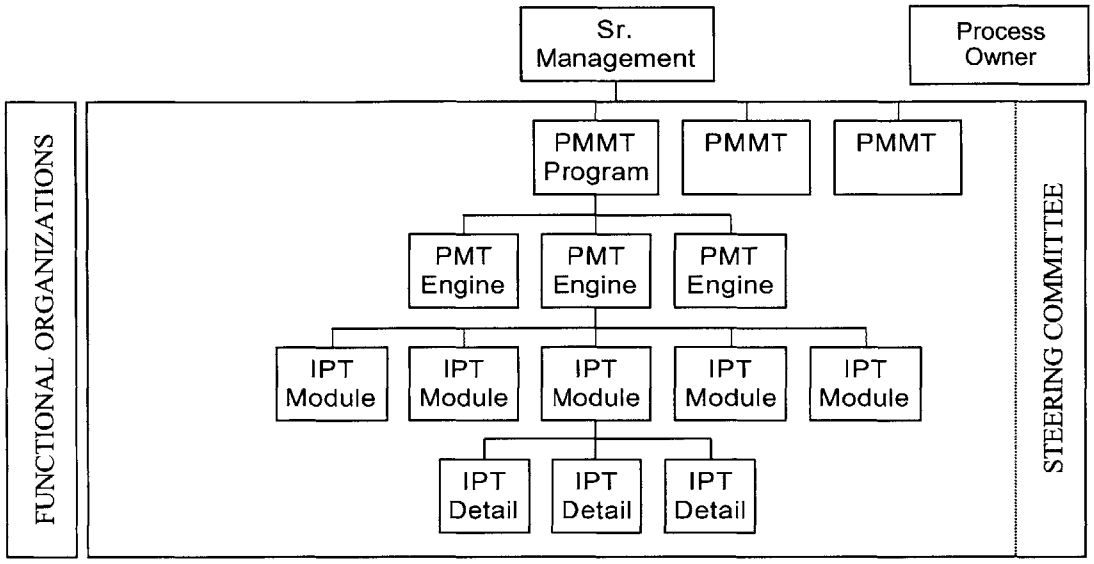
Pratt and Whitney Canada (PWC) is structured as a Matrix organisation constructed around an IPT (Integrated Product Team) concept as shown in Figure 1 below. The company's businesses are divided into five families of product each led by an Executive Team called the Program Model Management Team (PMMT). This in effect creates five smaller and nimbler companies with the PMMT acting as the executive branch of the company. These companies however still maintain the benefits of being part of a larger company (resources, funding, reputation). This in effect follows the model Alfred Sloan created at General Motors.

A Product Management Team (PMT) that manages the needs of each particular design of engine runs each engine within a family of engines. Working for the PMTs are several Integrated Product Teams (IPTs) that manage the individual modules of the engine.

The Project groups (the Project Director – PMMT, the Project Manager – PMT and the Project Engineer the IPT) maintain the leadership role of each team. The Project Manager has a role very similar to the role of the *shusa* at Honda as described in the book "The Machine that Changed the World", or the role of *Heavyweight Project Manager* described by Kim Clark and Takahiro Fujimoto in their book "Product Development Performance: Strategy, Organisation and Management in World Auto Industry".

The functional groups at PWC are organised into Module centers. Each engine module is assigned to a Module Director. All functions related to that module, Aerodynamics, Stress, Dynamics and Manufacturing report to the Module Director.

Once a program is launched and the teams established the individuals on the teams are moved to the program usually sitting in a co-located area.



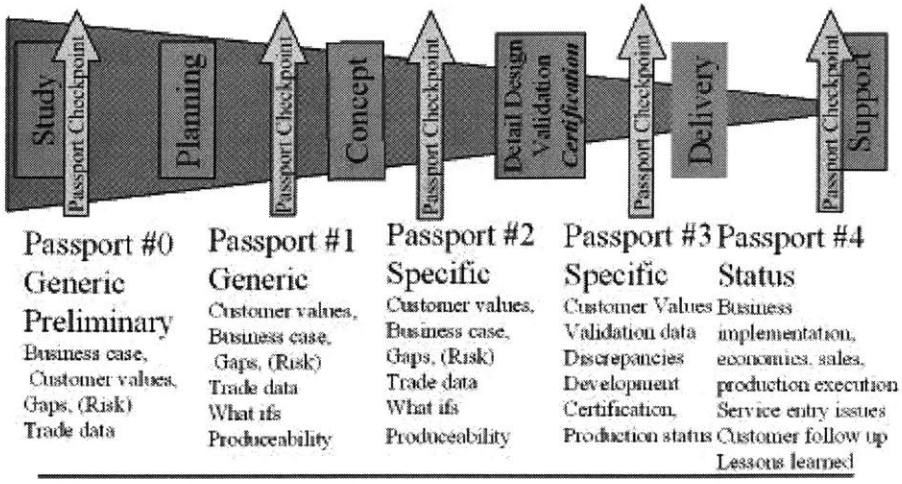
MANDATE

FUNCTIONAL ORGANZATIONS	PROGRAM MODEL MANAGEMENT TEAM	PRODUCT MANAGEMENT TEAM	INTEGRATED PRODUCT TEAMS	STEERING COMMITTEE
Empower the teams and Deliver their functional output According to the program Schedule	Provide Management direction for a series of Engines	Provides Management direction for an Engine Model	Meet the targets for each Components	Support and maintain IPDP namely by defining the Training Program and Strategy

Figure 1

3.2 Product Development

Pratt and Whitney Canada has adapted a phased–gated process to manage the Product Development of new aircraft gas turbine engines. What I mean by a phased-gated process is that the full development process is broken down into 5 distinct phases, and to move from one phase to the next one must pass a Sr. Management Review in order to start the next phase of development. The Process is referred to as the Passport process because the program must satisfy the established requirements at each review and receive a passport from senior management to proceed to the next phase. The process is shown in figure 2 below.



Pre Phase 0

Technology readiness is a constant ongoing activity in the company and corporation. There is a constant effort expended to improve the research, methods development and innovation capability of the company. In addition lessons learned are collected from all current programs. These provide the technology base for all new programs.

Phase 0 – Study

This phase allows the company to answer the question "Do we really want to do this?" During this phase business case data is generated, technical risk is assessed, trade study data and "What ifs" are established. During this phase the Advanced Engineering department establishes engine configurations and preliminary performance tables "for discussion purposes only" to share with PWC's marketing department and target customers.

A New Products Review Meeting is held in which the Senior Management of the company discusses whether to pursue this particular product. If the answer is yes a Passport 0 is issued and the program can progress to Phase 1.

Phase 1 – Concept design

This phase allows the company to answer the question "Do we have a competitive, viable product? Can we make it"? The Advanced engineering department determines a configuration for the new product. A draft product design requirement's specification is created. The input from each of the module centers is used to determine the optimum configuration for each component. Risk analysis and risk mitigation plans are laid out and completed. Costs are determined and a business case established. All this information is then gathered and presented to senior management in a gate review. If the product meets the company requirements a Passport 1 is issued and the product can be offered to customers.

Phase 2 – Pre-detail Design

This phase allows the company to answer the questions; "Do we know what we are making? Is it a competitive and viable product?"

In this phase Project engineering, which have been involved with the program since before Phase 1 now firmly takes over the management of the program.

Advanced engineering work together with the design department and the module centers to release a comprehensive product design requirement's specification. Integrated product teams are formed and the engine configuration firmed up. The design responsibility for the program is transferred from advanced engineering to the design department under the leadership of a chief designer. The design department fully defines the layout of the engine, while the performance department determines

the engine's performance and operability capability (how it will behave within the total operating envelope). Project engineering is constantly comparing the engine parameters against the customer values and specifications.

A detailed design review is held followed by a Sr. Management gate review. If all requirements have been fulfilled then a Passport 2 is issued and the Project is allowed to go into full detailed design, development and certification. After this point the company spending on the program increases substantially, and therefore gate 2 is a real "do or die" decision point.

Phase 3 – Detail design, followed by validation and certification of the product.

In this phase the product is designed, built, validated and certified. Experimental engines are given to the aircraft manufacturer so he too can develop and certify his aircraft. As shown in Figure 3 below a large percentage of the resources and cost associated with the project is expended during this phase.

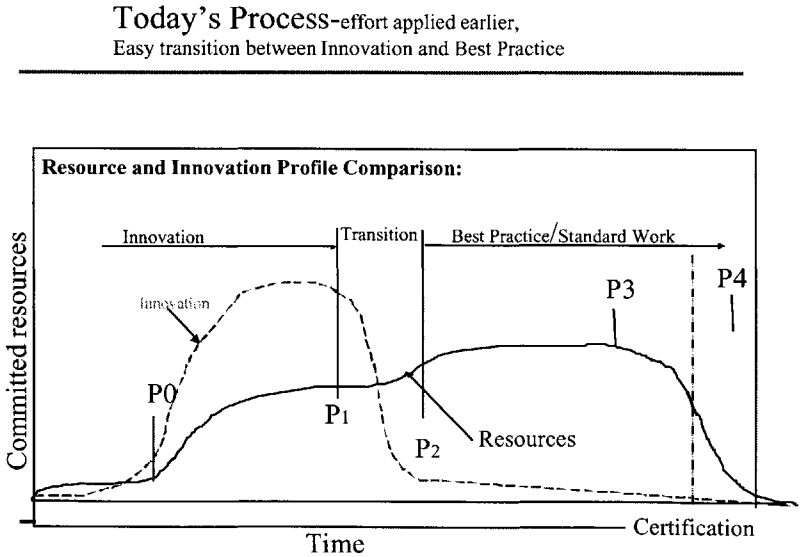


Figure 3

As shown in figure 3 this phase, in a perfect world, is basically a mechanical phase where a test and development plan, that follows best practices and standard work is followed. Unfortunately, often during this phase things do not go as planned. The three case studies discussed later in this chapter contain some of the things that can differ from the plan during this phase. I will go into those aspect and risk mitigation techniques such as "full knowledge" later when I discuss the three case studies.

3.3 Case Studies of various Pratt and Whitney Canada engine programs.

3.3.1 Case study of Engine "A3" program – 1994 vintage – A program with issues

Engine "A3" was the third member, of a new advanced engine family aimed at the very lucrative mid size business jet market. It was both larger and more advanced than the earlier two engines developed in this class. It was launched after a very hard competition had been won to power a new large mid size, advanced aircraft. To win the competition, optimistic commitments were made based on the premise that a way to bridge the knowledge gap would be found between the start of the program and the certification of the engine. The engine was oversold from the word go.

The overall plan was to start the development of engine "A3", after the completion of the development of engine "A2", (after "A2" had successfully received a Passport 3) the engine in the family just below engine "A3". This did not happen. The final design of engine "A2" had serious technical and performance issues that had to be addressed. Resources that were slated for engine "A3" were not made available. The development program of engine "A3" started off with a distinct shortage of resources and priority. Even though a well thought out plan had been laid out it was not executed due to lack of resources and priority.

The issues that had to be dealt with were very complicated and difficult to resolve. The configuration of the engine was frozen early in the program and every effort was made to make the configuration as defined work. While a huge effort was expended to find out **what** does and does not work little time was spent figuring out **why** things did or didn't work.

An interview with the program Vice President is included in appendix "A" and summarized below.

- Not enough resources put in up front. Never could recover that shortfall.
- Oversold from the word go. Did not have road map to achieve specification.
- The program was controlled and driven to the contract between the company and the customer. The original contract was considered a legal document and the company's legal department gave the principle input. The executors of the contract, the Project engineers, had limited input into the contract, and only limited understanding of the requirements on them, and the consequences of non-conformance, even though their performance had the greatest impact on the program and the contract fulfilment.
- Domino effect of not meeting specification – When performance efficiencies were not met, the resulting engine was too hot internally and therefore durability suffered.
- It is almost impossible during a development program to overcome fundamental errors made during the basic concept design of the engine. Once a configuration is frozen, the degrees of freedom to the designers, and development engineers are highly limited.
- Knowledge derived from earlier programs was basically what worked and what didn't. There was a lack of the **full knowledge** of why things did or didn't work, and the boundary limits for where they went from working and not working.
- With its limited resources Program did plan well and identified shortcomings early in the program. Because of this up front work, the majority of the issues were resolved before engine production incorporation.

3.3.2 Case study of Engine "B1" program – 1992 vintage – A highly successful program

An interview with the program Project Manager is included in appendix "A" and summarized below.

The "B1" is a jet engine aimed at the corporate jet market. It was the first of a new family of engines, the "B" family that was developed from 1992 to 1996. The family of engines was built around a common core and eventually 3 different engines made up the family, each producing more power and powering a larger corporate jet than its predecessor did. All the engines turned out to be a commercial success, being developed on budget, was very well received by the market and matured very quickly. The warranty, and rework costs of those engines, in their first few years of production, was much lower than typically experienced by other new engine introductions in the field.

The "B" family of engines was recognized as an important program for an important customer and a hand picked team was chosen as the project group. Resources were provided and three experienced Project Managers led the team. Integrated Product Teams (IPTs) were formed early on and a demonstrator was run prior to program launch. The "B" family of engines was a size of engine that was within the company's previous experience and "rules based designs" was used extensively. The specification targets were within the company's experience and were achievable. Flight-testing was used extensively to determine the engine's performance throughout the entire engine-operating envelope. Customer interaction was extensive with technical coordination meetings held on a regular bases.

3.3.2.1 Key Development Methodology used on the "B1"

1. Build a strong team, experienced and knowledgeable, organised into integrated product teams (IPTs). Have a clear understanding of each IPT member's responsibility and what output expected from whom.
2. The resources needed to do the program were provided from the word go.

3. Didn't oversell up front. Didn't sell above what had been demonstrated. Tests were done to see what margins were available, i.e. testing done above requirements level.
4. Allowed margin in the design in case things didn't pan out exactly as expected.
5. Created a no surprise environment. Everything in the program was visible to all parties, from top management to the junior engineers working in the program.
6. Prepared for the eventual Production of the engine early in the development program. Used features of the Development Process to emulate what is needed during production. Involved production personnel and used their input during design process.
7. Detailed planning, and attention to details. Tracked all the details such as component cost, performance etc. continuously throughout the development program.
8. Requirements at every level well and clearly documented. Very close contact with customer in line with his requirements, especially as they are modified since he too is developing a product, the total aircraft.
9. **Understood** lessons learned from previous programs. It is not good enough that one read the lessons learned rather it is important that one fully understands the underlying lesson and how they apply.
10. **High-risk** activity was done very early in program.
11. Relentless root cause analysis was used whenever a shortcoming was found during the development program. Time and energy was spent during the program, as well as the phase of initial introduction into the field to really understand each issue and the effort didn't stop when by trial and error the problem went away.
12. All issues were addressed concurrently. If an issue came up affecting part of the engine development effort, this did not result in all other effort stopping to address the one burning issue. The rest of the development still continued while the burning issued was being addressed. This allowed the program to keep completing the required tasks and when the burning issues were resolved the program was still on track.

13. A holistic view of the engine family was used. The basic growth path for this family was determined prior to the development of the first member of the family. This led to smooth, and cost effective development programs when it came time to grow the engines.

3.3.3 Case study of Engine "PW100" program – 1970's vintage – A highly successful program

An interview with the program Project Director is included in appendix "A" and summarized below.

The original application for the PW100 family of engines was the large turboprop corporate market that never developed. The engine family however found a home in the new regional airline market that turned out to be much larger and with very different requirements than the original intended corporate market.

The PW100 family of engines was and still remains today the dominant engine in the regional turboprop aircraft market. It has captured over 90% of the market and has established new levels of reliability and customer acceptance in that market

When it was developed this engine represented a new level of technology that the company had not used in previous engines. These included electronic fuel controls, cooled turbine blades and three-spool engine architecture. During the development program these technologies were successfully developed and incorporated into the engine.

The PW100 engines today represent the standard against what all other engines in the turboprop regional market are judged against.

3.3.3.1 Key Development Methodology used on the "PW100" family of engines.

1. Program was led by a hand picked and experienced team
2. Upfront demonstrator program was in place to address all risk areas.
3. Detailed risk assessment and mitigation.
4. Resources needed for the program were provided right from the start. When the decision had to be made whether to stick to the budget or resolve the issues, resolution of issues took president
5. Close teamwork effort especially between Marketing (the voice of the customer) and engineering.
6. Product was not oversold.

3.4 Lessons learned from the three engine case studies

To understand the differences between the three engine case studies it is valuable to introduce the findings of the so-called "Stanford Innovation Project" (Maidique and Zirger 1984,1985) (11). While this research was done for the electronics industry the findings of factors that contribute to project success can relate to any high tech product.

Based on data from 158 product development projects in the electronics industry, which consisted of pairs of successful and unsuccessful ones by financial criteria, the researchers concluded that the following eight factors are statistically correlated with project success:

- Understanding the customer
- Better cross functional coordination
- Higher contribution margin
- Utilization of existing technological and marketing strength
- Proficiency and resource commitment
- Planning and coordination in the R&D process
- Level of management support
- Early market entry

The table below summarizes how each of the 3 programs discussed in this chapter as well as the PW600 that is discussed in the next chapter correlate with the success factors.

	Engine "A3"	Engine "B1"	PW 100	PW 600
Stanford Innovation Project Factors				
Understanding the customer	No	Yes	Yes	Yes
Better cross functional coordination	No	Yes	Yes	Yes
Higher contribution margin	Yes	Yes	Yes	Yes
Utilization of existing technological and marketing strength	No	Yes	Yes	Yes
Proficiency and resource commitment	No	Yes	Yes	Yes
Planning and coordination in the R&D process	Yes	Yes	Yes	Yes
Level of management support	No	Yes	Yes	Yes
Early market entry	Yes	No	Yes	No
Other Success Factors				
Early Prototype testing	No	Yes	Yes	Yes
Resources provided up front	No	Yes	Yes	Yes
Technology demonstrated prior to customer commitments	No	Yes	Yes	Yes
Close to firm's areas of expertise and knowledge base	No	Yes	No	Yes

The two successful programs, the PW100 and the B1 had a high level of management support and therefore the required resources were provided at the start of the program. The fact that both programs were managed by hand picked and experienced teams also are an indication of the management support and commitment to the programs.

Both successful programs had demonstrator programs to ensure that the engine's capabilities were understood before commitments were guaranteed to the customer. A real effort was made to understand all the risk areas and to mitigate risk prior to program launch.

Rules based design and knowledge from previous programs was used extensively. Both engine programs were built upon previous company knowledge.

The expectation then follows that the PW600 should enjoy a high level of success.

4.0 Chapter (4) An optimized approach to Program Management and Product Development for Pratt and Whitney Canada

This chapter introduces an optimised program management and product development procedure for Pratt and Whitney Canada which combines the strengths of the progressive companies discussed in chapter 2 with the experiences of the successful programs discussed in chapter 3. We will then discuss a current program that is attempting to introduce the process.

As Alfred Sloan pointed out the strategic aim of a business is to earn return on capital. Before any program can start at Pratt & Whitney Canada it must first be sold to the Senior Management of the company who if they feel that the program has merit must then sell it to the board of Pratt and Whitney Corporation. The board of Pratt and Whitney Corporation must then get approval to go ahead with the program from the CEO of United Technologies. Each party in the decision making process is required to meet guidelines for return on investment for the program as well as meeting the EBIT (earnings before interest and taxes) targets for the year. In addition the decision-makers have to consider the effect each program has on the future market share in the product class that the program is addressing. Last but certainly not least the company has to calculate how best to utilise its limited resources to achieve the maximum return on effort. Needless to say an optimum product development process is required for the long-term health of the company.

Based on the information contained in chapters 2 and 3 we can determine key features for a product development process for Pratt & Whitney Canada. Alfred Sloan of General Motors established many of the key principles but the lean manufacturers such as Honda and Toyota perfected the methods of execution of how to maximise these principles. I will list the key principles and features and then develop the proposed process.

4.1 Key features of an optimum product development process for Pratt & Whitney Canada

1 Managers who are technically competent and know the product must lead development teams.

2 Managers must be focused on the bottom line, i.e. return on investment and yearly EBIT.

3 Development team must stay focused and work from facts. They must understand why things happen not just how they happen.

4 An advanced technology team separate from the development team needs to develop the long-range research. This advanced technology team however must not isolate itself from the day-to-day workings of the company and the incessant demands of the marketplace. Once the research is done and **proven** the development engineers take on the task of developing the technology into the product.

5 A mass produced product requires the complete and consistent interchangeability of parts and the simplicity of attaching them to each other.

6 There is a need to develop family platforms and have a full product line.

7 Product integrity is a basic requirement for any new innovation. Risk mitigation and rigorous testing is required before a concept is considered production ready. Products sold to customers must be fully tested before being shipped to a customer. Extensive and through prototype testing must be part of the product development process. When possible prototype testing should be done before customer commitments are firmly established so that the product is not oversold.

8 Product development must be led by a dedicated and strong Project Manager who has control of a dedicated and focused team. The Project Manager is responsible for the product and is the voice of the customer. The Project Manager must have close contact with the working engineers and the Project Manager and through him his team, must maintain close customer contact as well.

9 All required resources must be provided at the initiation of a program.

10 Simultaneous development must be used extensively. Downstream problem solving (process) starts before the upstream cycles (engineering) is complete. For this to work effectively there must be intensive and continuous information transfer between the upstream and downstream teams, which brings the downstream experience to the upstream effectively, and to make conflicts visible at the early stages of the program.

11 The development process should facilitate the generation of as many ideas as possible early in the design process. An optimisation process similar to the Toyota SBCE process is needed to funnel the ideas down till they become the optimum design.

12 The development process should encourage high pay-off but risky solutions, but always provide a backup that works.

13 A gated process as well as a process that controls the interface between functions is required in the product development process.

14 A development program must have a close and trusting relationship with the manufacturer and suppliers of the components that make up the product.

4.2 An optimum product development process for Pratt & Whitney Canada

Even though Pratt and Whitney Canada enjoys a dominant position in its market it must behave as if it were a predator. As pointed out in chapter 3 Pratt and Whitney Canada has already incorporated many of the best features of the companies discussed in chapter 2 and listed above.

The projects at Pratt and Whitney Canada are led by a strong "large project leader", a Project Director who is an executive of the company. He leads a tight knit and focused project management team who have total responsibility over the design, and engineering of a new product. It should be noted however, that even though the project team is focused and dedicated to the program, Pratt and Whitney Canada uses a matrix organisation in which the functional groups, do not report directly to the Project Director and are not focused on any one program.

The Project Director and his team have a close contact with customers and markets. The Project Management team is involved in the Marketing of the product, the development phase of both the engine (PWC's product) and the aircraft (the customers product).

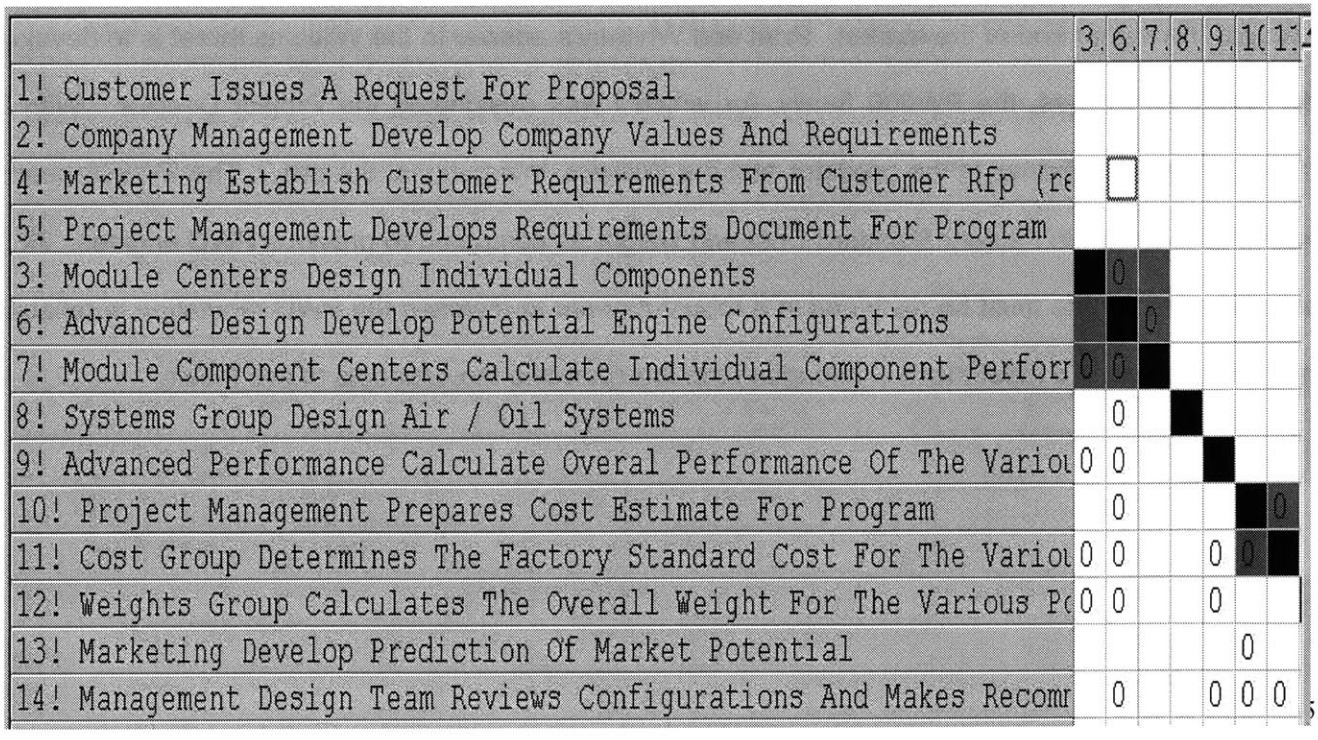
Pratt and Whitney Canada develops deep technical expertise in both its engineering and management ranks. An employee who had previously held a high level position in engineering usually in project management holds many of the executive positions in the company.

On our latest program the PW600 family of engines we want to build on these strengths and incorporate features from the progressive companies outlined in chapter 2 and the best features of the successful Pratt and Whitney Canada programs outlined in chapter 3 and summarised at the beginning of this chapter. These features fall under two general headings, Full Knowledge and Product Annealing.

1. Full knowledge refers to understanding the product fully at a component level early on in the program, when there is an ability to address issues in a cost-effective manner. Full knowledge requires knowledge of what can be determined with a high level of confidence using existing analytical tools and what must be tested using prototypes. In development you have to separate the things that you can analytically predict with great certainty and those you cannot. For those you cannot you need to set up a development program to gain the needed knowledge so as to reduce the uncertainty to zero.

   Full knowledge also requires the understanding of the dependency of the tasks. Who needs input from whom in order to proceed? A Design Structure Matrix (DSM) is a useful tool in this regard. Steven Eppinger in his paper " A model based method for organising tasks in Product Development"(10) details how the DSM can be used. Figure 4 below illustrates a sample DSM for the initial phase of a program.

Figure 4. DSM example of RFP to 1st Review



2. Product annealing refers to the method of not firming up a design early in the design process, but rather allowing the design to remain in a flexible form so that an optimum design can emerge.

I will use the following case study to illustrate how these features are incorporated in a real world development.

4.3 The PW600 Family of Engines

Pratt and Whitney Canada is the world leader in aircraft small turbine engines. It has a commanding market share in the turboprop and turbofan corporate aviation market. In the 1980's Williams International a company that makes cruise missile engines brought a product into the market, the FJ44 engine which created the ability for aircraft companies to produce a new product, the small turbofan business jet. This market became very lucrative and Williams had this market to themselves. Williams used their position in the market to develop derivative engines and further penetrate the Pratt and Whitney Canada Market.

Professor Utterback pointed out, in his class on disruptive technologies, that a company shouldn't let a competitor take over the bottom end of the market because because from that position he will surely grow into the higher end of the market. Pratt and Whitney's answer to the Williams threat is to develop a new family of engines, the PW600 family, for which I was designated the Project Director. With the PW600 Pratt and Whitney is the predator and the Williams International the prey. The PW600 needs a major improvement in Factory Standard Cost and weight as compared to previous PWC engines. At the same time the engine must be designed in a robust manner to maintain the PWC reputation in reliability, and performance. To meet these challenges I am incorporating the concepts of this thesis.

4.3.1 Full Knowledge

"Full Knowledge" is a development process in which an effort is made to fully understand how and why things work on a program, rather than just knowing what does or doesn't work. The key steps of full knowledge are:

1. The program is broken up into modules of a size that can be understood.
2. A determination is made as to what can be analyzed to a high degree of certainty and what you need to build prototypes or boundary objects to understand what will and what won't work and why.
3. The full knowledge effort is done up front.

To achieve the target performance and cost the PW600 has to introduce innovative designs and processes into the program. Professor James Utterback in his book, "Mastering the Dynamics of Innovation"(8) points out that to be successful, a predator needs more highly developed internal technical and engineering skills coupled with greater skills in process innovation and integration. This allows the predator company to introduce an innovative design that delivers dramatically better product performance or lower production costs or preferably both. The aim of the PW600 program is to deliver on both objectives by putting an integrated effort on both the product (engineering) and process (manufacturing as well as purchasing) design of the PW600 family of engines. Full knowledge is required in order to succeed.

The PW600 program is being manned by a team of hand picked experienced project engineers with a majority being veterans of the successful "B" family of engines discussed in chapter 3. A decision has been made that the first two members of the PW600 family be designed consecutively rather than concurrently and that a dedicated design team be provided to the PW600 program for an extended period of time. This in effect allows the PW600 to enjoy the following two characteristics of progressive companies as described in the book "The Machine that Changed the World"

1. A dedicated focused long-term team for the life of the program.
2. Learning from the first program directly built into the second program.

A detailed concept design effort was carried out before the architecture for the engine was established. The manpower assigned to the concept phase was an order of magnitude (5 times) larger than was previously used on former full engine concept design studies here at Pratt and Whitney. The engine design was broken up into modules, and a fully staffed analytical group recruited from the functional departments supported each module team. The company director of engine design as well as the company director of performance and operability led the concept design effort. The vice president of engineering participated in the weekly program reviews.

The concept design utilized principles taken from Toyota's set based design. The design process started by looking at the total solution space for each engine module in isolation as well as the overall engine architecture. All possible configurations for each engine module was sketched and evaluated. An optimum configuration was established for each module based on facts and analytical evidence. The designs were reviewed against best practices and lessons learned from previous successful programs. An interface control document (also called an A+B document) is being written to identify the feasible boundaries of the solution space on all sides of each engine interface so that all parties understands the feasible region of the other side of the interface. It explains the interface needs when one mates component A to component B. The interface document at its early stage tell the things that can and can not be done and what are the costs and benefits from the perspective of the mating component or function.

Because the PW600 was competing in a very competitive market, new and innovative designs are being incorporated. Each design went through a formal risk benefit analysis and where areas of risk were identified a risk mitigation plan, which included the design of a more conservative and traditional

design, was established. Where appropriate, prototype testing is being used to provide full understanding and full knowledge and therefore risk mitigation.

The IDEO concept (7) of "Fail often to succeed sooner" is being used. Two types of "boundary objects" are being used.

1. Individual component testing to understand the components at an individual bases.
2. A full engine demonstrator to understand the engine at a total system level.

The engine was broken down into manageable modules and a risk level was assigned to each module. Each module was reviewed to determine the best route to full knowledge be it analytical based on former predictions on similar components or whether it was better to build a prototype and test it. Following the philosophy that is taught in System Architecture an emphasis was made not only to understand the parts but how the are connected and interact.

Since this program was building this safety net all the module designers were encouraged to design innovative designs that gave the best compromise between weight, cost, performance and reliability even if the design was new and contained risk. During the early "full knowledge" testing we verified several designs that would have been considered too high risk without the full knowledge testing. We were also able to develop several other module concepts that didn't quite work out as designed but with some development we were able to make them work. We however had to abandon some concepts, which turned out not to work as designed and required modifications that no longer made them optimum.

In addition to the module component testing a full engine demonstrator was built and run in a test cell seven months after the commencement of detail design. This compares to 14 to 18 months in a typical program. The full engine demonstrator highlighted that many of the unique and innovative features actually worked as advertised and that further risk mitigation was no longer necessary. It also showed us areas that we had shortcomings, but since we were so far ahead of the game we now have time to

overcome these shortcomings in a cost effective and optimum manner. For some other innovative features we had obviously gone too far and we will have to revert back to conventional designs. All this full knowledge is available prior selling this engine family to any customer.

This allowed Pratt and Whitney's Marketing department in conjunction with the Program Director to compete in several tough fought competitions with knowledge of what they can commit to and what they couldn't. Because we knew how good the engine really was we could and did commit to aggressive targets and as a result have been extremely successful in the market.

Takahiro Fujimoto pointed out in his thesis (6) the importance of overlapping the downstream process (the manufacturing) with the upstream process (engineering) and thereby developing the product and its manufacturing system simultaneously. Mark H. Meyer and Alvin P. Lehnerd in their book "The Power of Product Platforms", (12) claim that companies that develop dominant platforms require an early and continuous integration of product design with manufacturing design. Kim B. Clark, W. Bruce Chew and Takahiro Fujimoto in their article "Product Development in the World Auto Industry" (5), pointed out that it is important that the upstream group continuously transmits preliminary information little by little, and the downstream unit sends its own information back upstream in a continual give and take. On the PW600 this overlapping is being accomplished in two ways.

1. Pratt and Whitney in house manufacturing process planners are working with each IPT so that manufacturing expertise is incorporated into each and every design right from the word go. In addition senior members of the Pratt and Whitney final assembly and test team are reviewing the engine layout continuously to ensure the final engine is easy to assemble in production and in the field when maintenance is required.
2. The Japanese concept of using the knowledge of suppliers is being used on this program. Suppliers with expertise are being chosen during the concept design of the program. These suppliers are taking on the responsibility of designing component systems that perform to agreed upon specifications in the finished engine. Since these suppliers have concentrated on their specific engine component for many years they are specialists in their components and

understand the subtleties of the component systems under their responsibility. Another way to express this is that the specific component is only a small part of the engine as far as Pratt and Whitney is concerned, and gets a small proportion of Pratt and Whitney's attention. On the other hand to the supplier it represents his total contribution and therefore gives it his full attention. A complete host of supplier produced innovative designs has already been incorporated into the PW600 family of engines thanks to this approach.

4.3.2 Product Annealing

Management has a great temptation to freeze the definition of a new product as early as possible. This greatly simplifies the task of managing a program. Things are well defined, left brained managers can put together detailed well organized program plans, individual designers can work comfortably on their components knowing that the boundary conditions will not change greatly and in general the program will appear well managed and well run. Sloan and his era of managers would appreciate a program run in this manner.

At Toyota, as detailed in Chapter 2, they have developed a Set-Based Concurrent Engineering design process. The heart of this process is similar to what IDEO does which is to generate as many ideas as possible early in the design process. At both IDEO and Toyota the design process resembles a funnel, with many ideas at the top, a few at the base and only one making it all the way through.

Traditionally, at Pratt and Whitney Canada the concept design of a new product was performed by a small group of very experienced Advance Design Engineers who together would come up with an overall definition of the product that meets basic requirements. Once the concept is defined the product is broken up into components and given to detail designers. These detail designers are experts in their field and provide the detail definition of the product.

The original Advance Design group starts off with many degrees of freedom and they quickly narrow down the concept to one prime design. When the detail designers get the job they are left with very few degrees of freedom.

Both management and many designers are comfortable with this approach. Management likes it because it is well defined and it is easy to see and plot progress. Designers like it because the boundary conditions remain constant and they have a straightforward task to design a component.

The trouble with such a system is that flexibility is lost early in the program and such a system does not allow the required interaction needed to optimise the design.

On the PW600 program we are introducing a system more aligned with product annealing, which allows a design to develop over time and then firm up, and the Toyota set based concurrent engineering process where flexible regions are defined and the design engineer works within those flexible regions (when he still has a lot of degrees of freedom).

Rather than using the traditional Advanced Design team to design the PW600 engine a large team consisting of Advanced Design engineers, Project engineers, functional group experts, cost and manufacturing engineers worked on the concept design of the PW600. As mentioned earlier, the concept design of the PW600 consumed an order of magnitude (5 times) larger number of people than a traditional program. Cost, weight and performance targets were set for each module. The module teams were given the freedom to define all the feasible solutions for their module as long as they met the three constraints. Daily design reviews were held so that each module could communicate the feasible boundaries of their solution space so that everyone understood the feasible region of others.

The complete design was managed through the use of weekly design reviews. As mentioned earlier, all pertinent management participated in these weekly reviews with the aim of coming up with the optimum solutions for the engine. These weekly design reviews are also being used to force the

funnelling of the solution to converge to a single point. In chapter 2 we pointed out that lean manufacturers ensure that problems are unearthed and addressed early in the program rather than let them move down the line till they become visible. The full knowledge approach as well as these weekly reviews in conjunction with the Passport reviews discussed in chapter 3 ensure that on the PW600 programs issues are identified early in the program and addressed.

To bring discipline to the procedure we are trying to enforce Sloan's principle of working from facts. The program has an internal Intranet site within which all the information on the program resides. At all program reviews, team members as well as management are encouraged not bring up an important problems without all the members of the committee having the facts placed before them prior to the review so that they are in a position to exercise their own individual judgement. In addition members are encouraged not to work from opinions or hearsay but work from the data.

4.3.3 Current Status PW600 Program

Professor James Utterback, in his book "Mastering the Dynamics of Innovation", points out that innovation can provide real cost savings from several sources but are often related to reductions in the number of parts, product complexity and process steps. He states that value is added by finding simple ways to do complex jobs and by making the product simple to build and use. The full knowledge approach has given tremendous insight into what is feasible and what is not. The end result is that the PW600 engine contains only 50% of the number of components when compared to a previously designed engine in its class. The PW600 high compressor that uses a configuration that provides the required pressure ratio and flow using 2 stages of compression rather than the traditional 3 was considered high risk. This particular module was therefore fully designed and tested, redesigned and retested before the PW600 configuration was frozen. Because we had fully mapped that particular innovative component we were able to design the rest of the engine around it and maximise the benefit of that innovation. There are many other innovative ideas being incorporated into this engine and the full knowledge concept is being used on all those that can benefit from its application.

As mentioned previously early on in the program a full engine demonstrator (prototype) was built, run in a test cell and flown on a test aircraft. This prototype represented an early version of the design, one that definitely did not meet best practice or even some of the basic company design rules. It represented a point in time of the design. Many in the company felt that the effort and resources spent on this prototype would be a waste of time. The end result, I feel, have proven them wrong.

The prototype ran 9 months after the start of detail design, which is 7 to 9 months earlier than if a traditional approach was used. More important it ran before commitments were made to some key customers. The prototype ran very well highlighting the conservatism in our best practices and design rules. It highlighted areas that need redesign many of them already identified by our analytical tools and design practices, and was corrected in the final design even before the demonstrator engine had run. What the demonstrator did show however is that some of the redesigns were not optimum or good enough and that even further design work was needed. The prototype showed that the engine performance did meet the optimistic design performance targets and that it was safe for Marketing to go out and sell some aggressive performance guarantees. The prototype engine in conjunction with the rigs used have highlighted areas that need redesign that we had not foreseen and these areas are now being addressed early in the program.

The prototype engine had a very positive effect on potential customers who now felt that the engine was no longer a "paper engine" but was real. Innovative suppliers came on board and were able to demonstrate there "high risk" proposals on a real engine and convince us that going with them, and thereby reaping the benefits of their innovation, was an acceptable risk.

The program is still in its early stages. "Full knowledge" requires that each module be mapped and fully understood. This is in the plan but has not been done yet. When this is completed the engines match can be optimised.

As with any new concept, implementing the concept of using prototypes has its challenges. A prototype must be manufactured fast, and in many cases it is only a cheap and dirty version of the real thing. In all cases it is not a perfect representation. If the prototype does not give the predicted result then the analytical groups dismiss the data saying it is not representative. The functional groups demand perfection from all testing and that is why traditional programs take 14 to 18 months to get the first bit of data. If there are any surprises in the data when it finally comes then it is usually too late in the game to introduce innovative concepts to address the issue. The key to prototyping is to represent the important parameters well, understand what the test is really telling, and benefit from the time gained. We are trying to follow the advice of Professor John Rydz from the University of Connecticut (formerly Vice President Innovation at Singer Corp) that the key to selling or understanding an innovation is a cheap and dirty prototype that correctly shows the concept.

The PW600 program is still in its infancy with the first member of the engine family just finishing detailed design and the second member the PW610 just starting its advanced design activity. To claim that the product annealing process worked smoothly would be a great oversimplification. This is a great cultural shock for all involved. Management of such a procedure is hard and it always looks as if the design budget is going to spin out of control. As soon as changes are made everyone claims that they need to do a complete redesign. What really must be done is to better define what the feasibility boundaries are.

Some of the concepts of the Toyota set-based concurrent engineering process were incorporated. The concept design team was required to review all possible alternative architectural designs possible for each module and then formally evaluate the benefits and shortcomings of each. A team led by the company's director of design reviewed the designs from a total engine point of view and together with the full knowledge analytical and test data, risk funnelled down to a definition that was optimum from an overall engine point of view. **Solutions that optimise total system performance are chosen.** In addition, borrowing a page from what the book "the Machine that Changed the World" was the real mass production invention of Henry Ford, consistent interchangeability of parts and the simplicity

of attaching them to each other is a feature that is being incorporated into the design of the PW600. These designs became baseline for the engine. If during later development these decisions turn out to be wrong we have left the door open to review them. How this works out only time will tell.

A detailed risk benefit analysis was done right up front in the program covering every aspect of the program from design, to cost to customer commitments. This is being monitored closely and being reviewed at a regular basis with top management of the company as well as the corporation.

In summary Pratt & Whitney Canada now has an optimised product development system incorporating many of the best features listed in Chapter 2 as well as the lessons learned from former successful programs listed in Chapter 3.

1. Pratt and Whitney Canada uses a structure similar to what Sloan developed at General Motors. The company is broken up into programs each lead by a Project Director who champions the program but has co-ordination from the senior management of the company. This decentralisation allows each program to have the strengths of a small nimble company as well as the resources of a large company.
2. A heavy weight project manager leads a team dedicated to the program.
3. The total number of people involved in the project is highest at the very outset of the program. Required resources are provided up front in program.
4. Simultaneous development (IPTs) is used extensively. There is strong overlap between the upstream (engineering) and downstream (manufacturing). There is a large degree of overlapping development between product and process. Production preparation is started early in the program.
5. Because of the IPTs there is intensive information transfer between the upstream and downstream processes.
6. Because of the Project Management structure there is intensive information transfer between different modules.

7. Prototype testing is being introduced early in the development of the product. A full host of boundary objects are used, some to validate a single concept, some to demonstrate a module and some to demonstrate an entire system.
8. The Project Director provides close and continual information flow from market to product design.
9. Following Honda's methodology all key suppliers are selected at early during the outset of product development. Supplier input is used to define how components are designed.
10. The basis of full knowledge is being incorporated. Full understanding of why things work or do not is being used to develop the product. Relentless root cause analysis is used whenever shortcomings are found.
11. A gated process is used to manage product development.
12. When possible prototype testing is done before customer commitment so product is not oversold. This allows Pratt & Whitney Canada to follow the Toyota system of pursuing high pay-off but risky solutions.

The table below compares how the PW600 program is incorporating the key features of the optimum development process detailed at the beginning of this chapter. As one can see all the features are being implemented.

Key features of an optimum product development process for Pratt & Whitney Canada	Incorporation into PW600
1 Managers who are technically competent and know the product must lead development teams.	Hand picked technically competent managers
2 Managers must be focused on the bottom line i.e. return on investment and yearly EBIT.	Heavy focus on budget, and cost
3 Development team focused and work from facts. Understand the why not just the what.	"Full knowledge" philosophy a way of life
4 Research done outside of program, prior to program launch	Innovation developed prior to program launch
5 Complete and consistent interchangeability of parts, and simplicity of attaching them	Design requirement
6 Need to develop family platform and have a full product line	Complete family being developed
7 Product integrity - Risk mitigation and rigorous testing	Risk mitigation review and plan
8 Dedicated and strong product manager.	Strong Project Manager runs program
9 All required resources provided at initiation of a program.	Resources provided up front
10 Downstream problem solving (process) starts before the upstream cycles (engineering) complete	Manufacturing, Assembly and test and suppliers involved
11 Generation of many ideas early in design process	Initial design phase was open to all ideas
12 The development process should encourage high pay-off but risky solutions, but always provide a backup that works.	System incorporated
13 A gated process as well as a process that controls the interface between functions	Passport process
14 A development program must have a close and trusting relationship with the program manufacturers and suppliers	Manufacturing, Assembly and test and suppliers involved

To understand the effect that incorporating the processes proposed in this thesis has, it is valuable to examine how the PW600 program would be managed in a more traditional manner. This is shown in the table below.

Process	Traditional	PW600
Concept Design	Small group of Advanced Design engineers	Large group -dedicated cross functional team
Concept Design	Frozen early in great detail	Used product annealing
Risk Mitigation	Limited, mostly using analytical tools	Extensive, using analytical and testing
Risk taking	Low, and when used high margins used	High, but evaluated early and backup provided
Manpower	Low at first, ramp up as program progresses	High at program initiation
Manpower	People brought in as needed	Dedicated team
Downstream Process	Brought in after design when it is ready for manufacture	An integral part of initial team with real input into design
Commitments to Cust.	Based on predictions with margins built in	Based on real demonstrator provided data
Suppliers	Bid for contracts based on PWC design	Brought in upfront and have real input into design
Full Knowledge	Understand engine in overall sense	Understand engine in detail at component level
First run of engine	18 months after start out of a 36 month development Program	9 months after start out of a 36 month development Program

It is clear that the product would be very different using a traditional program. It is not clear that Pratt & Whitney Canada would have won the competitions it did without running the demonstrator prior to the engine selection by the aircraft manufacturer. During the fall of 2003 the engine would have gone into test evaluation for the first time. It would have been built to the initial design. We however now know that the initial design is not optimum and will test this fall with a much-improved engine. In a traditional program the suppliers are brought in after design completion. The PW600 program is meeting some very aggressive factory cost targets that would not have been achieved without early supplier involvement.

5.0 Chapter (5) Executive Summary and Future Work

5.1 Executive Summary:

5.1.1Problem Statement

The eventual success or failure of a project is often determined by how the program was managed from initiation until it is finally certified and introduced into the field. This thesis looks at the management of the design, development and certification of aircraft jet engines which by their very nature are expensive propositions in which the company undertaking the project often is betting the total worth of the company on the program. To address the risks Project Managers have developed many processes such as Best Practices, Standard Work, and Design Reviews etc. This thesis looked at the processes used and developed some key steps that minimized the long-term risk in an efficient manner.

The following two program development techniques were developed:

1. Full knowledge.
2. Product annealing

5.1.2 Originality Requirement

This thesis is a unique application of several design principles learned in the MIT System Design and Management program to the product development process for large, technically challenging and expensive programs using the development of aircraft gas turbine engines as an example. A review of the worldwide product development processes is presented and an optimum process proposed for the product development of aircraft gas turbine engines is presented. The original concept of "full knowledge" is presented, as well as an adaptation of several of the techniques used by world leaders of automobile industry and adapted to the aerospace industry. Several case studies of previous programs are presented to provide potential lessons learned.

5.1.3 Content and Conclusion(s)

This thesis approaches the development of aircraft gas turbine engines with the view that the developer should behave as a predator as described by Professor James Utterback in his course, "Disruptive Technologies, Predator or Prey". The thesis further explores the characteristics of prey companies and postulates that the difference in behavior between the "lean automobile manufacturers", led by the Japanese and the "mass production automobile manufacturers" such as General Motors, is that the lean manufacturers acted as predators, and the mass producers acted as preys. The basic impetus of a prey is to make sure they don't make a mistake. Everything else is secondary and therefore all the processes of a prey company concentrate on what it takes not to make a mistake. The emphasis is on developing the maximum amount of product at the minimum cost and risk. The objective of a predator corporation on the other hand is to change the status quo. They are focused on the product. While they too would suffer if major errors were made, this fear is tempered by the need for innovation to overcome the strength of their preys. These companies address the issue of mistakes by giving a strong ownership of the project to its team and trust the team to overcome all issues. The emphasis is to maximize success and innovation and to minimize errors. The thesis combines the strength of both types of systems with that of the best experience from case studies of various Pratt & Whitney Canada programs to formulate a product development philosophy that is optimum.

The beginning chapters of this paper summarize the books and papers that discuss product development primarily in the automobile industry. The third chapter summarizes project management at Pratt and Whitney Canada the world leader in the design, development, certification and production of aircraft small gas turbine engines. The chapter also includes case studies of recent development programs, some highly successful and some not as successful. Chapter 4 presents an optimized approach to Program Management and Product Development. This final chapter contains an executive summary of the paper as well as concluding thoughts regarding areas for future study and development.

One of the primary conclusions from this research is that the aerospace industry can incorporate many of the techniques developed in the automobile industry, as well as several unique methods such as full knowledge, to increase the effectiveness of its product development process.

5.1.4 System Design and Management Principles

This thesis draws upon an amalgamation of SDM principles to achieve its overall objectives. Fundamental concepts from systems engineering, systems architecture, risk benefit analysis, technology strategy, supply chain management, lean engineering, project management and product development are combined in a unique way to provide a comprehensive review of the issues pertaining to product development in the aerospace industry.

5.1.5 Engineering & Management Content

By combining concepts from engineering and business, this thesis attempts to create a holistic view of the challenges currently facing the aerospace industry in regards to the design, development and manufacture of aircraft jet turbine engines. Engineering content includes many of the principles of Project Development, and risk benefit analysis. The author's extensive development experience with the development of aircraft gas turbine engines provides additional insight into the technical and strategic challenges faced by many aerospace engineers. Management content includes many of the principles of Project Management and Disruptive technology management.

5.1.6 Statement of Authorship and Originality

The work performed to write this thesis is the author's, and is original.

5.2 Future Work

Because the author of this thesis is also a Project Director at Pratt & Whitney Canada he is currently incorporating the concepts presented into a real program the PW600 engine. The obvious future work would be to observe how the PW600 program actually plays out and how the processes proposed in this thesis actually work out in a real world case as well as further refining them based on real world experience. It should be noted that this thesis looks at the development of an aircraft gas turbine engine program in isolation i.e. looking only at one program. The reality is that Pratt and Whitney Canada is has 29 development programs going on simultaneously. An extension of this project would explore the difficulties and compromises of doing this in an environment where several programs are ongoing simultaneously and extend the methodology presented in this thesis to cater for this real world situation.

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Appendix "A"

7.0 Vice President – Engine A3 Interview

Q1: Describe the Basic Design, Development philosophy you laid out for the Program when the program started.

A1: The philosophy was that we were going to put in place a very good equipment specification (Product Definition Requirements Specification) so that all key players knew the specification. We where going to set up the resources the Integrated Product Team (IPT), all the team players and leaders where going to be put in place. We held a suppliers conference and all the suppliers were on board up front. Our other aim was to have the most thorough test plan defined, a test plan that was audited against the compliance plan and we had initial contact with Transport Canada sooner than we had ever had on any other program.

M: In one sentence "Do a lot of work up front"

Q2: What key lessons learned did you use from previous Programs that caused you to adopt the above-mentioned philosophy?

A2: The "A3" was on the heels of the "A2". The "A2" was concurrent with the "A3" but the "A2" had started in 1993 and the "A3" launched in 1997. By that time the "A2" had completed its first customer and was on its second customer at the time, had a lot of lessons learned on the "A2" which where surprises that came too late in the program, surprises in Design, surprises in Manufacturing, all the usual surprises. So when we launched the "A3", we tried to incorporate lessons learned from the previous "A" engines in terms of execution. That meant IPT leaders where identified up front, identified the work breakdown structure, the budget, man-hours, the

complete allocation of resources, the suppliers were on board and had a test plan that put all the high risk items up front.

Q3: Philosophy to action – what procedures did you attempt to use?

A3: Philosophy Do the Work Up front.

Q4: What worked and what did you have to modify?

A3: What worked- We had just about every critical part in the Spin Pit categorising, before the second engine was up running. So in our Spin Pit program, we had all our critical parts in the spin pits very early, in fact some of the first parts made went to Spin Pits before they went into an engine. That worked very well. M: How come we missed the "A3" impeller? A: The first run was June 1998, certification date was supposed to be November 2000, first impeller failure was Spring of 1999 @ 55,000 cycles, and if you take a look at that, it was three months of testing, it was done fairly early on in the program. The problem is that now, in 2002, we are on our 4th design. In reality of the problem was identified very early in the program that the impeller had no life. We started on a redesign by introducing a split impeller and followed up by modifying that redesign. We made 3-4 different changes, so in one way the impeller is a big money drain on the program, in another way had we spun it in the time frame that previous programs used and had had this problem we would have been 2 years further behind. So being up front was a good thing but the bad thing was, we could not solve it. In this program on critical parts failed early in the program, the fan hub, 2 turbine discs and the impeller, so I had four critical parts that had to be redesigned early in the program. The fan hub recovered before we went into Production, as did the turbine discs, so there was some real good pay back there. The disappointment was that the design was flawed, there maybe reasons for that other than those already mentioned. A big problem on the "A3" was priority for resources. The first 20 months after first engine run we had 5 full time Project

Engineers as opposed to the required 12 and 1 program manager as opposed to 2. M: you where at 40% staffing. A program of that magnitude tried to run with 5 full time P.E.'s and 3 part time PE's. In the end you get what you put in. A lesson learned there, we said on the PW307 program we said we would never repeat and in comparison the PW307 program has 14 P.E.'s, and 3 program managers, 2 in the conventional sense and 1 on the Nacelle side.

Q5: Why where these modifications necessary.

A5: The impeller problem is basically we where not technology ready, we thought where ready but material and clearly four years later, we weren't. M: Why weren't we technology ready and what could we have done? I guess we went to a new material never used before in PWC? The good news about the impeller is that our own processes to release the impeller to the field, it would catch the flaw, the bad news is that we had been using this material for over a decade, and we had been using it correctly in a good application, but we don't know why it worked, we just know that it worked. So if the IMIA 34 impeller in service went through all the paces of validation testing and passed it was released. The "A3" came along and was using it in higher stress levels than its predecessor's started to go through the motions of validation and failed and three years later we understand why it failed. We also understand why the first application ten years earlier worked. When something works, you do not ask why it works

M: Is that a failing of Full Knowledge, in other words if you have to define Full Knowledge, now in hindsight, does that mean that you now have to not only know that it works, but how it works

Q6: In hindsight what do you now wish you would have done that you didn't do.

A6: No, I don't think so, because if you want to understand why everything works, you will not be competitive, you will spend money on things you do not need to spend money on. A different philosophy that might catch it is we don't use it to the extent we should is MERCI . If you have

something that works it is easy to feel we should go a step further and put it outside its tentative boundaries, then if it still works you do not know why it still works, but if it fails we then start to find out what its limits are, and we do this time and time again in our programs, stretching it to the next level, assuming it works but not understanding why it works. M: Should that be done from a Company point of view or should that be done within the programs or should that be done outside the program a Research or a body of knowledge collecting. It has to be in the culture of every department it has to be just second nature it should not be the onus of the Projects group or design community it has got to be in the culture that when you have a successful test or a successful design you then ask yourself if it is on paper you do a sensitivity study, if I just push this parameter a little bit further then what happens. If you are in the development world and test it just a little bit further to see what happens without even being asked, it should be second nature in the culture

Q7: In hindsight which actions that you did do really paid off in the end.

A7: There is a very good example on hindsight on the "A3" that is the single biggest contributor to why we have so many issues on the "A3" program. The W308 was entering an extremely competitive market and we where trying to knock off an incumbent, so we made a performance commitment, as a company, but we had no plan in place to close the gap. We knew that, we all went in knowing that we had a performance shortfall, and that was just a given, it was strategic we did it and we said that we would close the gap. Having done that we then produced models that lined up with the optimistic targets and we then went and designed the new engine. In hindsight knowing that you are going to have a performance shortfall knowing the engine is going to be hotter, you should have designed for it up front. Instead we designed as if we where going to close the gap, and then when the first run showed that we could not close the gap we where dead in the water and went into a spiral on temperature and performance. Had we said this

engine is going to be 150° hotter lets design for it and come at it another way we would have ended up with probably the exact same product that we have today, but we would have come at it with about 12 months of development effort sooner. M: What you are trying to say, work on a thing that reduces your risk to a number you understand because what you have here you have built a risk on top of a risk. Because of the risk of not meeting fuel burn, now you have built in another risk of Temperature, where you have said at least let us take the Temperature risk out of the equation. It was simpler than that. It was just a question of stepping back and believing what you can do first. An analogy would be let say you would have a budget gap, you have $100 million to spend and you have $110 million of work. If you have just launched the year on a $110 million pace come October your $100 million will be gone. A month before you run out of money is not the time to think what am I going to do.

What we should have said was to recognise a $10 million gap so in January start taking measures to close the gap, instead of progressing until its too late. It's a simple analogy to do with money, it is far harder to do on the technical side. Lets presume that we are not going to close the gap and approach it from that side but PWC always assumed that we would close the gap somehow but in reality we couldn't in the end. That is a lesson that we have effectively learned on our latest product the PW307. We have assumed that we where going to have a gap, On the PW307 we started from the other side and respected the gap. Time will tell if the gap gets closed or not.

Q8: From your experience can you give me an example of some tasks that you moved up to early in the program that that really paid off in the end?

A8: We have a few more than those that I have already mentioned. The conventional one's are simple and are normally done in this company. We do the birdshot, we do the blade off we do those and in fact we try top get into the Spin Pits as early as possible. However we also knew that on this program that we would have a gap, which was temperature. Prior to the first flight on any engine we as a company do a Pre Flight Reliability Test (PFRT). On the "A3" we arranged two

PFRT engines in parallel doing 50 hours PFRT's. One engine was going to do 50 hours of staircasing to clear all dynamics for a flight. On the other engine we decided to do all IMIT cycles to thrust but what we did was we decided that temperature was our #1 problem we made a 50 hour PFRT 300 cycles to a 120° higher than the Design Red line. a 120° higher than the Design Red line add 300 cycles to that value before 1st flight and to our surprise the engine had survived when we pulled it from the test cell. What is fascinating is the distress seen in the turbine in 1998 the same distress we're coping with 2002. We saw it early enough; we did as much as we could. You have to understand that it was a high technical challenge to the company, but at least we demonstrated it very early. Had we waited for the conventional testing, of running endurance to temperature to find this out we would probably have been another 12 months behind. It was fascinating that on the recovery plan we ended up with a completely new type of turbine design.

Q9: From your experience can you give me an example of some tasks that you did not do early in the program that in hindsight you wish you could have done earlier?

A9: I think the contract with our customer should have been vetted with our legal council as well as our engineers right when we started this program. We did not do that until it was too late. This was not a simple contract where you understand what your deliverables, which are when a customer's engine has to go out by this date. The contract was the first contract we have ever had at PWC, which had penalties for non-conformance and non-delivery. The contract is riddled with penalties that where decided in the legal sense. The engineers where attacking the program as if it was any other program and they where only somewhat aware of non-conformance and delivery penalties. In hind site what we should have done (and we have done now on our next program) is that the engineers, and not just the top level engineers, the execution engineers, the designers, development engineers and project engineers go over every line and highlight what needs to be done, where are we in trouble and where can we pre-empt. However because, on

the "A3", this was our 1st contract of this nature and it was our 1st experience with a new customer we basically did not do that well and we have been paying for it ever since.

Q9: Are there any tasks that you feel were done too early and would have worked better if they had been done later in the program?

A9: There is one that is not necessarily an answer to that question, but the "A3" had two customers it was the "A3"A and the "A3"C. The "A3"A was ahead of our customer every step of the way and we did a lot of work, and we did what was necessary e.g. the first two customer engines we did for our customer stood in a box for 12 months and then they where shipped back. In Engineering we knew that we where out pacing our customer we where much further ahead than they were and we should have pushed a little harder so that we did not spend those resources. However I am not sure even today what we could have done differently because our PWC philosophy is the "Customer is always right" and the customer was saying "Don't challenge our schedules" just give us the engines and so we did. That was a huge resource hit that we took, it was not just the money it was parked inventory for a year. It's two engines that we could have been using doing something else in our program. Another area that we do too early and it costs us too much is software, with our complicated Fadec we know we are going to have a number of builds in software and we build the software and we then validate the software so we can fly. Our validation process is very expensive. Safety is always our #1 priority, we have to find a way to not put as much effort up front because we must have validated as much as twice as much to get to the end product. M; What do you think validation costs? A: I know what validation costs: it is probably between $600,000 and $1,000,000 or each one build. Today our processes do not allow us to do it any other way. There are benefits to doing this but is there good value to do so much so thoroughly, so early? Probably a time will come when we find that when we don't do it, we get burned. Today in my own opinion is that in Development we do too much software validation too early.

Q10: How did the project work out, what worked and what did not work?

A10: In answer to the first question, How did the project work out, we are not in service yet, so the ultimate measure of that doesn't exist. I think the "A3" is a good engine and that it will be a money-maker. The program took longer than the 36 months that was budgeted for development. At the launch of the "A3" we had under estimated the challenge. We under estimated the size of the program, we under estimated the difficulties and we certainly under estimated the resources needed. However at certification we where on budget. That was a very good thing, it was a $220 million program and to bring such a program to certification at $220 million is not easy to do. One of the problems we had to answer was how to handle the two engine configurations the "A3"A & C. The "A3"A was the launch customer and the "A3"C past it, we found ourselves with a derivative ahead of the original although the type certificates appear sequentially A first and C second. The C is entering service ahead of the A. The "A3"C is entering service in 2 months, we have already produced 55 production engines. The "A3"A is yet to have a production engine. There are some logistics there where we had a nice plan to roll A to C and mid plan we have to roll C to A. I think our configuration control worked very well there, that was seamless and it could have been a disaster. In hindsight I thought it was a perfectly well executed program. The biggest roadblocks is the technical challenge quite frankly we over sold them.

Q11: What recommendations would you give to someone starting a new Program?

A11: The first recommendation is not just to read the contract, but to have a copy of the contract on every Project engineers desk. The Project engineers at the end of the day bring the program home. The Project engineer has to go through the contract and highlight his areas of responsibility. He must treat the contract like you would his bosses' objectives. This applies to any program we work on.

The second thing is the lessons learned, we all have a feeling that we are using and applying lessons learned, but every program makes a new set of mistakes, but when you peel back the layers they are not new. One of the things I have implicated in my objectives is that in every program the Engineering work will be written to the lessons learned. The "A3" is going to do it this year when it put it's first product into service and my recommendation is to anybody going forward is to find those lessons learned and make sure you understand them. If they are not documented, then go and find the people and interview them understand what their pains were. Don't just listen to them, understand how is it going to apply to your program.

8.0 Project Manager – Engine B1 Interview

1. **Describe the Basic Design, Development philosophy you laid out for the Program when the program started.**

- Design concept demonstrator before 1st first "B1" design/run.

– Short duration design/ development Program. Design Go to Certification in 36 months.

– Hand picked first class Project team. Appropriately staff Project Engineering with depth of knowledge, experience and willingness.

– Implemented "Integrated Product Teams".

– Separate budget categories to control expenditures for each major task.

– Conservative design with "what we know" works. Do not "Over Commit" on deliverables.

– Simple/low technology design approaches to maximise first time success and hopefully minimise cost.

– Basic Design had degrees of freedom built into it. A larger core than needed was designed in case there was a need for growth or temperature margin.

– Design with the whole operating envelope in mind. Design for altitude performance and associated parasitic losses.

– Design with producibility in mind. Design for assembleability. Attention to producibility during design and development part manufacture (Raw Material Clearances, internal machined parts and externally produced parts)

- Productionizing tooling and process using development hardware.

- Common development, production and field service tool numbering (i.e. PWC #'s)

- Brought in key partners to minimise financial risk. Partnership with MTU with Low Pressure Turbine.

- Design the engine with future derivatives in mind. Common core in readiness for increased thrust versions.

- Manage design configuration from GO and throughout the program.

- Ongoing Customer involvement.

- Attention to engine vibrations (test cell and installed) and aircraft Cabin Noise.

- Standard Work/Best Practices launched at PWC with "B1" program.

- Detailed "Product Design Requirements Specification" up front based on customer and PWC requirements.

– Cut bureaucracy where it makes sense. Minimise use of Engineering Source Approval.

- "High Risk" development tests up front.

- Flight test early in program.

- Modelling engine for Operability and validating during development test cell running and flight.

- Dedicated Performance and Operability IPT.

– Prepare for Production during the entire development program. Build some of the later experimental engines using production personnel. Build development customer engines and

certification Maintenance Demonstration and Block Test engines in Production.

- Quarterly Program Reviews with Senior Management.

- Spin pit testing initiated before first engine run.

- Work engines at PWC and Customer using Maintenance and Overhaul Manuals. (i.e. attention to Field Readiness, repair readiness,...).

- Tracking manhours used build Customer engines to set required basic build hours in Production Ass'y/Test.

- Maintain key characteristic "hardware" and "engine at test" measurement data base.

- Engine assembly tooling designed by customer support.

- Co-locating Project Engineers and Development Engineers.

- Weekly Design Job meetings to manage/schedule changes.

- Early involvement of the certifying authorities, the JAA with Transport Canada and PWC regarding engine Certification and Validation .

- Early Design and Validation of Shipping Container.

- Accumulate 4,000 - 5,000 development hours pre-entry into service.

- Dedicated Discrepancy Management process.

- Red Flag procedure to stop Production and incorporate late changes into first engine deliveries.

- Complete all certification testing to increased thrust levels and rating structure to demonstrate margin.

- Test and validate potential production and field service repairs (ie spin pit fan Fly Back limits)

2. **What key lessons learned did you use from previous Programs that caused you to adopt the above-mentioned philosophy?**

- Manage budget and expenditures ("A1").

- Production Readiness (PW100 and "A1").

- Detail plan required hardware quantities ("A1").

- Producibility ("A1").
- Design for Altitude performance ("A1").
- Early Spin Pit testing (PW100 and "A1").
- Attention to installed engine vibration and cabin noise (JT15D and "A1").
- Design for internal and external LRU removal ("A1").
- Detail measurement of impact of engineering changes..
- Closely manage hardware logistics ("A1").
- Attention to Factory Standard Cost ("A1").
- Involve Production in part Manufacture.
- Recording all hardware deviations using a computerised system(PW100 and "A1")
- Manage development engine configuration. .

3. Philosophy to action – what procedures did you attempt to use?

- Product Design Requirements Specification.
- Engineering Change Management Engineering Operating Procedure (EOP)
- Quality System (MRD's)
- Development and Flight Hardware Quality Standard (EOP 75)
- Production MRP to order development hardware.(Did not work).
- DTIS to monitor hardware/engine weight (Did not work).

4. What worked and what did you have to modify?

- Using production manpower during pre-certification engine build and test (worked).
- Experimental use of the MRD system had to be modified (Needed modification).
- Early configuration (BOM) management (Needed modification).
- Development Instructions etc did not exist and left Dev't Engineers exposed.

5. **Why were these modifications necessary.**

- Many procedures address "Post Certification" (Production) type activities.
- Several procedures and people responsibilities were not available in departments or clear with personnel.

6. **In hindsight, what do you now wish you would have done that you didn't do.**

- Project Engineers with Responsibilities and Authority.
- Visibility and inclusion of the other divisions of Pratt and Whitney lessons learned.
- Detailed Risk Assessments by modules and component.
- Detailed Sourcing Strategy for "short term" Development and "longer term" Production.
- Much closer attention to development hardware costs and readiness for Production Factory Standard Cost (FSC).
- Use of sterio-lithography casting techniques before tooling commitments- see what works and then spend.
- Weight management process during module design and the development program.
- Clear Project Engineer and Development Engineer responsibilities.
- Detailed attention to tooling costs and expenditures.
- Clear Control System "Statement of Work" with Hamilton Standard and task tracking.
- Closer scrutiny of partner producibility info and sourcing directions.
- Detailed review of installed noise data on customer engines which may have surfaced hooting tendencies.
- Configuration control and management of systems such as air, oil, fuel, noise, ...
- Use field service diagnostic tools in development (ie BOV and EEC laptop equipment).
- Ongoing development measures of key "system parameters" and re-check with system analytical model.

- Relentless root cause analysis on HPC2 compressor airfoil stator rub found in dev't.
- Responsible Design/Analytical person from respective Module Centres attached to their commodities thoughout the Development Program.
- Strengthened ownership from OPM concerning tooling, development hardware deliveries, producer readiness and FSC.
- Dedicated Procurement attention to negotiating Production part costs.
- Development sources to progress quick hardware turnaround with Engineering Changes.
-Detailed Level III plans from producers to enhance scheduled release of Product Information and eventual hardware progress monitoring.
- Analytical predictions for development test result outcome before actual test.
- Engine FMEA consideration of OEM installation (ie fire wire, ECS/Bleed system, ...)
- Customer Solutions use actual Development Program results/data to support MSG3 analysis and "On - Condition" field maintenance approach.
- Dedicated PROGRAM ROOM to post progress and data.

7. In hindsight which actions, that you did do, really paid off in the end.

- Common core suited "B1", PW 545 and PW535 – planned family from word go.
- Validation of all Component Maintenance Manuals using development engines and hardware.
- Run all certification tests to increased rating and thrust levels.
- Attention to vibration and noise.
- Production readiness.
– Used robust production review system in development.

8. From your experience can you give me an example of some tasks that you moved up early in the program that really paid off in the end?

- High risk tests such as bird ingestion, fan blade off, Inclement Weather, flight testing, etc.

- West Virginia (Overhaul) exposure to engine teardown.
- Validation of engine ass'y and test tooling on IMIT and block endurance engines.
- Off sight engine testing at MTU and Nordam.
- DTIS tracking by part number and serial number along with running time and time at temperature.

9. **From your experience can you give me an example of some tasks that you did not do early in the program that in hindsight you wish you could have done earlier?**

- Module Centre manhour commitments to tasks.
- Development hardware actual cost tracking.
- Factory Standard Cost management.
- Sourcing Strategy management.
- Use of International Sourcing.
- Suitably funded strategic "Dual Sourcing" activities.
- Understanding accessory and externals "in-situ" vibration levels (ie T_{14} probe)
- Noise testing.
- Detailed documentation of results from engine strip after key tests. Customer Engine, IMIT and Endurance engine Quality teardown.
- Separate categories to measure various development task costs for future program reference and budgeting.
- Engine testing with Cessna nacelle system and thrust reverser.
- Negotiate Long Term Agreement's with key suppliers earlier.
- Production part costs based on MFA and existing comparable parts.

10. Are there any tasks that you feel were done too early and would have worked better if they had been done later in the program?

- No, the earlier the better.

11. **How did the project work out, what worked and what did not work?**

- The program worked very well with the right assortment of Project Management talent/experience.
- Program expenditures managed within expectations/business case.
- Reasonably smooth transition into Production and Field Service.
- Factory Standard Cost above expectations.
- Engine weight exceeded specification targets.

12. **What recommendations would you give to someone starting a new Program?**

- The right Program Engineering Team will lead to success.
- Solicit lessons learned from as many sources as possible (Engineering, Operations, Partnerships, OEM's, ...)
- Complete a detailed capacity planning review early in program (ie test cell , spin pit, manufacturing, procurement sources, ...)
- Detail task cost estimates based on previous program experiences/data.
- Detailed PDR/CDR's with dedicated attention to appropriately close action items.
- Design reviews for all Facility items.
- Project Engineering representative manage Research Funded tasks applicable to program needs to pull on deliverables and quickly incorporate outcomes.
- Work closely and effectively with Manufacturing and Purchasing (understand their issues and

needs).

- In depth reference of previous program expenditures/lessons learned.
- Program Manager total responsibility for budget contingencies.
- Separate EO's for major tasks to collect detail costs, confirm compliance with estimates and obtain MFA for future programs.

9.0 Project Director – PW100Engine – Interview

Q: Describe the Basic Design, Development philosophy you laid out for the Program when the program started.

A: The first group of PW100 engines was certified in 1983. This was followed a few years later by a whole series of derivatives higher power engines. The original intended market for the PW100 was the big turbo props intended to be successors to the big King Airs in other words corporate aircraft. In addition to that 50% of the market was assumed to be the new emerging Regional Market. In 1979 the Regional market was seen as a potential for growth, deregulation was being talked about but had not yet really taken place. We could see it all coming and could see the opportunity. To our disappointment our traditional major OEM customers in the US turned out to be uninterested in the Regionals, nor did they actively pursue the Corporate market in that size, and so it fell to Embraer, De Havilland and a year later Aerospatiale joined in with the ATR 42 with the ATR consortium. The Embraer Brazilia was pretty close in its original concept to what was thought to be the big corporate turboprop, in order words 20000 lbs gross weight 300+ knot, a corporate shuttle type airplane, however the market took off in the direction of the regional. The regional market at the time was thought to have a centre of gravity in the mid 30 seat range and therefore the Regional aircraft companies wanted an engine somewhat bigger and more

powerful than what the big corporate airplane wanted. This is one of the early decisions we had to make and one of the early areas of controversy. The ideal engine size for the corporate air plane would have been about 1700 horsepower thermal, 1500 - 1400 on the shaft in other words an engine the size of the CT7 as it was then. In fact that was the size that we made our demonstrator which was called the TDE-1. This 3 shaft demonstrator engine incorporated all the novel features and was run extensively as a risk reduction and learning tool prior to committing the detail design of the real engine. We had never before done an engine requiring cooled turbine blades, the two spool all centrifugal compressor was novel and it was the first time we had done that long a shaft at high speed. The demonstrator was kicked off in 1976 well before we had to make program commitments. One of our early worries was the handling quality of the two spool arrangement considering the high inertia of the low spool and its loading. The demonstrator had provision for variable IGVs and a bleed valve. We were pleased to confirm that neither was required which greatly simplified the engine. We also solved the manufacturing concerns on the long power turbine shaft and demonstrated that we could keep it subcritical. Did you ever go to the trouble to finding out why you had originally figured out that they would need it and why you where pleasantly surprised or did you just take the fact that it worked and went on. We didn't have the analytical tools that we have today and we didn't pretend that we knew everything. The work that had been done up to that point was all single stage research centrifugal and those single stage machines didn't have to deal with the inlet conditions coming from another compressor in front, particularly a centrifugal with a pipe diffuser that was introducing quite a significant inlet distortion and so our concern was that that distortion would compromise surge margin and that the speed mis-match between the two stages on a decel would be a problem. We learned how to produce a long skinny shaft, balance it and keep it subcritical. The other big issue was cooled blades. We where neophytes on cooled blades as it was the first time we had ever done it. We refined it for the real engine but the basic original design worked quite well. What was it based on? obviously you must have based it on something, was it the literature was it going through the operation. The baseline was a transfer of technology from Hartford and then we did our own analysis and testing of models prior to designing the turbine. We did flow visualization and pressure loss measurements using large size models, optimised and refined the cooling schemes. Our turbines are

very much smaller than those in the large Hartford engines, so we had to develop our own cooled blade technology. It worked so well, we had few difficulties with the blades in the development program.

Q2: What key lessons learned did you use from previous Programs that caused you to adopt the above mentioned philosophy?

A2: All of us Project Engineers involved in the PW100 had previously spent a lot of time on the PT6 and JT15D so there was quite a bit of basic development experience across the team. In addition the designing team had been through the rigours on the PT6 and JT15D and so we had a fairly solid analytical and practical grounding in both turboprops and turbofans. One of the keys to success is having an experienced team. It sounds like you had a very experienced team, you started off with an experienced team. We did then what we have attempted to do on programs since, which was to skim the cream of all the most experienced people in the organisation to staff up the core of this new engine. We took many of the most experienced people off the PT6/15D and put them on the PW100 and then back filled those more mature programs with the less experienced people who learned and carried on. We where fortunate in those days that in any given timeframe we only had one big program at one time, so we could focus all our energies on that one big program. Other teams worked on the derivatives which where on the mature engines and far less demanding or at least narrower in scope. You had resources up front, the right amount of resources and the right type of people. You can always complain that you want more, you never have enough to do things at the pace you would like to do, but certainly we had all the resources that where necessary to do the job. As we went into the engine development program this was rather a massive undertaking the engine was bigger and more complex than anything we had ever attempted previously and we also had some very ambitious goals in terms of performance and so forth. We where competing against an already established engine which had a fairly high level of maturity through the US Military; the CT7 a derivative of the T700 turboshaft engines. They gave us quite a run in those early days as our engine was bigger, heavier and thirstier. This created something of an uphill battle when we where trying to compete against the CT7 at Embraer on the Brazilia. At that time the Brazilia was targeted to be a

20,000 LB gross weight airplane and here we where coming in with an engine which was significantly heavier and bigger. Granted it had a lot more growth potential but it was growth potential that neither Embraer nor we believed that the airplane needed. We where pleasantly surprised when they selected us after a rather in depth and vigorous competition. I suspect they selected us mainly because of our well-established reputation and our relationship with Embraer from the days of the PT6 and the various airplanes that they had done previously. They recognised the value of the growth potential and our relationship. They were willing to tolerate a somewhat heavier more thirsty engine and later on as the airplane needed more power as the airplane itself grew, we where able to step up to that power with essentially zero risk to them, so it was a very happy marriage. In the case of the Dash 8 and ATR airplanes the engine was more aligned with the airplane size and weight. We designed the engine so that it could grow easily and targeted its initial size for the mid 30 seat size airplane, which was in fact the original design point of the Dash 8 100 and the original ATR 42. The engine at 2100 thermal was sort of bang on what those airplanes needed. The engine was designed very robustly with the growth path designed in from the outset and the growth plan right from the time we laid the engine out was that we would preserve the HP rotor and the structure and casings and everything and we would grow the LP rotor. It being a free independent rotor we would simply bump the flow and pressure ratio of the LP rotor and introduce cooling on the LP vane which on the base version was uncooled. That gave us an easy growth path to add another 20% power at relatively low risk. Did someone lay out that plan right from the word Go? Yes we did that jointly with Marketing and Engineering, one of those team efforts where there really was no real distinction between the Engineering players and the Marketing players other than who they reported to within the organization. The dynamics where very much as equals and was very positive in terms of pulling the best ideas from everyone and since everyone was very familiar with the strategy and the arguments behind it and all the rest when it came to selling it to our own Management or Customers it was a very consistent pitch, where we were all in unison. I think that was one of the main reasons for success throughout the PW100 is the tremendous team we had which initially was Engineering & Marketing but later on pulled in Customer Support and after a few early faltering episodes with

Customer Support and a bit of a change amongst some of their management, we then had also a very positive co-operative joint effort among the three key organisations facing the customers.

Q3: Philosophy to action – what procedures did you attempt to use?

A3: One of the key tenants was the strong belief of those that where running the program is that you have to believe what the engine tells you, whether you like it or not the engine never lies. You must test extensively and though rig tests are necessary, you don't take it as a firm result until you see the result confirmed by the engine. The other one was that there are tough decisions to be made where the consequences can be major. You run up against major problems where a program is threatened with running over budget, running late, you have technical difficulties to solve which cause further delays, there is always the pressure to cut back and meet the budget sometimes at the expense of achieving the goal. There was a point just before the first run of the engine when we had to resist management pressure to cut back when there was clearly no hope of meeting a short term interim budget goal in order to save the program.

Q4: What worked and what did you have to modify?

A4: All through the program there were all kinds of issues, one particular one that comes to mind is we had our sister division Hamilton Standard as the controls supplier and we had tremendous difficulties in getting the Hydro Mechanical design team to communicate with the electronic design team of the control system. This was an electronic control working through a mechanical device as was the state of art in these early days of electronic control. They weren't the FADEC of today. They where trimmers on top of a mechanical and it was rather a delicate job to keep the two from tripping over each other, the mechanical portion had to be fully capable of running the engine in the absence of the electronic and the electronic had to provide the features that the customers wanted which where akin to FADEC features. Accomplishing this required that the mechanical function sort of follow along behind electronic function, rather a major challenge and a lot bigger challenge than we had anticipated when we kicked off. The almost total lack of communication between the key players within Hamilton caused us a tremendous

amount of grief to the point where in the end we had to escalate it to the Presidents level and there were some rather major waves before Hamilton forced their people to communicate with each other. Eventually it all worked out, but it only worked out after we had effective communication among the players. Prior to that the communications between these Hamilton organisations that where actually doing the design and development of the control was via our guys a very indirect communication path that often lost things in the transmission.

Q5: Why where these modifications necessary.

Q6: In hindsight what do you now wish you would have done that you didn't do.

A6: One of the things I would have done, was to recognize the importance of direct and effective communication. Had we recognised this communication issue earlier and taken action much earlier we could have saved a lot of grief and expense. Later on in the program there was another lesson where when we had gone to the second growth derivative we had pushed that original hot end which was designed for the original PW120/115 really too far and we could see the warning signs in the development and endurance tests. We rationalised to ourselves that that it was acceptable on the basis that the conditions we where running were really extreme, we where running the engine much hotter than the normal mission required we where running it much longer. We argued that this was in excess of what the operators in the field really could do and beyond what they needed and therefore the shabby condition of the hot end following those tests was acceptable. There was no question about it in terms of safety or integrity. Well that engine went into service and turned out to fall short of expectations. Some of this was due to the fact that by that time we had built up the expectations with an earlier airplane and earlier engines of doubling and tripling our competitors hot end life where the typical hot end life of our PW115/120s were near 6000 hours. The PW125/6 model when it hit the street was delivering between 2000 - 2800 hours on the wing before it needed a hot section repair and while this exceeded our guarantees and satisfied the original business case model it fell very short of the expectations we had

created with our earlier engines and was therefore unacceptable. We have to live up to the expectations that we create.

Q7: In hindsight which actions that you did do really paid off in the end.

A7: The demonstrator was a big one, the rigorous testing was another one, a third one that made a big difference which at the time we took a lot of flak for was the multitude of engineering changes in the early days of Production. When production uncovered a lot of things that weren't a 100% right on the producibility side which also indicated weaknesses in terms of how the engine would be standing up in service we took rather an aggressive action to fix those things rapidly and we took a lot of flak from the Front Office for the number of Red Flags we put up. Our policy at that point was fix it now because it ain't going to get better and this high production rate we where running if we had allowed it to continue it would have gotten away from us so that was one also that paid off big time on the program being so successful. In hindsight we should have paid more attention to produceability earlier during development. Another one that paid off very handsomely later on more in the economic side was when we where in this period of improving the hot end on the PW125/126 taking a lot of flak from operators we put out the improvements and campaigned them, but we campaigned them on a pay for use basis, so we discounted the replacement parts, in other words providing pro rata credit to the customer but the result was that we actually made money on those campaigns so we got a windfall. The way that the internal accounting went we came out not looking that favourable because warranty budget got charged the full value of the parts and the spare parts sales organisation had this huge windfall, but at a company level we came out ahead big time. Another one where it was a big economic benefit was when we where competing at Fokker and BAE, I discovered that GE was only offering a CT64 which was not a very competitive engine and Rolls Royce where only offering an improved Dart. I recognised then that we had a huge advantage with our PW124 series engines in that we where much more efficient and much lighter. Because of our advantages we could afford to bump up the price, so I made an arbitrary decision that fortunately Marketing went along with to increase the dollars per horsepower that we charge for the engine. Normally engine derivatives of a higher power sell at lower dollars per horsepower. In this case

we actually went to higher dollars per horsepower. I also padded the engine weight by about 60 lbs, so as a result on those engines we never paid a cent of weight reduction and we got to gross margins that where up in the mid 50% range and so of course that made the program extremely attractive financially. A key lesson – know your competitive position.

Q8: From your experience can you give me an example of some tasks that you moved up to early in the program that that really paid off in the end?

A8: We have a policy of trying to do the high risk tests or the tests where a turnback would be very expensive early in the program. Things like birdshot we did right up front also icing, ice ingestion, shaft shear and all that stuff right up front and overspeed tests, all the tests that would have major re design implications had we failed. In fact one of them did fail and that was a containment test of the LP turbine. When we originally performed the LP containment test we broke the engines back, failed rather spectacularly when the whole back of the engine came apart and that led to a rather massive re-design of the turbine support case. The result of doing it early in the program resulted in the cost to fix being modest.

Q9: From your experience can you give me an example of some tasks that you did not do early in the program that in hindsight you wish you could have done earlier?

A9: Something that comes to mind right off is Controls, but that was more of a management issue than a test.

Q10: Are there any tasks that you feel were done too early and would have worked better if they had been done later in the program?

A10: No

Q11: How did the project work out, what worked and what did not work?

A11: As we all know now the PW100 program was a great technical and financial success.

Q12: What recommendations would you give to someone starting a new Program?

A12: At the start of a program the key thing is to honestly assess where we are at in terms of technology, the risk assessment is key. Up front, where are we sticking our necks out? What are the areas of novelty? What is our technical readiness level? Do we really understand what the requirements are? In the case of the PW100 we assessed technical risk. The mutli shaft arrangement, the long PT shaft the twin spool centrifugal compressor arrangement the need for variable geometry and the electronic controls system where all seen up front as significant risk items and therefore we tailored the demo up front to address as much as we could. We addressed essentially all of that except for the control where the cost was prohibitive. Another one is having the resources when you launch the program rather than pouring them in after you are in trouble. In this case the PW100 did have the resources pretty much right from the beginning though we did have a build up period. In those days the programs where longer fuse, so that was built into the plan for the program, it went from 1979 - 1983 and was basically a 4½ year program which in these days we try and do it in 3. It doesn't work in 3 unless your whole team is there from day 1, fully primed and the demo behind you. Obviously it was before the days of IPT's, before standard work. Yes and no. Before IPT's we had teams, the project engineers each had a team it was not called an IPT but it was an IPT in function. They pulled in the appropriate players, the need for leadership on the team was no different than it is now. Those teams that had good leaders excelled, those that didn't faltered. On Standard Work we had DRM's and other forms of guidance material it was not quite as regimented, and perhaps not being as regimented allowed for a little more freethinking and fresher ideas. One of the reasons that I championed to get rid of the Standard Work term and in fact making it a Best Practices term is that just the whole connotation of Standard Work is static, if you are static you are dead.