Materials Substitution in Aircraft Gas Turbine Engine Applications

by

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Abstract

Technological advances in modern aircraft have led to the development of a wide variety of new materials which have the potential to be used in many aerospace applications. This is particularly true for high temperature engine materials. However, incorporation of these materials into engine components has been limited. This is perhaps due to the way in which aerospace engineers select materials for aircraft applications. No industrywide, consistent, unbiased method is used to compare materials for use in a given application.

This study establishes a methodology for comparing material alternatives. Multiattriute utility analysis is used as a way to compare performance attributes deemed relevant for a given component. Attribute levels for the material alternatives are then used to obtain utility values. These attribute levels are adjusted to represent decision maker's perceptions using subjective probability assessment techniques. Furthermore, production costs are obtained through the use of technical cost models which describe the manufacturing process required to produce the component. Combined, these techniques provide a systematic method for comparing materials.

The methodology is employed in a case study involving exhaust ducts for medium sized, non-man rated engines. Three material alternatives are considered based on their potential for use in this application. These are investment cast superalloys and SiC/SiC composites prepared by two different processes, one using a slurry infiltration technique and the other employing a chemical vapor infiltration technique. The study shows a substantial competitive advantage for superalloys. In addition, it indicates areas suppliers of each of the three materials to focus their efforts in order to improve their competitive position.

Thesis Supervisor: Dr. Joel P. Clark
Title: POSCO Professor of Materials Engineering

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1. INTRODUCTION

Technological advances in aircraft design and desired performance characteristics have continually been limited by the unavailability of materials with suitable properties. Government agencies, in conjunction with private aircraft manufacturers, are in pursuit of new materials technologies which will result in many advances in aircraft performance. The U.S. government's Integrated High Performance Turbine Engine Technology program (IHPTET) seeks to "double the capability of today's most advanced turbine engine by the end of the century."[1] Programs such as this and the National Aerospace Plane (NASP) continue to drive the development of new materials. The result of this push has been a proliferation of new materials and technologies with the potential for use in a variety of aircraft types for both airframe and powerplant applications.

1.1. Aerospace Materials

The aerospace industry has historically been a major driving force behind the development of new structural materials. This is largely due to the very stringent performance requirements in parts throughout an aircraft. Currently, state of the art materials and cutting edge technologies are employed in a variety of aerospace applications.

1.1.1. Airframe Applications

Airframe applications have experienced a significant push towards the use of new lightweight materials, most notably polymer matrix composites. The airframe is considered to consist of the primary and secondary structural components of the aircraft. Components necessary for flight are primary while general unstressed, not flight critical components are considered secondary. In even the most advanced military aircraft, the airframe makes up over 25 percent of its weight.[2] As a result, reducing the weight of the airframe can have a major impact on its performance. Incorporation of new light weight materials into the airframe is essential to achieving some of the more ambitious goals of many government aerospace initiatives. However, this reduction in weight cannot be achieved at the expense of the necessary mechanical properties.

Advanced military aircraft, which often exhibit the cutting edge of aerospace 222technology, have seen greater use of organic matrix composites and are expected to use even more metal matrix composites, reinforced powders and new metal alloys in the next two decades. (See Figure 1) [3].

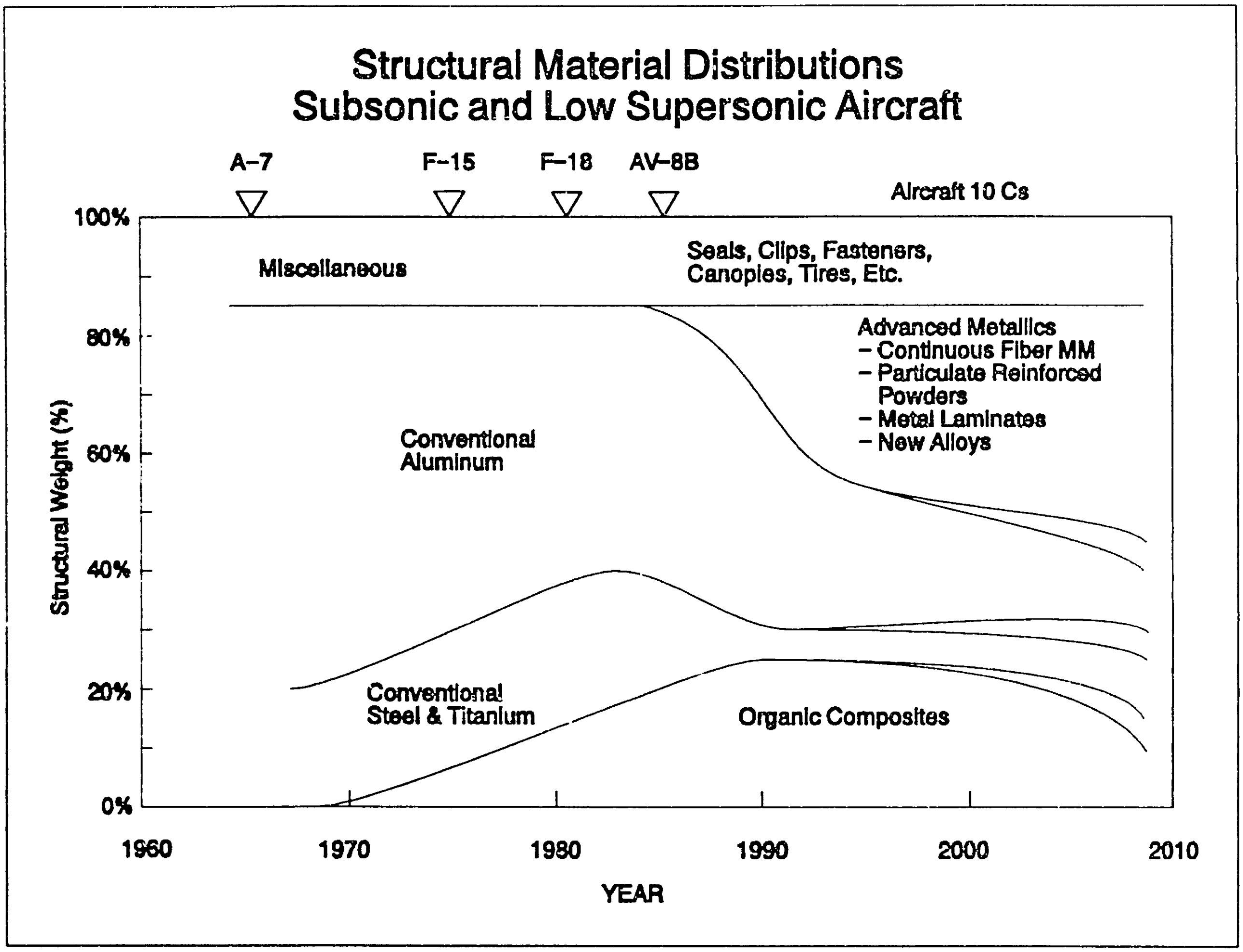
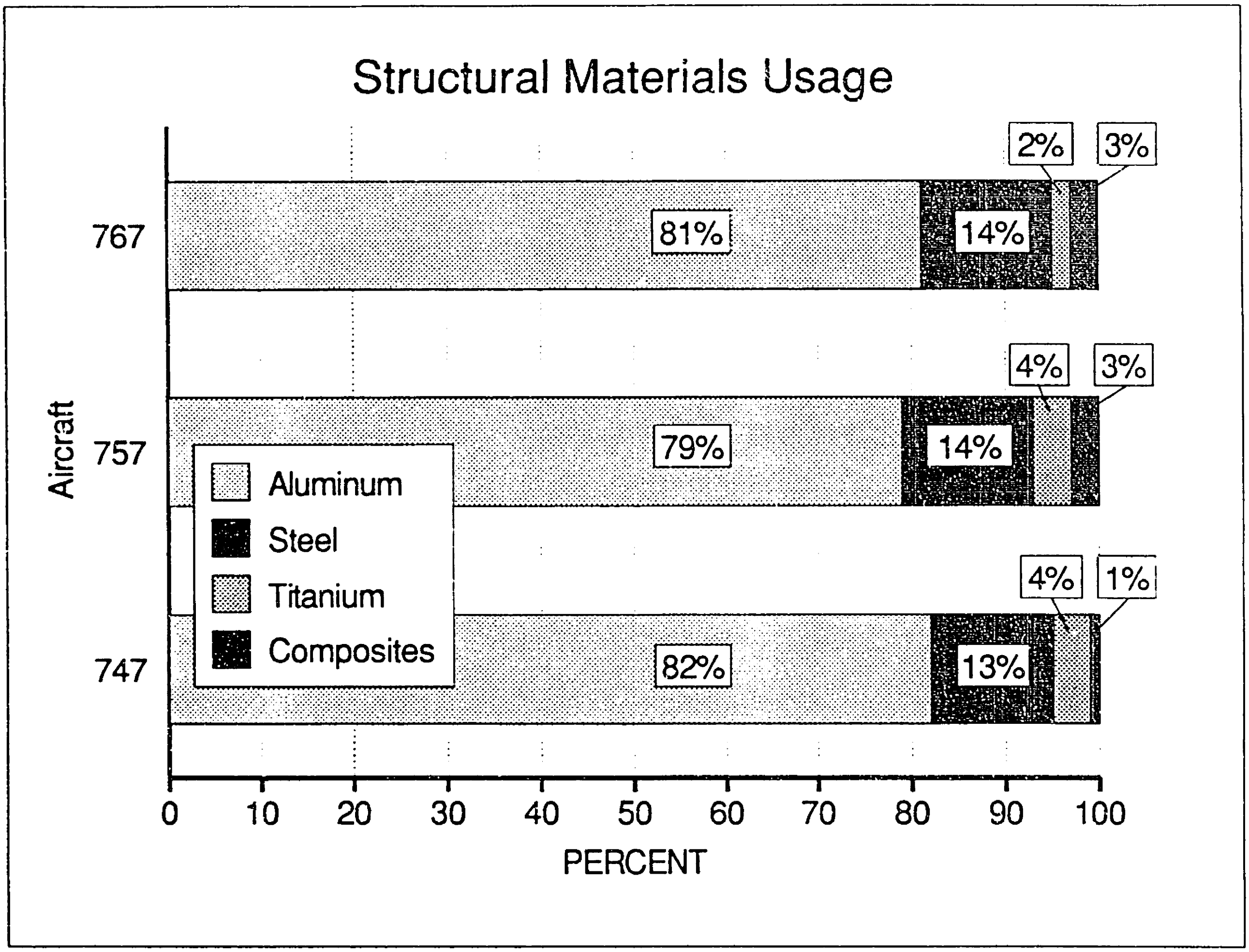


Figure 1: Structural Material Distribution: Aerospace Applications

Commercial aircraft have also experienced this trend. Boeing's 757 and 767 have used composites to a greater extent than its earlier aircraft (747) and, overall, composites are expected to make up an even greater percent of aircraft structural materials in the 1990's. (See Figures 2 & 3) [4].



2Figure 2: Aerospace Materials Usage: 747, 757, 767
2

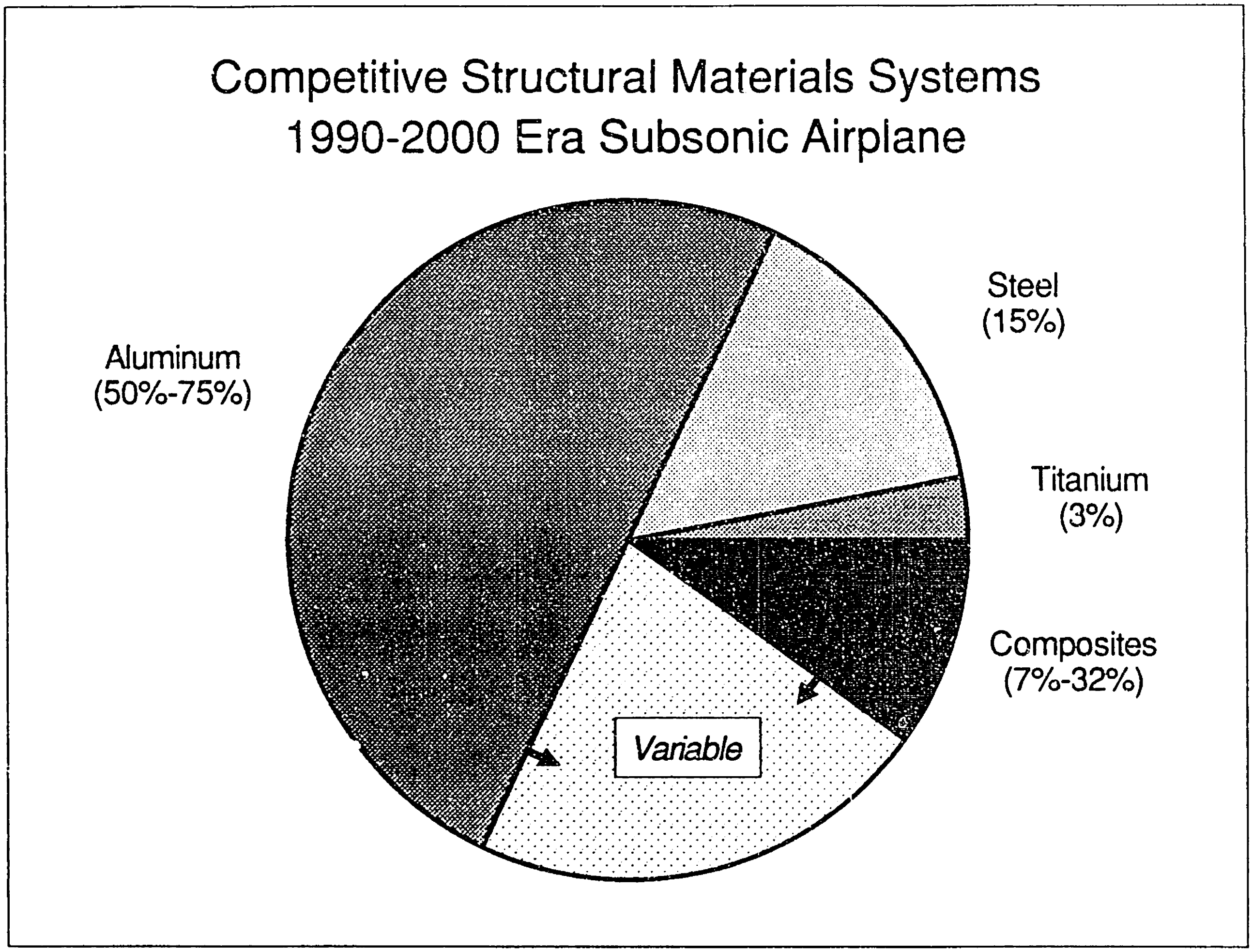


Figure 3: Projected Structural Material Usage: Aerospace Applications

While new materials are clearly forecast to be used in future airframe designs, aluminum continues to be the primary airframe material. Even the U.S. Navy's newest fighter, the F-18, is primarily aluminum. Alloy development has enabled the use of aluminum forgings and extrusions to be used in aircraft skins, rib spars, bulkheads and honeycomb cores. [2] Furthermore, new processing techniques such as superplastic forming have resulted in aluminum and titanium alloys which are lighter and more cost effective. [5] However, other materials are making inroads into airframes.

To date, polymer matrix composites have made the most progress towards widespread use in airframes. Typically, the fiber reinforcement is either graphite or polyacrilonitrile, but others such as Kevlar® have seen some use. The matrix material is usually an epoxy resin, but can sometimes be a polyester or polyimide.

Organic matrix composites have not only been widely used in experimental and military aircraft, but are increasingly being used in commercial applications. The latest generation of Boeing aircraft, the 757 and 767, have utilized more composite materials than their predecessors. However, it is in the specialty aircraft where polymer matrix composites have seen the most use. The Beech Starship Model 2000 "all composite" airframe has made use of a variety of composite materials and innovative designs. The use of composites resulted in a lightweight plane, whose structural components weighed only 1800 kilograms. [6] The Navy's F18-A fighter plane uses organic matrix composites in its wing skins, horizontal tails, speed brakes and dorsal covers. Furthermore, the AV-8B fighter uses another breed of organic composites employing bismaleimide (BMI). [7]

In addition to typical airframe application, many other aircraft parts are likely candidates for materials substitution. Fasteners, sealants, adhesives, landing gear and electronic components are all subject to the same desire for weight reduction as the remainder of the aircraft.

1.1.2. Engine Applications

Aircraft engines pose a different set of material substitution problems. As is the case of airframe applications, stringent materials requirements exist, but often engine materials must also maintain their properties at elevated temperatures. While this has limited the use of polymer matrix composites in most engine applications, other material alternatives have been developed. Polymer matrix composites are predicted to find use in low temperature engine applications such as frames, casings, ductings and stators. These applications typically experience temperatures up to 300°C, but future polymer matrix composite development will likely increase their operating temperatures to as high as 600°C. [1] Improvements in traditional alloys and metal matrix composites have resulted in the potential use of these materials in many applications. Titanium metal matrix composites show a great deal of promise as replacements for nickel based superalloys in compressor blades.

In higher temperature applications, ceramic and metal matrix composites, as well as new advanced alloys processed in innovative ways, are challenging conventional materials. In the past, nickel (and occasionally cobalt) based superalloys have dominated many high temperature engine applications. As the demand for high temperature materials grew, new processing techniques were devised which effectively raised the maximum operating temperature for blades made from superalloys with a columnar grained microstructure. This technology was then revised to produce single crystal components. This resulted in improved materials properties including increased creep strength, better thermal fatigue resistance and corrosion resistance, and the ability to use these materials at still higher temperatures. Pratt and Whitney's PWA 1480 nickel based superalloy can be used up to 1900°F and researchers there expect to be able to push this temperature limit up to 2000°F. [8] However, nickel based superalloys are reaching their theoretical limit. Melting temperatures for these alloys are around 2400°F. New materials must be developed if engine operating temperatures are to continue to rise as is demanded by several engine development programs. Likely candidates for this are monolithic ceramics, ceramic matrix composites and, possibly, metal or intermetallic matrix composites.

Intermetallic matrix composites can be used at high temperatures, but severe problems remain. The development of new intermetallics and fibers which are compatible is needed before these materials will see much use. Currently, the reinforcement material is either silicon carbide or alumina fibers. Matrix materials vary from titanium and iron aluminides for use up to approximately 1000°C, to nickel and niobium alloy aluminides for higher temperature applications. Problems with chemical compatibility and thermal expansion mismatch exist among many fiber/matrix combinations. Furthermore, processing and fabrication of intermetallic matrix composites remains very difficult and costly. [9]

Looking even further ahead, monolithic ceramics have great potential in aerospace applications due to their relatively low density, high strength, high melting temperature and chemical inertness. Widespread application of ceramics remains in doubt due to their poor ductility, low fracture toughness and low resistance to thermal shock. [2] However, monolithic ceramics may find use in some engine applications such as combustor liners, where the mechanical requirements are not overly stringent.

More promising than monolithic ceramics are ceramic matrix composites. The addition of continuous fiber reinforcement results in improvements in many of the areas which monolithic ceramics are lacking, such as fracture toughness and impact resistance. Ceramic matrix composites have seen some use in modern engine design. A French Mirage 2000 was flown with ceramic matrix composite inner and outer flaps at the 1989 Paris Air Show. A silicon carbide matrix reinforced with continuous carbon fibers was used for the outer nozzle flap, while a silicon carbide matrix reinforced with continuous silicon carbide fibers was used for the inner flaps. [10] While ceramic matrix composites have still seen only limited use in aircraft engines, the demand is predicted to grow due the continued demand for higher temperature, lightweight materials.

The demand for new improved materials to meet more stringent requirements of advanced aircraft is clearly resulting in a proliferation of new materials choices throughout an aircraft. Low temperature applications, such as airframe components, are seeing the use of more polymer matrix composites and some lightweight alloys. Higher temperature applications offer opportunities for the use of metal matrix composites, new superalloys, titanium aluminides and titanium aluminide intermetallics, as well as carbon-carbon and ceramic matrix composites.

2. PROBLEM STATEMENT

The demands of many specialized aircraft have led to the development of a wide variety of new materials and technologies which have the potential to be used in many other aerospace applications. This is true of both airframe and engine applications. While many new materials suitable for use in engine components have been developed, few have seen much use. Polymer composites show promise in low temperature compressor components, while metal and ceramic matrix composites, carbon-carbon composites, monolithic ceramics and new high temperature alloys are well suited to the higher temperature demands of the combustor, turbine and exhaust sections of the engine. Unfortunately, the progress of many of these materials into new applications has been very slow. While polymer composites continue to be used in increasingly large quantities in airframe applications, higher temperature materials continue to be limited to only specialty aircraft and applications.

This raises two important questions. Are the new materials optimal for use in any applications other than the ones for which they were originally designed? And if so, is the materials selection process failing to recognize these optimal choices? The answer to both these questions lies in the use of a systematic approach to materials selection. Unfortunately it appears that no such approach is being taken by aircraft engine designers. Instead, a variety of methods have been employed when choosing a material for an aerospace application. Perhaps the most common is to simply use the current "tried and true" material unless technological advances in other portions of the aircraft necessitate the use of a new material. This type of thinking is due in part to issues of reliability and Federal Aviation Administration (FAA) certification requirements, but also results from a lack of confidence or information on the part of the engine designer. He may not be aware of or concerned with alternative materials, or simply may not be willing to accept the risks associated with something which has yet to be proven.

Another common approach has been to determine the engineering performance criteria required of the part and then to simply choose the material which can meet these minimum standards at the lowest cost. While this can be a reasonable decision making procedure, it often dismisses choices with vastly improved properties at only a marginally higher cost. More elaborate schemes for addressing the materials selection problem also exist. Teams of engineers often work together to identify various design requirements. Lists of candidate materials are then assembled and the one that most closely fits the design specifications is used. [11] This method suffers from the inability to distinguish between materials alternatives which meet the minimum performance requirements.

Materials selection decisions are also sometimes made based on a variety of other issues such as material availability, supplier reliability and ease of fabrication. Design engineers will often choose a material simply because they have confidence that the supplier will be able to deliver the component in a timely and reliable fashion.

The methods being employed in the materials selection process are varied. While the aerospace industry has seen a large growth in the amount and types of materials it uses, there is no indication that the materials employed in many applications are optimal. This study will attempt to provide a more consistent means of comparison of materials for aerospace applications. The approach will be two fold. First it will consist of a materials blind study which focuses on an engine designers preferences for pertinent performance characteristics. Second, it will evaluate the designer's views of the likelihood of new materials achieving their predicted performance levels in the application of interest. This is particularly important in the aerospace industry where reliability and certification are often a major concern.

Because this study intends to identify and compare relevant performance requirements of engine components, it is necessary to investigate a specific engine component. While the conclusions from this study will only reflect the competitive position of materials in the specific application, the true intention is to establish and demonstrate the effectiveness of the methodology employed in evaluating the materials alternatives. Furthermore, it will also assist in making some general statements about the materials selection process in the aircraft engine industry as well as identify some of the important design issues which affect materials selection.

Several factors influenced the selection of a case study. First and foremost was the existence of materials alternatives for the application. While it has already been demonstrated that a large number of materials alternatives exist for many aerospace applications, it is still important to identify a specific application and its materials possibilities. Often materials which appear well suited for a given application due to superior properties in one area of interest, fail to meet additional performance requirements. Such is often the case of monolithic ceramic materials which offer excellent thermal properties, but are very limited in many mechanical properties. It is therefore important to investigate a specific application which will not have too stringent a set of requirements so as to effectively eliminate all the materials alternatives.

The existence of materials alternatives was not the only consideration when selecting a case study. To make the study more interesting and meaningful, it was important to choose an engine component for which there was serious consideration by the aerospace industry of using the alternative materials. This requirement led to additional considerations when selecting an engine component to investigate. One such issue was the availability of materials suppliers. Engine designers are highly unlikely to use new materials in engine components unless a reliable supply is available.

Other considerations involved the risk of the project and the FAA certification requirements. Certain applications are inherently more risky than others due the structural requirements or the type of engine. FAA certification requirements also vary and thus approval is more easily achieved for the use of a new material in certain applications.

Before selecting an actual engine component, it was necessary to select a specific engine or engine type. Due to the considerations already discussed, it was decided that the study would focus on a medium sized, non-man rated engine. A non-man rated engine was chosen to minimize the effects of the costs of certification. Requirements for approval of non-man rated aircraft, such as missiles, are much less stringent and accordingly much less costly. By selecting an application of this type, a clearer picture of materials trade-offs will be determined. Furthermore, engine designers are generally willing to take more risks when human passengers are not involved. Since the use of new materials necessarily involves risk regardless of the material chosen, it was thought that by minimizing the effect of the risk, the study would again yield results which more closely represent the trade-offs between materials and not the riskiness associated with the use of a new material. It should be noted that while these efforts have been taken to reduce the effects of these external factors, risk and certification are still important issues to engine designers when considering the use of a new alternative material.

In addition to the selection of an engine type, it was necessary to select a specific engine component for this study. Modern aircraft gas turbine engines consist of four sections, each with distinct thermal and mechanical requirements. These regions are the compressor, the combustor, the turbine and the exhaust. The compressor takes air from the outside, increases its pressure, and feeds it into the combustor. In the combustor, fuel is mixed with air and burned. The combustor expands and accelerates the gas which is then forced into the turbine section. The turbine extracts energy from the gases in order to power the compressor and electrical systems of the aircraft. In the process, the gases are slowed and the remaining high speed gas is directed through the exhaust to produce thrust.

Due to the different performance requirements within each section of the engine, the materials substitution issue is dramatically different across the engine. Compressor components, specifically blades, have stringent mechanical requirements, but need not operate at very high temperatures. Stiffness, as well as creep, fatigue and impact resistance are important considerations for materials for use in compressor components. In contrast with compressor, combustor components must withstand extremely high temperatures, but relatively little mechanical stress. For this reason a different class of materials can be considered for this application. The turbine section of the engine operates under difficult conditions from both a temperature and mechanical standpoint. Hot gases from the combustor impinge directly on the first stage blades, thus creating an extremely high temperature environment. Furthermore, due to the mechanical demands of extracting energy from the gas flow, stiffness, fatigue and creep can all be important considerations for turbine components, especially turbine blades. Finally, the exhaust section receives hot, fast moving gases from the turbine and must properly direct them out of the engine in order to obtain the maximum thrust. This requires that exhaust materials have good high temperature properties and can be formed to relatively strict tolerances. Figure 4 shows the temperature distribution in a typical engine.

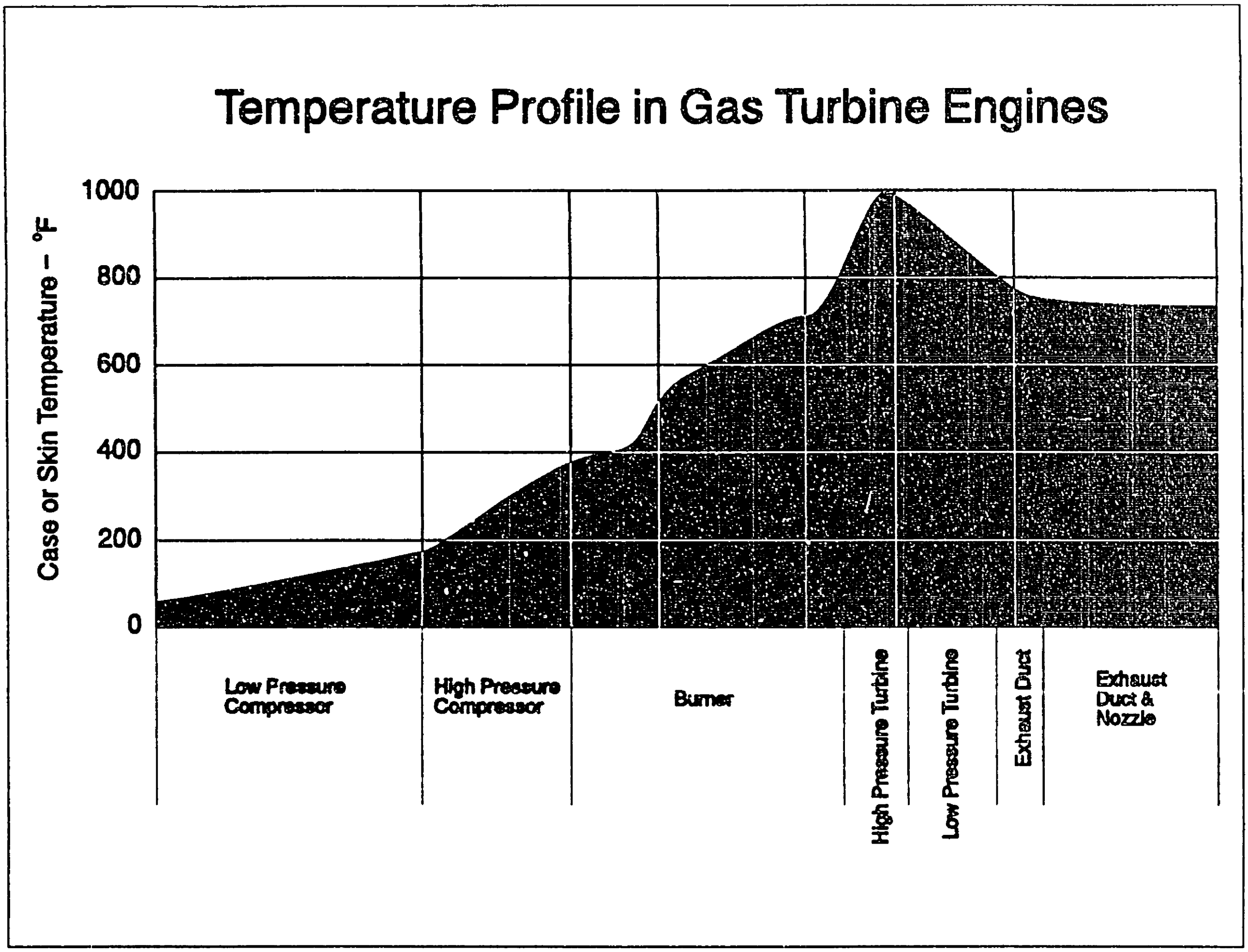


Figure 4: Temperature Distribution in Aircraft Gas Turbine Engines

For purposes of this study, it was important to select an application where several alternatives already existed, but no pressing demands for improvements necessitated new materials research. Based on these criteria, components in the turbine section were not chosen. Turbine components, especially blades, face some of the most adverse environments in the engine. New materials are usually developed specifically for this application. This study attempts to look at the way in which new materials which have already been developed for cutting edge applications, such as turbine blades, are evaluated for additional applications in the aircraft. Furthermore, because the goal of the study was to investigate high temperature materials, components in the compressor were not selected. Both combustor and exhaust components face similar materials requirements and are well suited for this study. However, some work has already been done towards developing, prototyping and testing exhaust components. Therefore, an exhaust duct was selected to be studied.

Exhaust ducts typically experience temperatures over 750°C and experience relatively low externally applied stresses. Various materials, such as superalloys, monolithic ceramics, ceramic matrix composites and carbon-carbon composites, could possibly be used in fabricating exhaust ducts.

This investigation will examine the issue of materials substitution in exhaust ducts for medium sized, non-man rated aircraft (missiles) with an eye towards looking at the potential for superalloys and ceramic materials in this application. It will develop a framework for comparing the performance attributes which are considered when selecting a material, and the likelihood of new materials attaining their stated performance levels in practice in this application. This will allow us to look at the optimal materials choices for this application, and to know the areas which the other candidate materials need to improve in order to be competitive.

3. MATERIALS ALTERNATIVES

Currently, most exhaust ducts for aircraft gas turbine engines are made from nickel based superalloys. However, the increasing temperatures of modern engines have necessitated the use of higher temperature materials in exhaust ducts. Exhaust gases are often upward of 750°C, and with improvements in other parts of the engine, this temperature is likely to rise. In the past, engine designers had little choice in selecting a material for the exhaust duct. Superalloys have been the only materials available with sufficiently good mechanical properties at such high temperatures. While superalloys have been successfully used, their use does have drawbacks. Probably the most important among the disadvantages is their density.

The advent of new materials such as ceramic matrix composites, monolithic ceramics, carbon carbon composites and intermetallic matrix composites, now gives the engine designer additional choices in designing the exhaust duct. Ceramics have traditionally been thought of as high temperature materials with some mechanical difficulties, such as poor impact resistance and creep and fatigue properties. Their low fracture toughness and poor impact resistance have long been an obstacle to the use of ceramics in many applications. However, advances in the processing of both monolithic ceramics and ceramic matrix composites have resulted in greatly improved mechanical properties. This is leading to the consideration of these materials for use in new applications such as exhaust ducts for aircraft gas turbine engines.

3.1. Superalloys

Nickel based superalloys have seen extensive use in many high temperature applications. While they are probably best known for their use in turbine blades, superalloys are employed throughout the aircraft engine, including exhaust components.

Currently, superalloys account for up to 70% of the weight of an aircraft engine. [12] Nickel based superalloys generally contain a number of elements in addition to nickel. These usually include chromium, cobalt, molybdenum, aluminum, titanium, niobium and small amounts of carbon. In addition, sometimes other metals such as tungsten, tantalum and vanadium can be used to replace some of the other components. For example, Rene 77 contains 58% nickel, 18.5% cobalt, 14.6% chromium, 7.9% aluminum, titanium and niobium, and 4.2% molybdenum and tungsten. [12]

Each of these added materials contributes to the good high temperature properties of the superalloy. Chromium supplies oxidation and corrosion resistance and helps with strengthening. Molybdenum and sometimes tungsten, niobium and tantalum are used to increase the solid solution strengthening of the matrix. Aluminum and titanium provide the major strengthening by precipitating nickel, aluminum titanium $Ni_3(Al,Ti)$ intermetallics. Cobalt is often used as a replacement for nickel.

The great advantage of nickel based superalloys in high temperature aerospace applications lies in their excellent mechanical properties across a large temperature range. Both wrought and cast alloys maintain good properties well above 1500°F, with PWA 1480 (the most advanced cast alloy) maintaining its properties at about 1900°F. Many of these advances have been achieved through advances in processing technologies, specifically casting. Pratt & Whitney's directional solidification and single crystal casting processes has enabled the development of the PWA 1480 alloy for use in turbine blades at up to 1900°F. Second and third generation alloys should have even greater temperature capabilities, with service temperatures possibly as high as 2000°F. [8] Typical cast superalloys have both yield (0.2% offset) and tensile strengths well above 100 ksi and moduli of elasticity up to 30,000 ksi. [13]

The use of nickel based superalloys in aerospace applications is not without disadvantages. The most significant problem is their density. The push towards higher thrust to weight ratios makes it desirable to reduce weight throughout an aircraft, including the engine. Another consideration is the theoretical limits of the temperature capabilities of superalloys. Innovative processing techniques have continually improved the service temperature of superalloys. However, they are approaching their melting point and thus their theoretical limit. Another problem is processing and manufacturing difficulty. This can also have a significant impact on the cost of the component.

3.2. Monolithic Ceramics

Monolithic ceramics show great promise for eventual use in many aerospace applications. Typical ceramic materials can be used at temperatures well above the service temperatures of superalloys. Furthermore, ceramics have relatively low densities and, thus, their use could result in significant weight savings. Also, ceramics typically offer superior resistance to corrosion and oxidation superior to most other materials. Unfortunately, monolithic ceramics have poor mechanical properties. Issues of impact resistance and fatigue have kept ceramics from being used in most engine applications. Furthermore, ceramics are extremely difficult to machine, and, accordingly they are often very expensive to use in applications with complex geometries or applications which demand tight tolerances.

The demands for higher temperature, lighter weight materials has led to significantly improved monolithic ceramics. Improved process control and better starting products have enabled manufacturers to produce more fully dense products. This has yielded ceramics with better reliability and improved mechanical properties. Unfortunately, these advances have not yet yielded ceramics with properties good enough for all but a few applications. Even where ceramics could be used, the cost usually prevents them from being competitive.

3.3. Ceramic Matrix Composites

Ceramic matrix composites attempt to exploit the excellent thermal and chemical resistance properties of monolithic ceramics by improving their mechanical properties through the use of a reinforcement material. Reinforcement materials are available in several forms; particulates, whiskers and fibers, both discontinuous and continuous. The main function of the reinforcement phase in ceramic matrix composites is crack deflection. When cracks propagating through the ceramic matrix encounter the reinforcement material, they are deflected, resulting in a more tortuous crack path, increased energy dissipation and thus longer times to failure. For this mechanism to be effective, it is important to achieve good compatibility between the reinforcement and the matrix. Issues of thermal expansion mismatch, chemical compatibility and the relative elastic moduli of the two materials are important considerations when choosing fiber and matrix materials. Control of the interface between the fiber and matrix is essential. Relatively weak interfacial bonds are necessary to allow for fiber pullout and crack deflection.[14]

While there are a large number of fiber/matrix combinations which may be suitable for ceramic matrix composites, relatively little work has been done towards developing such products. Most ceramic matrix composites employed today use either silicon carbide or carbon as the reinforcement material. This is especially true in the case of continuous fiber reinforcements, where few material alternatives are available. As for matrix materials, a number of different ceramics are often used, including a variety of glasses, magnesia, silicon nitride and, most often, silicon carbide and alumina. [15]

Another important concern is the geometry of the reinforcement material. Fiber reinforcements can be aligned in specific orientations to give the most desirable properties. In addition to having random fiber orientations, plies of unidirectionally aligned fibers can be stacked to create a two dimensional reinforcement. Furthermore, two dimensional fiber cloths and three dimensional fiber weaves can be used, depending on the mechanical properties required of the final part. This is the case when interlaminar debonding is a problem.

Possibly the most important consideration when using ceramic matrix composites is the selection of a processing technique. Numerous methods have been developed including hot isostatic pressing, slurry infiltration of a fibrous preform and chemical vapor infiltration.

3.3.1. Hot Pressing and Hot Isostatic Pressing (HIP)

Hot pressing involves the sintering of a ceramic under an externally applied pressure. The additional pressure aids in the densification process which is important for obtaining good mechanical properties. Hot pressing is achieved by sintering the ceramic in a refractory die. In the case of hot isostatic pressing (HIP), the ceramic is encapsulated in a deformable refractory and then gas pressurized at an elevated temperature to cause densification of the matrix material.

In the case of ceramic matrix composites, a fiber preform is impregnated with the matrix material in powder form. This is done be applying a ceramic based slurry to the fiber plies prior to layup. The impregnated preform is hot isostatically pressed, resulting in the densification of the ceramic matrix around the reinforcement. While there has been considerable success in using this technique to form ceramic matrix composites, it is not with its problems. The encapsulation necessary for HIP is often difficult, due to the need for an encapsulant which will not react with the ceramic. Also there can be considerable damage to the fiber architecture and to the fibers themselves. This will likely result in greatly reduced mechanical properties. Furthermore, HIP is difficult to use when forming parts with complex geometries. [16] For this reason, HIP is not often considered a reasonable technique for producing certain parts for aerospace applications.

3.3.2. Slurry Infiltration

The slurry infiltration technique involves prepregging plies of fiber reinforcement with a ceramic based slurry, followed by a densification step. Typically, either a continuous fiber or fiber tows, or a two dimensional fiber cloth are impregnated with a slurry. The slurry consists of ceramic powders, which will form the matrix of the composite, and a binder. The impregnated fibers are layed up on a mold to obtain the desired part geometry. Densification of the ceramic matrix and binder removal are achieved by a variety of methods including hot pressing, autoclaving and mechanical loading at elevated temperatures.

Slurry infiltration can be used with most fiber architectures and part geometries, although these may limit the choice of densification process. There is however some concern about forming a fully dense product. [17] Binder removal can often be difficult and result in undesirable porosity. This will result in diminished mechanical abilities. It is also possible for fiber damage to occur, which would also hurt the physical properties of the composite.

3.3.3. Chemical Vapor Infiltration

In the chemical vapor infiltration process, reactive gases are forced through a fibrous preform. Under highly controlled conditions, the gases react and deposit a ceramic within the preform to form a composite.

Chemical vapor infiltration holds several advantages over other methods of producing ceramic matrix composites. The use of extremely high temperatures often needed in hot pressing or melt processing techniques is eliminated. More importantly, there is a much smaller risk of damage to the fiber reinforcements. On the other hand, chemical vapor infiltration can be a very lengthy and expensive process. Infiltration times can be exceedingly long and often several infiltration steps are needed to obtain dense final parts. Even after many infiltration steps, it is difficult to reduce the porosity of the composite below 10 to 20 percent. [16] As a result, processing equipment and labor costs can be very expensive. Furthermore, higher deposition rates on the fibers closest to the surface of the preform often leads to trapped pore spaces with the composite. Consequently, a machining step is often necessary to reopen pore spaces for additional infiltration steps. This is also expensive and can result in significant fiber damage.

3.3.4. Other Processing Techniques

Several other methods also exist for forming ceramic matrix composites. These include melt processing techniques and polymer pyrolysis methods.[18]

All of these methods still face major obstacles to widespread applications. Melt processing techniques require extremely high processing temperatures and pressures. This will likely result in extensive fiber damage. The polymer pyrolysis technique uses much lower temperatures but suffers from the lack of polymer precursors needed to produce the ceramic matrix. Furthermore, shrinkage of the matrix may result in internal stress and also limits it to applications with simply geometries. The lanxide method also suffers from an inability to produce many different ceramic matrices and its limitation to simple geometries.

3.3.5. Processing Techniques for Ceramic Matrix Composite Exhaust Ducts

The geometry and property requirements of exhaust ducts eliminates several ceramic matrix composite processing techniques from consideration for use in producing this component. The contoured tubular shape which must be made to strict tolerances can not be achieved by the hot pressing, lanxide or polymer pyrolysis techniques. Furthermore, the high processing temperatures and pressures used in melt processing techniques often results in poor mechanical properties which are unacceptable in exhaust duct applications. This leaves only two feasible processes for producing ceramic matrix composite exhaust ducts, the slurry infiltration and chemical vapor infiltration techniques.

4. METHODOLOGY

The development of new high temperature materials has presented the engine designer with many more materials choices. The alternatives offer various advantages and disadvantages when compared with one another and the existing technology. This has left the engine designer with difficult decisions concerning the optimal choice of material or processing technique. This study attempts to establish a framework for consistently determining the optimal choice. The techniques employed are well known methods used in the areas of engineering decision analysis and operations research. The focus of the study will be to provide a basis for comparison of materials alternatives in high temperature aerospace applications. The methods employed are multi-attribute utility analysis, subjective probability assessment and technical cost modeling. Multi-attribute utility analysis is used to determine a materials blind comparison of the performance characteristics considered important for a given application. Subjective probability assessment is then applied to determine the "believability" of the claims of new materials suppliers of achieving specific performance levels. Finally, technical cost modeling is used to determine a best case cost which can be achieved for producing the part from a given material by a given process. In this way, materials alternatives can be compared on the basis of what could be achieved in production.

4.1. Technical Cost Modeling

Determination of the cost of producing a final part is an essential part of establishing the competitive position of the materials alternatives. It is a common misconception that the aerospace industry is completely performance driven and has no concern for cost. [19] While it is true that many government sponsored aerospace development programs have specific performance requirements, they still also have cost limitations. Furthermore, cost is an important factor when considering materials substitution in non-essential situations. Therefore, it is essential to analyze the cost of producing a part from the various alternatives when judging the overall competitiveness of the material. Unfortunately, part cost is not always easy to determine. Manufacturing of a part usually occurs in a plant with many other products. It can then be difficult to determine which costs of operating that plant should be associated with each part. Further compounding the problem is the fact that many new technologies, have not been implemented on a mass production scale and thus there is little basis for cost estimation.

Several simplistic models exist for cost estimation. However, they usually do not accurately represent the differences in producing the same components from different materials or processing techniques. One such method involves estimating the part cost using some empirical relationship based on part weight. This techniques ignores part complexity and difficulties with processing. Other methods estimate a machine rent and use the part cycle time to compute the cost. This approach ignores other factors that contribute to cost such as labor and materials. Another approach involves calculating a burden rate which is representative of the labor and equipment requirements of production. Unfortunately this technique has several serious drawbacks. First, it is unclear how to accurately calculate the burden rate. Also, cost estimation by this method does not reflect part geometry or the differences in production costs associated with different materials. [20]

A more systematic approach to cost estimation is clearly needed. This can be accomplished by technical cost modeling. This method can provide a means for comparing the cost of producing a part from several different materials for a given processing techniques. Considerations such as part geometry, differing tool requirements and processing difficulties are all considered in the cost estimation. Furthermore, this method allows for cost comparisons of parts by a variety of processing techniques.

Technical cost modeling attempts to determine overall part cost by calculating the individual factors which contribute to cost. These are usually labor, materials, equipment, tooling, maintenance and facility costs. Furthermore, the production process can be broken down into a number of unit operations. The preceding factors can all be calculated for each individual step of the process. Each of these can be estimated based on the underlying engineering principles. The physics of the process as well as the limitations of the machinery used often dictate many of the parameters which effect the cost of each of these components.

4.1.1. Labor Costs

Labor costs are calculated from the annual production volume, the product cycle time, the labor requirement of the equipment and the wages paid including overhead. The product cycle time varies not only with the production step, but also possibly with the materials being used and the part complexity. The labor requirement of the equipment can be fractional if the same workers are used to operate more than one piece of equipment.

4.1.2. Material Costs

Material costs include the cost of the materials in the final product plus any processing materials and the value lost to scrap. Calculation of the material costs of a part require a knowledge of the scrap yields for each step of the process. This allows for the calculation of material losses due to scrap. Sometimes scrapped materials can be sold at lower prices. In this case, material costs due to scrap loss is appropriately reduced.

4.1.3. Equipment Costs

Equipment costs are the annual costs of renting processing machinery. The crucial factor when calculating such costs is determining whether or not the equipment is dedicated. In many applications, machinery is used exclusively for the production of a given product. This may be done because the plant only produces one kind of part, or simply because switching the machinery to another line is too expensive. In this case the equipment is considered to be dedicated. Equipment costs of a single part are then calculated by dividing the amortized cost of the machinery by the annual production volume. When the manufacturing line is used to produce a variety of products, the equipment is non-dedicated. In this case, the percent of the line being used to produce the part must be factored in when calculating equipment costs.

4.1.4. Tooling Costs

Tooling costs can be somewhat more difficult to estimate than equipment costs. First, the total number of tools over the lifetime of the product should be determined. If this number is not excessively high, it is likely that the manufacturing plant will purchase all of the tools at the beginning of production in order to avoid a shortage. In this case, the total tooling cost can be obtained and amortized over the product lifetime. This is then divided by the total number of parts produced over the product lifetime to get the tooling cost per part.

On the other hand, if product lifetimes are long, or the total number of tools required is large, then it may be beneficial to purchase tools on an annual basis or as needed. In this case, tools may be considered to be expendable processing materials. Tooling cost is then just the cost of a set of tools divided by the number of parts which can be made from the tool set.

Unfortunately, in both cases, tooling costs can be difficult to estimate since it is not easy to determine the tool life, product life, or cost of a set of tools.

4.1.5. Maintenance Costs

Keeping production running smoothly requires periodic maintenance of equipment as well as a variety of administrative and miscellaneous functions. The cost of these activities is usually difficult to calculate on an individual basis for a given plant. Instead, a fixed percent of the equipment cost is often a good estimate.

4.1.6. Facility Costs

Besides the cost of processing equipment in the plant, there are also costs associated with housing the machinery, storage space for the raw materials and partially and completely finished parts, as well as office space for workers. All of this also adds to the overall part cost. The building space required can either be estimated by looking at an existing plant or if none exists, by estimating the space needed to easily accommodate each piece of equipment plus storage requirements. Once the space requirement is determined, it is easy to calculate the cost using published building rental prices.

4.2. Multiattribute Utility Analysis

The determination of the competitive position of materials alternatives in a given application requires an understanding of the relative importance which the product designer places on all of the relevant performance characteristics. Often a material is chosen because it is superior to all others in only one relevant attribute. Sometimes this leads to non-optimal choices. Often product designers are willing to pay a little more or give up some performance capabilities to have a material which is improved in other respects. Multiattribute utility analysis (MAUA) can be used to capture these trade-offs. MAUA is a decision analysis technique which attempts to assign a measure of value to various combinations of performance characteristics. From this a measure of utility for all possible sets of performance characteristics can be defined. This results in a mathematical expression to describe the preferences of the decision maker and thus allows for a rigorous comparison of all alternatives. [21]

The concept of utility is often used in microeconomics to describe the desirability of one alternative relative to another. For a set of alternatives A and B, utility is defined such that: [22]

1. $U(A) > U(B)$, if A is preferred to B

2. $U(A) = U(B)$, if A and B are equally valued

Furthermore, the magnitude of the difference of the utilities of two alternatives is representative of the degree to which one is preferred.

The existence and usefulness of utility analysis is dependent on six axioms. These are complete preorder, transitivity of preference, monotonicity of preference, existence of probability, monotonicity of probability and substitution, each of which is described below. [23]

1. Complete Preorder: For each possible pair of consequences, an individual will either prefer one to the other or will find them to be equally preferable. This axiom basically states that individuals can make choices between alternatives, which reveal their preferences.

2. Transitivity: If an individual prefers A to B and also prefers B to C, then he prefers A to C. This axiom is reasonable for individuals, but may not hold for groups with different sets of preferences.

3. Monotonicity: Individuals always prefer more of a good thing to less of a good thing. Again, this assumption is reasonable in many cases, although there are situations in which it is not true.

4. Existence of Probabilities: In uncertain situations, where the resulting consequences are uncertain, the probability of each possible consequence exists and can be quantified. While the quantification of such probabilities can be quite difficult, the proposition that such quantification is possible is reasonable.

5. Monotonicity of Probability: Individuals prefer a greater chance of achieving a good outcome than a lesser chance. This axiom is similar to the above monotonicity axiom, again stating the usually reasonable assumption that more is better.

6. Substitution: This axiom basically implies that individuals have linear preferences with respect to probability. For example, if an individual prefers A to B, then a 50:50 chance between A and some other alternative C is preferred to a 50:50 chance between B and C.

These axioms make it possible to treat utility as a cardinal scaling function for levels of characteristics. Additionally, levels of utility can be measured by using probability to assess an individuals intensity of preference for various levels of a characteristic according to the following relationship.

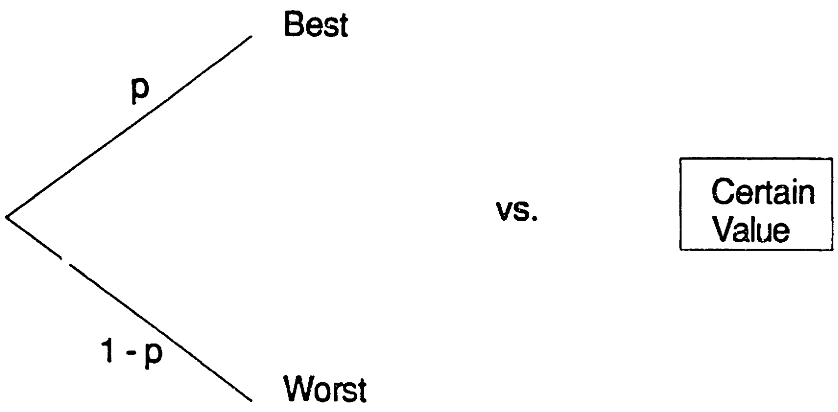
$$U(\text{lottery}) = \Sigma p_i U(X_i)$$

where p_i = the probability of achieving outcome X_i

$U(X_i)$ = the utility of outcome X_i

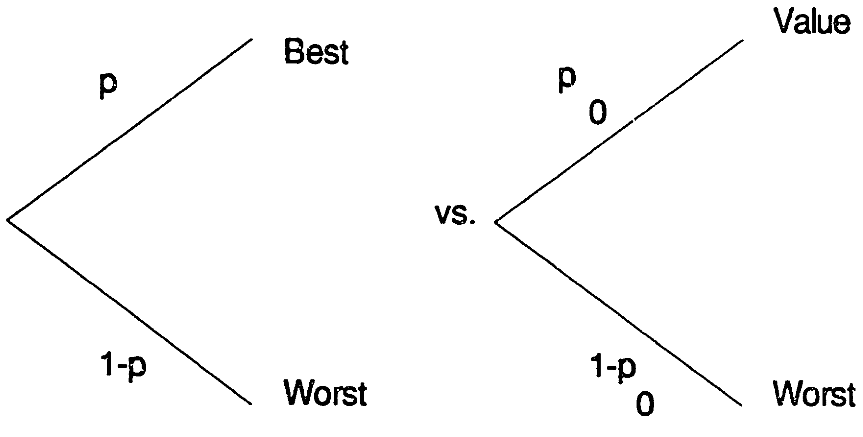
This relationship enables us to readily evaluate an individual utility for a given level of a characteristic by comparing it with levels of that characteristic for which the utility is already known. This can be accomplished through the use of binary lotteries of the form $(X_1, p_i; X_2)$. This represents an event with an uncertain outcome. The outcome X_1 occurs with the probability p_1, and the outcome X_2 occurs with a probability, $1\text{-}p_1$. In practice this can be done by two methods, the certainty equivalent method and the lottery equivalent method. In both cases a practical range for the utility function is determined. Utilities of 0 and 1 are assigned to the worst and best levels of the characteristics, respectively. Figure 5 represents the two techniques for assessing utility.

Certainty Equivalent Method



$U(\text{Best}) = 1,\ U(\text{Worst}) = 0$
$U(\text{Certain Value}) = p(1) + (1\text{-}p)(0)$

Lottery Equivalent Method



$U(\text{Best}) = 1,\ \ U(\text{Worst}) = 0$
$p(1) + (1\text{-}p)(0) = p_0\ U(\text{Value}) + (1\text{-}p)(0)$

Figure 5: Certainty and Lottery Equivalent Methods

The certainty equivalent method compares a certain value with a binary lottery between the best and worst possible outcome. In this case all that is needed is to determine the probability of achieving the best possible outcome which makes the lottery equally desirable as the certain outcome. The utility of the certain value equals this probability.

$$U(\text{Certain Value}) = pU(\text{Best}) + (1\text{-}p)U(\text{Worst})$$
$$U(\text{Certain Value}) = p \bullet 1 + (1\text{-}p) \bullet 0$$
$$U(\text{Certain Value}) = p$$

The lottery equivalent method involves the comparison of two binary lotteries, one with a fixed probability, p_0, and the other with an unknown probability, p. Again, determining the unknown probability which makes the two lotteries equally desirable enables one to determine the unknown utility. In this case the utility is p/p_0.

$$p_0U(\text{Value}) + (1\text{-}p_0)U(\text{Worst}) = pU(\text{Best}) + (1\text{-}p)U(\text{Worst})$$
$$p_0U(\text{Value}) = p$$
$$U(\text{Value}) = p/p_0$$

While in theory both of these techniques are valid, it may be preferable to use the lottery equivalent technique. Certainty biases are often encountered when using the certainty equivalent method. This results from a desire to over value certain outcomes when compared with probabilistic outcomes. The lottery equivalent method minimizes this effect. [24]

In theory, this is all that is needed to completely determine an individual's utility for any given level of characteristics. Unfortunately, for studies involving even just a few characteristics, this would require an enormous number of lottery equivalents. However, this number can be significantly reduced if utility independence of the attributes is assumed. Utility independence requires that the preferences over lotteries of one attribute do not depend on a fixed level of any of the other attributes. This implies that the shape of the utility function for a single attribute does not change at various levels of other attributes.

If utility independence exists, the problem of finding the multiattribute utility function is greatly simplified. Independent single attribute utility functions can be determined, as well as scaling factors which indicate the relative contribution of each attribute to the overall utility. This allows for the direct calculation of the utility of any set of levels of performance characteristics according to the following expression:

$$1 + KU(X_1 \ldots X_n) = \Pi[1 + Kk_iU(X_i)]$$

where K = normalizing factor

X_i = level of attribute i

k_i = scaling coefficient for attribute i

Through this approach, the multiattribute problem has been reduced to that of finding the single attribute utility functions and their scaling factors. This is often accomplished using the Keeney - Raiffa interview approach. [25] The main components of this technique are (1) determination of the relevant attributes, (2) administration of a questionnaire which explores the decision makers preferences using the lottery equivalent method, (3) data analysis to determine the utility functions and (4) interpretation of the results.

4.2.1. Attribute Selection

Selection of attributes to be included in a multiattribute utility study is a critical part of the procedure. It is obviously important to include all attributes which the decision maker believes to be important. However, the interview technique can be long and cumbersome if too many attributes are included. This can yield questionable results and thus reduce the usefulness of the study. Furthermore, it is important to select attributes which have utility independence. Utility independence is the key assumption which allows for the use of single attribute utility functions in determining the multiattribute utility function. If two or more attributes do not possess utility independence only one should be included, or some other representation of those attributes should be introduced as a single attribute. This approach is often valid since attribute which exhibit utility dependence are generally linked in a way that makes inclusion of only one of them necessary.

4.2.2. Utility Questionnaire

The purpose of the utility questionnaire is to determine the single attribute utility functions and scaling coefficients. This is accomplished by using the lottery equivalent method. However, first, a range of values for each attribute must be determined. These represent the end points of the single attribute utility scales. Following this, the questionnaire should have sections devoted to determining the single attribute utility values and the scaling factors. For the single attribute utility functions, a minimum of one lottery equivalent is necessary. However, if more intermediate points are desired for the utility function, then additional lottery equivalents can be presented. Determining the scaling coefficient requires only a single lottery equivalent since it represents the multiattribute utility at a single point. Additionally a section may be included to explore the direct trade-offs between the attributes to corroborate the lottery equivalent results.

4.2.3. Data Analysis

A completed questionnaire contains all of the information needed to construct the multiattribute utility function. However, at this point the data is in the form of probabilities used in lottery equivalents and must be manipulated to obtain the overall utility function. Before any data reduction takes place, it is first essential to ensure utility independence. This is usually accomplished during the interview by asking questions concerning the effect of one attribute on the others. With this requirement satisfied, it is valid to find the single attribute utility functions and scaling coefficients. While the scaling coefficients are readily obtained from the lottery equivalent results, utility functions are not. Instead, values for single attribute utilities are found at specific points. Single attribute utility functions can be approximated by fitting a function of the appropriate form to the points where utility is known.

The choice of an appropriate functionality depends on the number of points at which the utility has been determined, the risk behavior of the decision maker and the relationship between utility and the level of the attribute (*i.e.* does the utility function increase or decrease with increasing levels of the attribute).

Decision makers exhibit three kinds of risk behavior over a range of levels of a given attribute. These are risk aversion, risk neutrality and risk proneness. Risk neutrality means that the decision maker is indifferent to the choice between a certain outcome and a lottery with an expected value equal to the certain value. This implies that the utility of the expected value of the outcome of the lottery equals the expected value of the utilities. In the case of risk aversion, the decision maker wishes to avoid the risk associated with the lottery and as a consequence prefers the certain outcome, even though the expected value of the utility is the same. Similarly, risk proneness implies that the decision maker prefers to take a chance on achieving a better outcome, even though the expected outcome is once again the same. In this case, the utility of the expected value is higher than the expected value of the utility.

$$\text{Risk Neutral: } U[E(x)] = E[U(x)]$$

$$\text{Risk Averse: } U[E(x)] < E[U(x)]$$

$$\text{Risk Prone: } U[E(x)] > E[U(x)]$$

These relationships make it possible to determine the risk behavior of the decision maker from the utility results already obtained. The utility of the expected value can be obtained directly from the interview results. The expected value of the utility at that same point can be calculated using the utilities of the best and worst possible outcomes. A comparison of the two yields the risk behavior of the decision maker with respect to the attribute of interest.

Another factor which may aid in the selection of an appropriate utility function is the way in which risk behavior varies over the range of the utility function. The most common are those where risk monotonically increases or decreases, or remains constant with either increasing or decreasing utility.

The case of constant risk neutrality is the simplest to deal with in terms of fitting an appropriate expression to the utility data. In this case the utility function is linear.

Often, risk aversion decreases with increasing utility (and conversely increases with decreasing utility for functions which are negatively correlated with the level of the attribute). A variety of mathematical forms exist which satisfy this condition. The following expressions can be used to represent the scenario when three and four utility points are available (for functions which are positively correlated with the levels of the attribute):

Three Point: $U(x) = h + k \ln(x + b)$

Four Point: $U(x) = a + bx + c \ln(x + d)$

Risk prone behavior can also be described by a variety of mathematical forms. One common approach assumes constant risk prone behavior over the entire range of the utility function. For three known values of utility, this can be expressed as follows (for functions which are negatively correlated with the levels of the attribute):

$$\text{Three Point: } U(x) = a - b \exp(-cx)$$

A more extensive treatment of this subject can be found in *Decisions with Multiple Objectives* by Keeney and Raiffa [25]

If the risk behavior of the decision maker does not vary monotonically across the entire range of the utility function, then none of the above expressions will be valid. Instead, a polynomial of sufficient order to fit all known utility points can be used. This allows for changing risk behavior in one region of the utility function and a different change in risk behavior in another region.

Once single attribute utility functions and the scaling coefficients are determined, all that remains is to assemble them into the multiattribute utility function according to the expression already given. Unfortunately, because this expression is multiplicative it is usually easier to calculate the normalization factor, K, but to leave the remainder of the expression as it is. Instead, attribute levels can be used in the single attribute utility functions. The resulting single attribute utility values, along with the scaling coefficients and the normalization factor can then be used in the multiattribute utility expression to obtain an overall utility value. Calculation of the normalization factor comes straight from this expression which can be reduced to the following and solved numerically:

$$K + 1 = \Pi(Kk_i + 1)$$

For i greater than or equal to three, multiple solution for K exist. In this case the solution with the smallest absolute value is chosen.

4.2.4. Intrepretation of Utility Results

Once completed, the data analysis can yield utility values for any set of attribute levels. As a result, utility levels for various alternatives can be obtained. By necessity, this will yield a comparison of the alternatives based on all of its attributes. This is a valid result for the ranking of the alternatives according to the decision maker. The procedure can be repeated separately for other decision makers, but results cannot be combined, rather they should be viewed separately as individual preferences.

One other issue of importance concerns the sensitivity of the results to response given by the interviewee. The lottery equivalent method is often unfamiliar to the interviewee. Consequently, the responses may not be completely reflective of the relative value of the attributes. Furthermore, the interviewee may be unable to distinguish between small changes in the probabilities which make the lotteries equivalent. Usually responses are obtained by a technique called bracketing in which the interviewer converges in on the response from both directions. While this technique can be very successsful, the interviewee is usually limited to responses which are within the magnitude of the change in probability suggested by the interviewer. It can therefore be important to look at the effect of small changes in responses on the overall utility of a set of levels of attributes

4.3. Subjective Probability Assessment

Multiattribute utility analysis is a very useful technique for comparing alternatives based on a set of levels of characteristics. However, it is limited in that it requires exact knowledge of these levels. This is a reasonable expectation for existing technologies, but in the case of new alternatives, it is often difficult to state with accuracy the levels of the relevant characteristics. Often the material is only being produced on an experimental scale. Testing of materials under these conditions can yield results which are vastly different from those seen in the same material processed on a large production scale. Furthermore, testing is usually conducted on small laboratory specimens, which may not necessarily represent the behavior of the material in a larger part with a complex geometry. Additionally, laboratory test conditions may not accurately reflect the operating conditions the component will have to endure. Also, performance levels for new materials are usually available only from the potential material supplier and may thus be reported in a biased manner so as to put the best possible face on the results. This bias is further compounded by biases against new materials on the part of the end users. Finally, in many cases, new materials are still in the experimental stage and accordingly only projected values for their levels of performance characteristics are available. Even if these projections are reasonable, there is still some probability that they will not be achieved.

For all these reasons there is some uncertainty concerning the levels of attributes for new materials and technologies. However, this does not mean that MAUA is useless. Instead, it requires that adjustments be made to account for this uncertainty. In MAUA, single attribute utility values are calculated using well defined levels of each characteristic. In the scenario previously described, this is no longer possible. Use of values reported by materials suppliers will result in rankings of the alternatives which do not truly represent the decision makers preferences. Instead, values which represent the decision makers expectations of the performance levels of the new material must be employed. This requires examination of the degree to which the decision maker believes the values reported by the materials supplier.

Many factors can affect this situation. Company reputation may play a large role. If the decision maker has had favorable past experiences with the supplier, he may judge their results more favorably than otherwise. Past experience with the type of material may also be a major factor. If the decision maker has seen others fail in their attempts to use this material, he may be less inclined to believe the "hype" about the material. Other factors might include the decision maker's experience with other new materials and stage of development of this material. Past experience with other new materials may have led the decision maker to conclude that reported levels of attributes are systematically higher than indicated by independent testing of parts fabricated from the material. Furthermore, decision makers may treat materials from which parts have been prototyped or otherwise proven differently from those in earlier stages of development.

The decision maker's interpretation of the levels of attributes reported by the materials supplier can be quantified in terms of a probability distribution describing the likelihood of achieving various levels of each attribute. Integrating the product of the utility at a given point and its probability over the entire range of values of the attribute yields a corrected single attribute utility value.

$$U(i) = \int_{-\infty}^{\infty} U(x)\, p(x)\, dx$$

Where $U(i)$ = the utility of attribute i

$U(x)$ = the utility of level x of attribute i

$p(x)$ = the probability density function

This can be used as before in calculating a multiattribute utility value. These probability density functions can be obtained using subjective probability assessment techniques.

4.3.1. Evaluation Techniques

There are a number of methods available to assess subjective probabilities. These methods basically fall into three classifications; probability methods, value methods and probability-value methods. Probability methods involve the evaluation of the probability of the occurrence of a specific event. Value methods require the subject to identify limits of the attributes which correspond to given probabilities. Finally, probability-value methods involve a combination of the two techniques. [26] Some of the most common techniques employed are the variable interval method and the fixed interval method. The variable interval method is a value technique which asks the subject to identify the limits of an interval of the level of an attribute which he feels will have a specific probability of containing the actual value. The fixed interval method requires the subject to assign a probability to the occurrence of the actual value lying in a specified interval. [27]

Despite the success which some have had in determining subjective probabilities, the technique is not without its pitfalls. A number of biases can have significant effects on the results. It is important to understand these biases and minimize their effects in order to obtain more accurate assessments. Some common modes of judgment which may result in biased responses are (1) availability, (2) adjustment and anchoring, (3)representativeness, (4) unstated assumptions and (5) coherence. Availability refers to the bias of a subject to the most easily remembered information. One event may stand out above all others and cause the subject to assign more weight to this event than it deserves. Adjustment and anchoring occurs when the subject reacts to the initial scenario and subsequently adjust his responses from then on. This may yield vastly different results depending on which scenario is presented first. Representativeness describes the situation where the subject bases his responses on a small amount of information which may not be truly representative of the entire scenario. In this case the interviewer must be careful to use complete information. Unstated assumptions on the part of the subject may also effect the results. This is best dealt with by stating all assumptions at the onset of the interview. Finally, coherence biases result when the subject bases his responses on the ease with which he can come up with a plausible scenario to describe the occurrence. This is often affected by the way in which the questions are posed and can be minimized by having the interviewer present a number of possible scenarios. [28]

While there are often problems with assessing subjective probabilities, it is still a effective way to deal with the uncertainties presented by new materials. Accurate results can be obtained through the appropriate choice of evaluation technique and careful consideration of possible biases.

5. COST MODEL DEVELOPMENT

Cost estimations for the material alternatives were made through the development of several technical cost models. In all, three models were used in this study. Exhaust ducts are currently made of nickel based superalloys and are investment cast. The Materials Systems Laboratory developed a cost model for the investment casting process prior to the beginning of this study. [29] This model was revised and updated where needed, to reflect the state of the art in investment casting, as well as current economic conditions. Potentially competitive ceramic matrix composites can be produced by a number of processing techniques described in Chapter 3. However, due to the complex geometry and strict tolerance requirements for exhaust duct fabrication, several of the methods were deemed inappropriate as was discussed in Chapter 3. Two viable techniques, slurry infiltration and chemical vapor infiltration, were selected for this study. Accordingly, technical cost models were developed for each of these two processing techniques.

All of the cost models used in this study were developed on Lotus 123 spreadsheets, and have a uniform format. This was done for consistency and to facilitate the use of these models. Figure 6 shows the layout of a typical technical cost model.

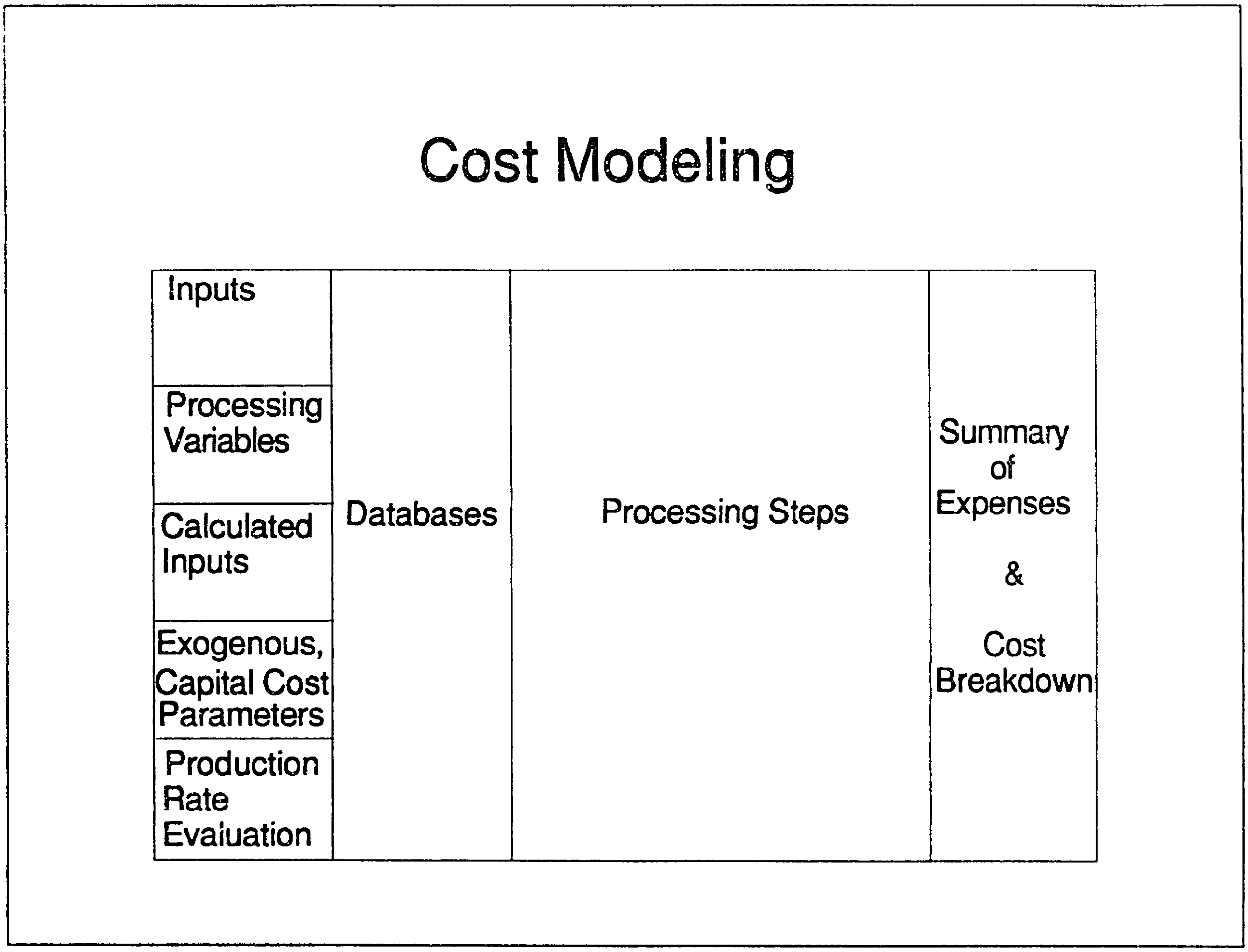


Figure 6: Technical Cost Model Layout

The worksheet is broken up into groups of columns which are the width of the screen. All inputs are limited to the first three pages of the model. Page one consists of a series of inputs relevant to the specific component to be produced, the processing specifications, current economic conditions and process yields. Process yields are used to determine the number of parts needed to be produced in each step of the process. The number of parts necessary at the end of each step is divided by the unit porcess yield and rounded up to give an integral number of parts required for each processing step. The result is a revised production volume for each unit operation. Table

1 shows a hypothetical example of the calculation of the effective production volumes necessary for each step of the manufacturing process.

Table 1: Sample Calculation of Effective Production Volumes

Step	Yield	Calculation	Production Volume
# 1	1.00	Round(14030/1.00+0.5)	14030
# 2	0.80	Round(11224/0.80+0.5)	14030
# 3	1.00	Round(11224/1.00+0.5)	11224
# 4	0.99	Round(11112/0.99+0.5)	11224
# 5	0.90	Round(10000/0.90+0.5)	11112
		Total	10000

The next pages consist of materials and possibly equipment databases. These consist of the prices, relevant physical properties, capacities and other applicable information about processing materials and equipment. Next there are a series of pages describing the unit processes used in the overall processing technique. Each page consists of a section where relevant information is either brought in from the input section of the model or calculated from these inputs, and section where costs are calculated and tallied. Finally, there is a results section where the costs from each unit operation are summarized and totaled. In addition, cost sensitivity to various inputs is often explored at the end of the model.

While some of the inputs are specific to the processing technique being modeled, others represent factors common to all of the models. These include some inputs specific to the case study such as production volume and part dimensions, while others describe general economic conditions such as wages and benefits, workdays per year, the equipment accounting life, the opportunity cost of capital, the maintenance rate and the building cost and amortization period. Table 2 lists the inputs common to the three cost models.

Table 2: Inputs Common to the Three Cost Models

Case Study Specific Inputs

	Units	Value
Production Volume	#	2400
Length	inch	25
Width	inch	8
Thickness	inch	0.375
Part Volume	sq.in.	75
Product Lifetime	years	3

Exogenous Inputs

Wage	$	15.00
Benefits	% of wage	30
Work Days per Year	#	180
Shifts per Day	#	3
Equipment Accounting Life	years	5
Opportunity Cost of Capital	%	12
Maintenance	% equipment cost	30
Building Cost	$/sqft.	50

The production volume is based on an estimated 200 parts per month predicted by the Aluminum Company of America (ALCOA). [30] Part dimensions are dictated by the physical requirements of an exhaust duct. Product lifetime is an industry estimate reflecting the length of the production run for a duct in a specific engine. Furthermore, because of the large capital investments in these plants, three production shifts per day were assumed in order to obtain maximum usage of the equipment.

5.1. Investment Casting Cost Model

Investment casting is a well established materials forming technique, and is very well understood. The Material Systems Laboratory's investment casting cost model is based on actual industry practices and thus is a good representation of the best case cost of producing a part by this technique.

In investment casting, a permanent pattern is made of the part to be produced, from which wax patterns are molded. The wax patterns are assembled into trees which are dipped in a ceramic to form a refractory shell. The wax is removed and the shell is fired to form a mold for the casting. The metal is then poured and allowed to solidify. The refractory shell is then removed and any runners and headers are cut off. Inspection and machining steps may also be necessary. Figure 7 shows a flowchart of the unit operations included in the investment casting technical cost model.

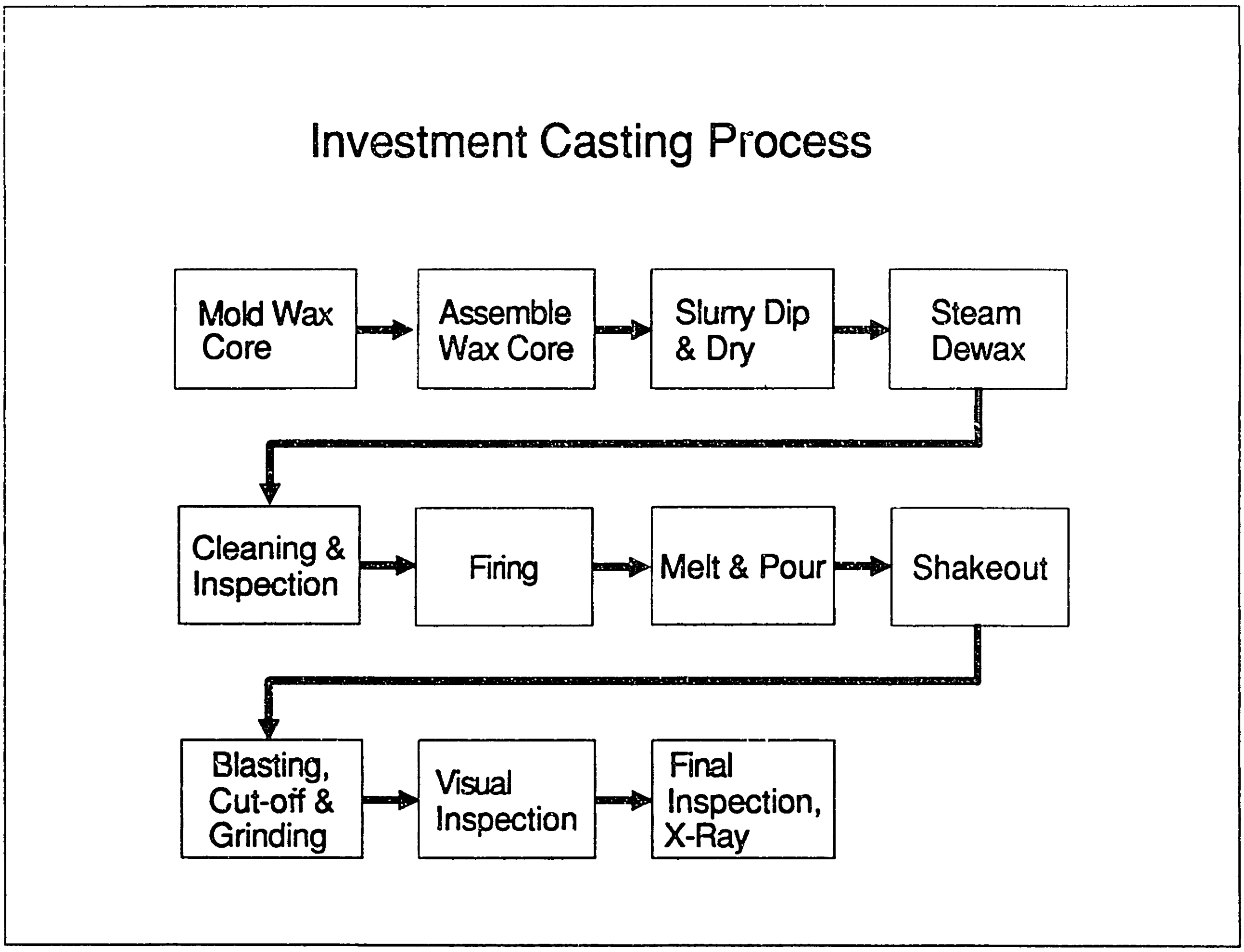


Figure 7: Investment Casting: Flowchart of Unit Operations

5.1.1. Investment Casting Cost Model Inputs

Most of the inputs to the investment casting model are standard. However, a few are noteworthy. For a complete listing of the inputs and the model in its entirety, see Appendix A.

Recent advances in casting technology have resulted in alternatives to the standard method. Traditionally, metals are poured using gravity to force the molten material into the mold. This results in lost material in the runner. An alternative method involves using a vacuum to pull the metal up the runner and into the molds. Removal of the vacuum allows the excess metal in the runner to flow back in the molten metal supply reservoir. This is known as the counter gravity vacuum method (CLA). While the equipment involved in the CLA method is more expensive, it is often results in reduced part costs due to the reduction in material losses and savings in the cutoff operation. The CLA method is usually used when casting superalloys, due to the relatively high cost of the material. [29]

Another consideration unique to the investment casting model is whether or not the part is cored. Cores are required when cast parts are designed with internal passages. Part complexities that require internal cavities can increase the production costs. In the case of an exhaust duct, no core is needed.

Also of interest are the process yields. Yields for each step of the process are usually closely guarded by the manufacturer and thus only estimates are available. Yields can have a large effect on the overall part cost since they effect the number of parts needed to be produced in each step of the process. As a result, it is important to look at the effect of these values on the final cost results of the model. Tables 3 and 4 list production inputs specific to the investment casting cost model as well as the unit operation scrap rates and the calculated effective production volumes for each step of the process.

Table 3: Investment Casting Cost Model Production Inputs

CLA or Gravity	CLA
Material	Superalloy
Part Weight	11.5 lbs.
Is the Part Cored?	No
Number per Configuration	50

Table 4: Investment Casting Cost Model Scrap Rates

	Scrap Rate	Units	Number
Number necessary to start		pieces	4395
Mold wax pattern	1.00%	pieces	4351
Assemble wax pattern	0.50%	trees	4329
Slurry dip and dry	2.00%	trees	4242
Steam dewax	0.00%	trees	4242
Cleaning and inspection	1.00%	trees	4199
Firing	0.00%	trees	4199
Melt and Pour	1.00%	trees	4157
Shakeout and Blast	0.00%	trees	4157
Cut-off and grinding	5.00%	parts	3949
Final Machining	20.00%	parts	3159
Visual Inspection	20.00%	parts	2527
Final Inspection, X-ray	5.00%	parts	2400

5.1.2. Investment Casting Results

The results of the investment casting cost model for the case of an exhaust duct for a medium sized aircraft gas turbine engine are given in Tables 5 and 6. The dimensions of the duct are that of an 8" x 25" x 0.375" sheet wrapped around to form a contoured tube.

Table 5: Breakdown of Cost by Unit Operation: Investment Casting

	TOTAL COST	COST/PART	PERCENT
Material	$610,334	$254.31	26.59%
Facilities	$7,559	$3.15	0.33%
Mold Wax Pattern	$23,135	$9.64	1.01%
Assemble Wax Core	$2,189	$0.91	0.10%
Slurry Dip and Dry	$23,237	$9.68	1.01%
Steam Dewax	$3,512	$1.46	0.15%
Cleaning and Inspection	$3,309	$1.38	0.14%
Firing	$29,008	$12.09	1.26%
Melt and Pour	$60,747	$25.31	2.65%
Shakeout	$2,789	$1.16	0.12%
Blasting,Cutoff & Grinding	$26,744	$11.14	1.16%
Final Machining	$1,491,016	$621.26	64.95%
Visual Inspection	$4,104	$1.71	0.18%
Final Inspection, X-ray	$8,073	$3.36	0.35%
	$2,295,755	$956.56	100.00%

Table 6: Breakdown of Cost by Function: Investment Casting

	TOTAL COST	COST/PART	PERCENT
Facilities	$7,559	$3.15	0.33%
Labor	$1,539,554	$641.48	67.06%
Tooling	$20,817	$8.67	0.91%
Equipment	$52,606	$21.92	2.29%
Materials	$610,334	$254.31	26.59%
Maintenance	$64,885	$27.04	2.83%
	$2,295,755	$956.56	100.00%

In Table 5, material costs are removed from each unit operation and listed separately so as to give a more accurate picture of the costs associated with each step. Overall part cost for a superalloy exhaust duct produced by investment casting is estimated to be about $960. The primary contribution to this cost comes in the final machining step where flanges and other attachment accessories must be machined. Machining is very labor intensive and thus the labor contribution to cost is very high at 67.06%.

5.2. Slurry Infiltration Cost Model

The slurry infiltration technique for processing ceramic matrix composites is a relatively new technique, and is done almost exclusively on small production scale, by hand. However, this model investigates the costs of producing parts by an automated, production style version of this technique which would likely be used to produce larger quantities of exhaust ducts. As a result, some of the assumptions in this model are speculative and based on perceptions about what a slurry infiltration processing plant might look like. Furthermore, the Aluminum Company of America (ALCOA) is investigating the production of ceramic matrix composites by this process, with exhaust ducts as one target application. The process used in this cost model is based on ALCOA's perception of what would be involved in implementation of this process. [31][32]

In the slurry infiltration process, cloths of two dimensional fiber weaves are infiltrated with a ceramic based slurry, cut into plies and layed up on a mold. This fiber preform is then autoclaved, or sometimes mechanically loaded at high temperatures, to cause densification of the ceramic matrix. The part may then be machined and inspected. Figure 8 shows a flowchart of the unit operation envisioned by ALCOA and employed in this cost model.

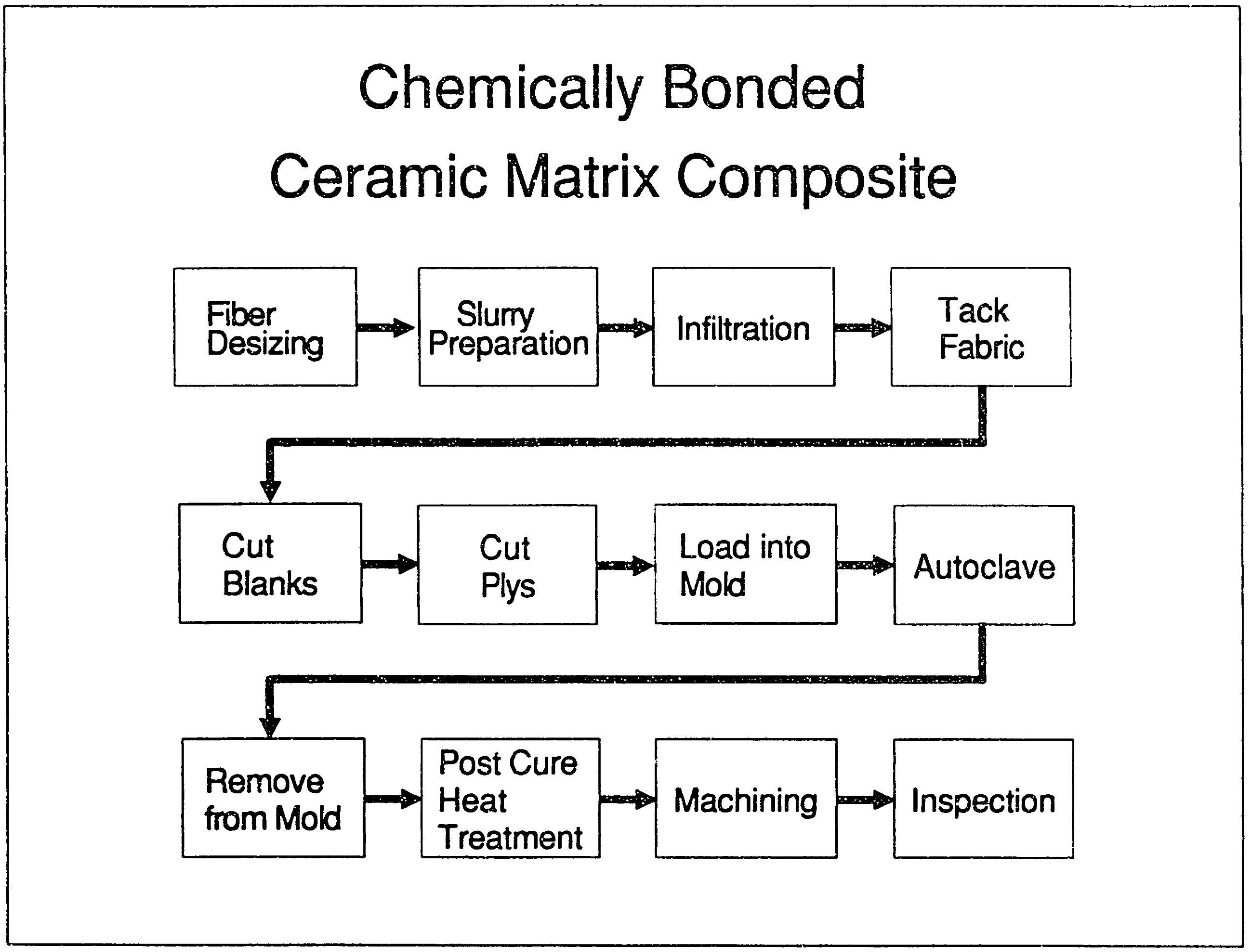


Figure 8: Slurry Infiltration Flowchart of Unit Operations

5.2.1. Slurry Infiltration Cost Model Inputs

Most of the inputs to the slurry infiltration model are self explanatory. For a complete listing of the inputs and the entire model, see appendix B. However, one unusual aspect is the use of an effective geometry. Parts produced by this method must be bagged and autoclaved. Calculation of the number of autoclaves needed to meet the required production volume requires knowledge of the number of parts which can fit in an autoclave. Part dimensions often do not represent the volume of space required for the part in some operations such as autoclaving. Instead, effective dimensions which represent the space requirements of the part are used. These are inputs which are based on the geometry of the part. In the case of the exhaust duct, the effective geometry was 10" x 10" x 10".

Also of interest are the process yields. Similar to the investment casting process, yields are very difficult to obtain. In this case, the problem is further exacerbated by the fact that the process is not yet operating on a production scale. These inputs can only be estimated based on the expectations of engineers in the field. Since cost model results may be very sensitive to these values, it is important to investigate the effects of variations in yields on cost.

The slurry infiltration model also has a few other unique options. Fiber coating is optional and is assumed to take place off-site, at a cost of $1500 per square meter. Tacking of the infiltrated fiber cloth is also considered optional.

Tables 7 and 8 list production inputs specific to the slurry infiltration cost model as well as the unit operation scrap rates and the calculated effective production volumes for each step of the manufacturing process.

Table 7: Slurry Infiltration Cost Model Production Inputs

Fiber Material	Silicon Carbide
Matrix Material	Silicon Carbide
Ply Thickness	0.0125 inch
Plies per Part	30
Volume Fraction of Fibers	0.50

Table 8: Slurry Infiltration Cost Model Scrap Rates

	Scrap Rate	Units	Number
Number to Start		plys	106928
Fiber Desizing	0.0%	plys	106928
Slurry Preparation		-----	------
Infiltration	1.0%	plys	105858
Tack Fabric	0.0%	plys	105858
Cut Blanks	0.0%	plys	105858
Ply Cutting	2.0%	plys	103740
Load into Mold	5.0%	parts	3285
Autoclave	5.0%	parts	3120
Remove from Mold	0.0%	parts	3120
Post Cure Heat Treatment	10.0%	parts	2808
Machining	10.0%	parts	2527
Quality Control	5.0%	parts	2400

5.2.2. Slurry Infiltration Results

Tables 9 and 10 show the results of the slurry infiltration model for a medium sized aircraft gas turbine engine exhaust duct. The duct is made of a silicon carbide - silicon carbide composite using Nicalon® fibers and has dimensions of a tube with a 0.375" wall thickness, 8" length and 25" circumference.

Table 9: Cost Breakdown by Unit Operation: Slurry Infiltration

	TOTAL COST	COST/PART	PERCENT
Material	$5,439,738	$2,266.56	48.9%
Fiber Desizing	$107,080	$44.62	1.0%
Slurry Preparation	$1,235	$0.51	0.0%
Infiltration	$18,397	$7.67	0.2%
Tack Fabric	$0	$0.00	0.0%
Cut Blanks	$29,708	$12.38	0.3%
Ply Cutting	$738,398	$307.67	6.6%
Load into Mold	$2,307,689	$961.54	20.7%
Autoclave	$65,903	$27.46	0.6%
Remove from Mold	$2,028	$0.84	0.0%
Post Cure Heat Treatment	$392	$0.16	0.0%
Machining	$535,505	$223.13	4.8%
Quality Control	$1,879,112	$782.96	16.9%
	$11,125,184	$4,635.49	100.0%

Table 10: Cost Breakdown by Function: Slurry Infiltration

	TOTAL COST	COST/PART	PERCENT
Materials	$5,439,738	$2,266.56	48.9%
Labor	$2,251,584	$938.16	20.2%
Equipment	$2,186,466	$911.03	19.7%
Maintenance	$1,190,983	$496.24	10.7%
Facilities	$56,412	$23.51	0.5%
	$11,125,184	$4,635.49	100.0%

Once again, material costs were removed from the unit operations in order to give a more representative cost associated with each processing step. Overall part cost is estimated to be $4600 or almost five times the cost of the same part made from an investment cast superalloy. Materials costs comprise almost half, 48.9% of the total cost due to the extremely high cost of silicon carbide woven cloth. The remaining cost are mostly seen in the "Load into Mold" and "Quality Control" steps, both of which have high equipment costs. The "Load into Mold" step involves laying up each previously impregnated ply onto a die. Accordingly, the cost of the tool is included in this step. Labor costs, at 20.2%, are also significant. This might be reduced by additional automation. Also, this process requires less machining than investment cast superalloys since flanges and other attachment features are directly formed in the layup process.

5.3. Chemical Vapor Infiltration Cost Model

Like the slurry infiltration technique, chemical vapor infiltration is a relatively new method and is usually done only for small production applications. this model is based on the assumption that small scale production facilities would be appropriately scaled up. Furthermore, it is based on production facilities envisioned by ALCOA and those currently used at DuPont. [31,33]

The chemical vapor infiltration technique involves flowing reactive gases through a fiber preform already in the shape of the final part. The preform is made by laying up two dimensional fiber cloths on a mold. It is then successively infiltrated and machined until a nearly dense part is formed. This is necessary because deposition of the matrix material occurs more rapidly near the interior of the preform. At some point during infiltration the matrix becomes continuous at the surface, preventing further infiltration even though the interior is not fully dense. Machining is done in order to reopen the trapped pore spaces in the interior so infiltration can continue, resulting in higher part densities. Figure 9 shows a flowchart of the unit operations involved in chemical vapor infiltration.

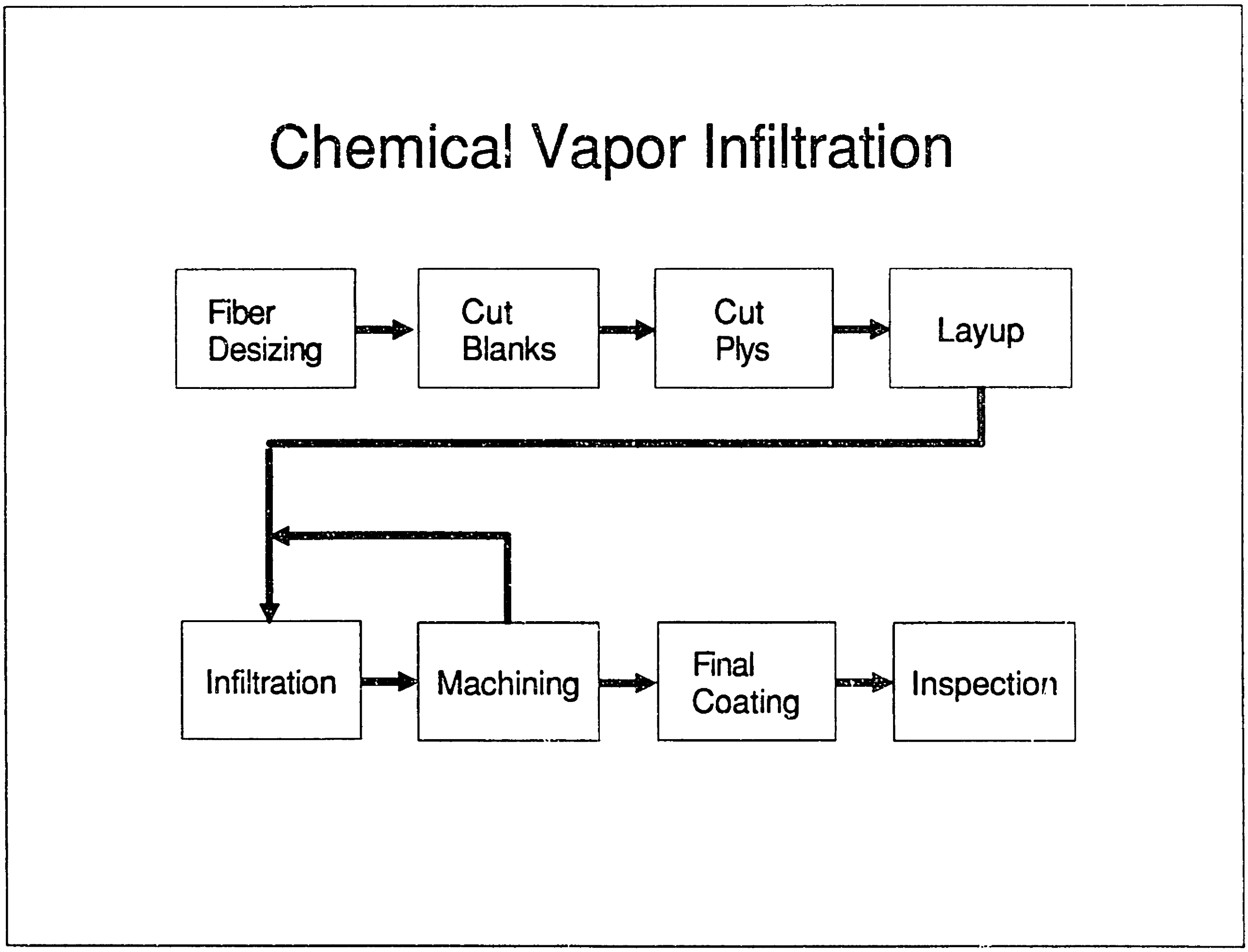


Figure 9: Chemical Vapor Infiltration: Flowchart of Unit Operations

5.3.1. Chemical Vapor Infiltration Inputs

The chemical vapor infiltration model is very similar in many respects to the other models. For a complete listing of the model, see Appendix C. The iterative nature of the infiltration and machining operations has necessitated a unique approach to certain steps of the production process. The user is required to input the number of infiltration (and machining) steps needed to produce a sufficiently dense final part. Because infiltration times can change after each successive infiltration step, a function describing the change in infiltration times, as well as the infiltration time for the first two passes must be inputted. The user can select from three forms for the infiltration time function, exponential, linear and constant. All other infiltration times are calculated based on this information. Special attention was paid to this feature because infiltration times can have a very large effect on both the equipment and labor costs. When the model calculates the costs associated with the iterative operations (infiltration and machining), it determines the total time needed to complete each of these steps for the entire production volume. The equipment and labor requirements can then be found in the usual manner. The long infiltration times and potential need for multiple infiltration steps, as well as the expense of the infiltration equipment, makes the overall part cost very sensitive to the inputs in the infiltration step. Because these inputs are estimates, it may be very important to look at the effect of variations in these parameters. Once again, process yields may also play an important role, since low yields during or after the infiltration step will require additional infiltration operations at a substantial cost.

Tables 11 and 12 list production inputs specific to the chemical vapor infiltration model as well as the unit operation scrap rates and the calculated effective production volumes for each step of the manufacturing process.

Table 11: Chemical Vapor Infiltration Cost Model Production Inputs

Fiber Material	Silicon Carbide
Matrix Material	Silicon Carbide
Ply Thickness	0.0125 inch
Plies per Part	30
Volume Fraction of Fibers	0.50

Table 12: Chemical Vapor Infiltration Cost Model Scrap Rates

	Scrap Rate	Units	Number
Number to Start		plys	13543
Fiber Desizing	0.0%	plys	13543
Cut Blanks	1.0%	plys	13407
Cut Plys	1.0%	plys	13272
Layup	0.0%	parts	3539
Infiltration (first step)	1.0%	parts	3503
:		:	:
:		:	:
Machining (last step)	10.0%	parts	2808
Final Machining	10.0%	parts	2527
Final Coating	0.0%	parts	2527
Quality Control	5.0%	parts	2400

5.3.2. Chemical Vapor Infiltration Results

Tables 13 and 14 show the results of the chemical vapor infiltration cost model for an exhaust duct made of a silicon carbide - silicon carbide composite. Here it is assumed that two infiltration (and machining) steps were needed.

Table 13: Cost Breakdown by Unit Operation: Chemical Vapor Infiltration

	TOTAL COST	COST/PART	PERCENT
Materials	$1,057,023	$440.43	4.74%
Fiber Desizing	$24,988	$10.41	0.11%
Blank Cutting	$10,248	$4.27	0.05%
Ply Cutting	$35,810	$14.92	0.16%
Layup	$176,785	$73.66	0.79%
Infiltration	$17,274,229	$7,197.60	77.47%
Machining	$1,054,643	$439.43	4.73%
Final Machining	$225,015	$93.76	1.01%
Final Coating	$592,369	$246.82	2.66%
Quality Control	$1,847,826	$769.93	8.29%
	$22,298,937	$9,291.22	100.00%

Table 14: Cost Breakdown by Function: Chemical Vapor Infiltration

	TOTAL COST	COST/PART	PERCENT
Materials	$1,057,023	$440.43	4.74%
Labor	$3,672,024	$1,530.01	16.47%
Equipment	$8,367,565	$3,486.49	37.52%
Maintenance	$9,048,960	$3,770.40	40.58%
Facilities	$153,364	$63.90	0.69%
	$22,298,937	$9,291.22	100.00%

Material costs are again removed from the units operations in order to give more representative costs. Overall part cost is estimated to be about $9300. In this case, it is evident that overall part cost is dominated by the large expense associated with the infiltration step. This step accounts for 77.47% of the total part cost. Equipment and maintenance costs (which are a function of equipment costs) account for 78.10% of the total when costs are broken down by function, much of this arising from the high cost of infiltration equipment. Accordingly, cost reductions might be achieved if the infiltration times or the number of infiltration steps could be reduced.

5.4. Cost Modeling Results

The results of the three cost models indicate a substantial advantage for investment cast superalloy exhaust ducts. This material will be likely to see continued use in this application unless there are significant performance advantages associated with using one of the other choices. Of the alternatives, the slurry infiltrated SiC/SiC composite duct is the more cost competitive. Fiber development may result in decreased material costs which would improve the cost competitiveness of the slurry infiltration technique. This is significant since materials account for 48.9% of the toatl part cost. Also, further automation could lead to a reduction of labor costs. To a lesser extent this will also imporve the cost competitiveness of slurry infiltrated 222composite ducts since labor accounts for 20.2% of part cost. SiC/SiC exhaust ducts made by the chemical vapor infiltration technique are significantly more expensive, costing more than twice that of the same part produced by the slurry infiltration technique. Without large cost reductions or vastly superior properties, this process is not likely to be considered for this application. Unfortunately, significant cost savings may be very difficult for this process. Long infiltration times contribute significantly to the large equipment and labor costs. Reaction kinetics dictate these times and thus cost cutting may be difficult in this area.

While on the surface it may appear that investment cast superalloys are clearly the least expensive, it is still important to consider the effects of certain parameters on these costs. As previously mentioned, the cost models are susceptible to variations in some of the inputs. Most notable of these are the process yields, production volume, material costs, and in the case of the chemical vapor infiltration model, the number of infiltration steps.

Figure 10 shows the effect of the overall yields on the cost of an exhaust duct for each of the three processes. Increasing the yield will result in a substantial improvement in the cost of ceramic matrix composite ducts produced by chemical vapor infiltration. Those produced by slurry infiltration will also experience some cost savings if process yields could be improved.

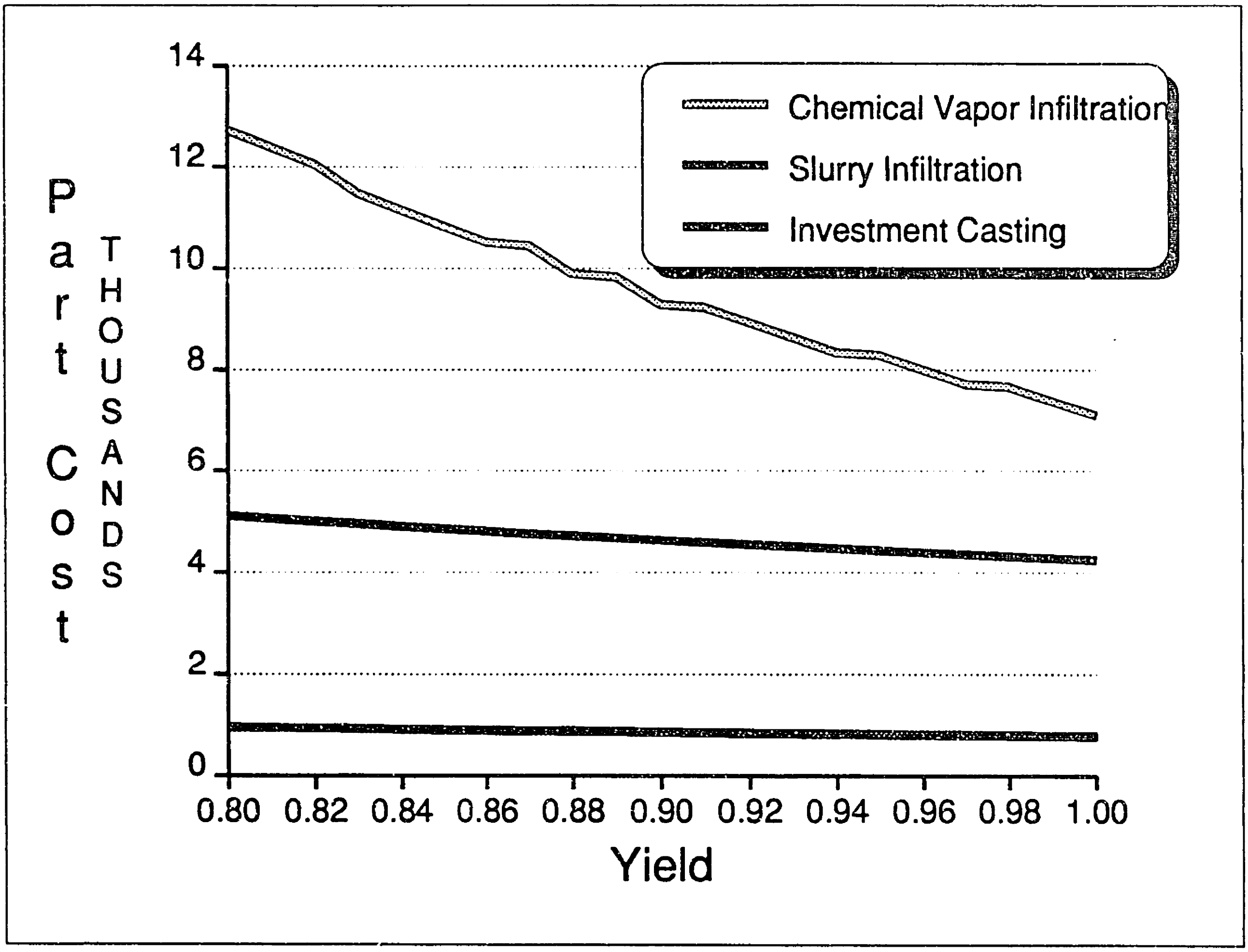


Figure 10: Overall Part Cost as a Function of Process Yield

Figure 11 looks at the effect of production volume on overall part cost. Increased production volume results in small decreases in part cost in all three cases. However, it doesn't significantly effect the relative position of the alternatives. The cost models for the two ceramic matrix composite processes are based on small production capabilities and thus some additional savings may occur if plants were scaled up differently.

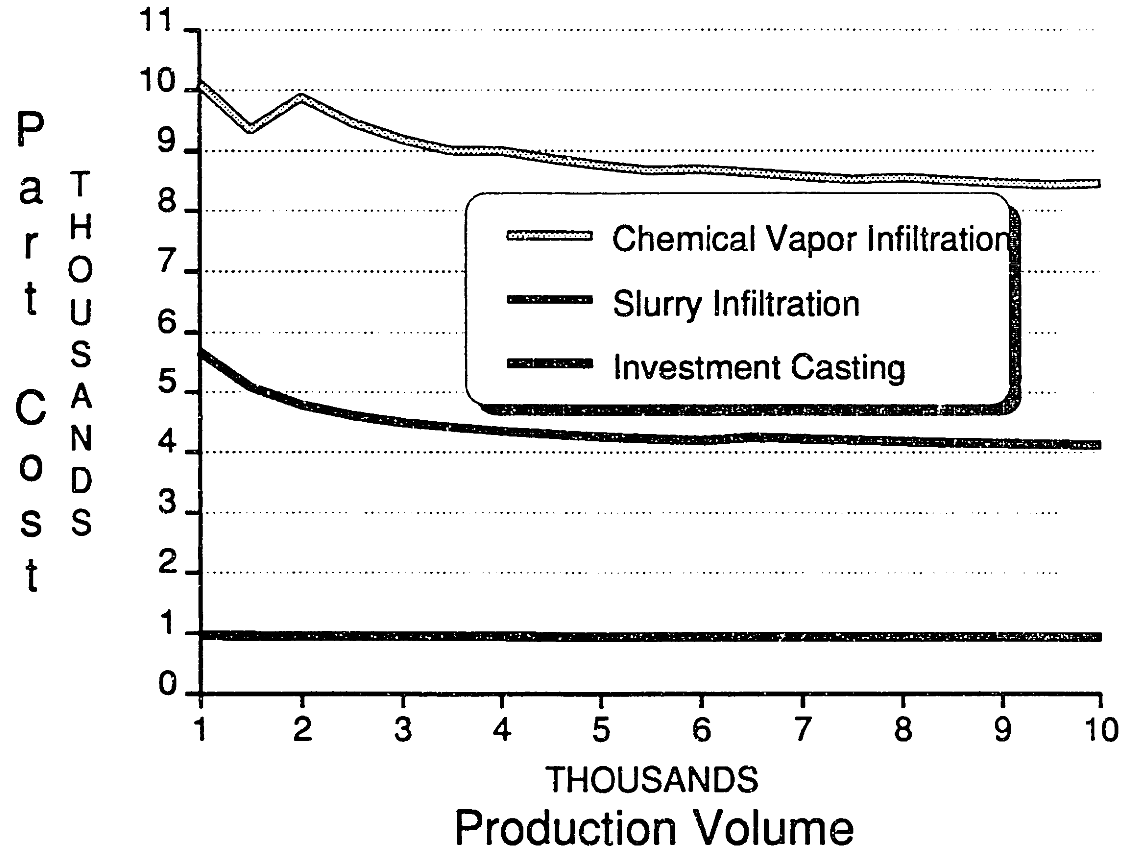


Figure 11: Overall Part Cost as a Function of Production Volume

Figure 12 shows the effect of ceramic fiber price on part cost. In this case baseline investment casting cost is given for comparison. Decreases in fiber prices or the use of alternative, less expensive ceramic fiber cloths will result in significant cost savings for parts produced by the slurry infiltration technique, as well as modest savings for the chemical vapor infiltration process. This could lead to a situation where slurry infiltrated ceramic matrix composite exhaust ducts are much more cost competitive.

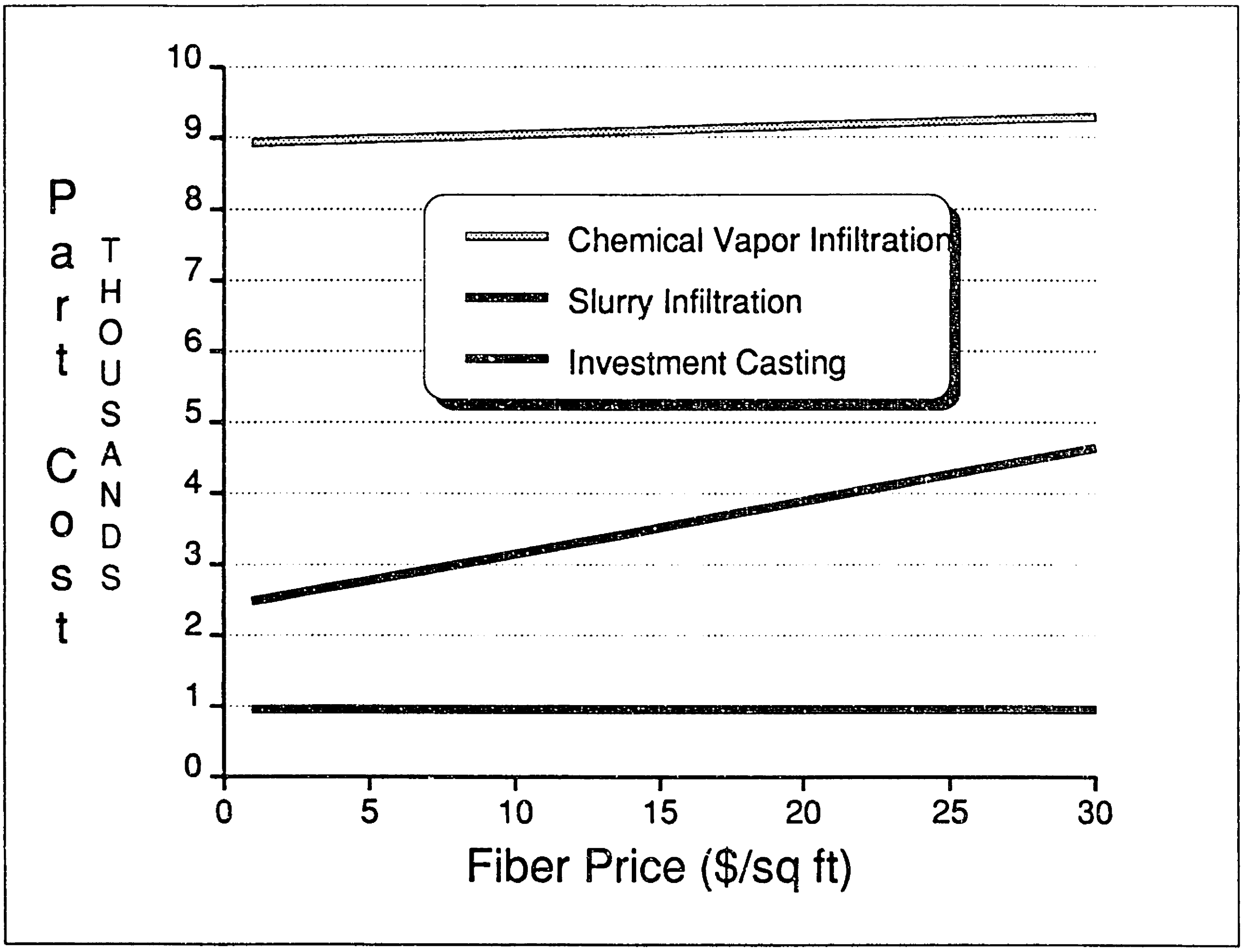


Figure 12: Overall Part Cost as a Function of Ceramic Fiber Price

Figure 13 shows the effect of the number of infiltration steps required in the chemical vapor infiltration process on the overall part cost. Baseline values for parts produced by investment casting and the slurry infiltration technique are given for comparison. If the part could be produced in a single infiltration step, overall cost would be greatly reduced to below $5700. This, along with other cost savings might make chemical vapor infiltration cost competitive with the slurry infiltration technique. However, if additional infiltration steps are needed, there will be a dramatic cost increase for parts produced by chemical vapor infiltration. Clearly this technique cannot be considered competitive solely on the basis of cost unless the duct can be produced using only one infiltration step. Accordingly, chemical vapor infiltration appears to be limited to applications with part thicknesses small enough (<0.25") to allow for the formation of dense parts in a single infiltration step.

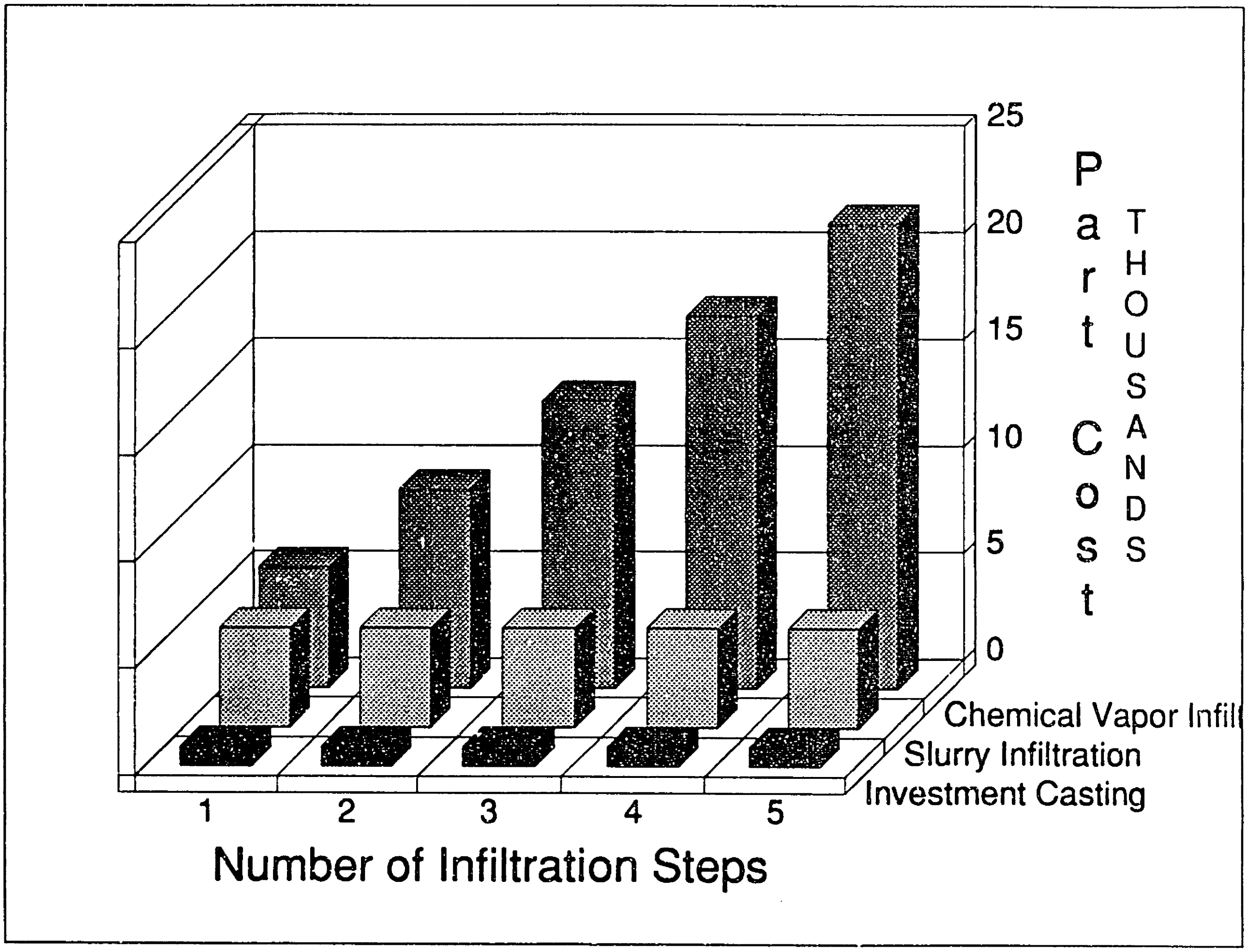


Figure 13: Overall Part Cost as a Function of the Number of Infiltration Steps (Chemical Vapor Infiltration)

Cost analysis has indicated a significant advantage for investment cast superalloys. However, there is some indication that his gap can be narrowed by improved process yields for the ceramic matrix composite processing techniques, especially chemical vapor infiltration, and reduced ceramic fiber prices. Furthermore, ceramic matrix composite suppliers claim to offer a substantial performance improvement over the currently available superalloys. These presumed performance advantages may make up for all, or at least part, of the cost differences among the alternatives.

Table 15 gives a summary of the cost of producing an exhaust duct by each of the processing techniques under various assumptions.

Table 15: Summary of Costs

	Superalloy	Slurry Infiltation	CVI
Yield			
0.80	$957	$5117	$12722
0.90	$857	$4635	$9291
1.00	$777	$4250	$7099
Production Volume			
2400	$957	$4635	$9291
10000	$950	$4128	$8464
Fiber Price			
$10 sq.ft.	$957	$3150	$9040
$30 sq.ft.	$957	$4635	$9291
Number of Infiltration Steps			
1	$957	$4635	$5631
2	$957	$4635	$9291
3	$957	$4635	$13474
Baseline Cost	$957	$4635	$9291
Best Case Cost*	$770	$2407	$3647

*Best Case Cost represents the part cost at 100% process yield, production volume of 10,000, fiber price of $10 sq.ft. and only one infiltration step for the chemical vapor infiltration process.

Ducts produced by chemical vapor infiltration could be made much cheaper at higher yields and by using fewer infiltration steps. At a 100% yield and two infiltration steps the cost would be only $7099, while the use of only one infiltration step would reduce the part cost to $5631. The best case cost for the chemical vapor infiltration technique is $3647.

Slurry infiltrated exhaust ducts would cost considerably less at lower fiber prices. A reduction of the price of woven SiC cloth to $10 sq.ft. would result in a part cost $3150. Furthermore, a best case cost for slurry infiltrated exhaust ducts would be $2407.

Investment cast superalloy ducts would only see minor cost reductions if process yields and the production volume increased. In the best case scenario, the part cost would be $770.

While best case costs for the ceramic matrix composite ducts are much lower, it is important to bear in mind that these are not actual part costs, but the best possible cost obtainable given improvements in the four areas considered; process yield, production volume, material cost and the required number of infiltration steps. It is extremely unlikely that part cost will ever approach these amounts. However, they are useful in that they represent cost reduction possibilities.

6. Multiattribute Utility Analysis

Cost is only a one area in which alternatives must compete to be selected in a given application. Usually a number of performance attributes are also factored into a materials selection decision. Unfortunately, it is often difficult to quantify the relative importance of the attributes considered when selecting a material. Multiattribute utility analysis overcomes this difficulty as was described in Chapter 4. Single utility value for a set of attribute levels can be found using multiattribute utility analysis. Materials alternatives can be represented by their attribute levels and thus assigned utility values which allow for easy comparison among the alternatives. Accordingly, the first step in a multiattribute study of alternatives in a given application is the selection of relevant attributes.

6.1. Attribute Selection:

For this study, attribute selection was done by conducting a preliminary survey of engine designers. The text of the survey suggested a few obvious attributes, such as operating temperature, part weight and cost, and asked the engineer to comment on the relevance of each, to list other important attributes, and to supply acceptable ranges of levels of the attributes. For a complete listing of the preliminary survey see Appendix D.

The preliminary survey yielded an extensive list of attributes which engine designers felt were important to consider when selecting a material to be used in the exhaust duct application. These were mechanical properties, such as strength and modulus; thermal properties, such as thermal conductivity, expansion and shock resistance; environmental issues, such as oxidation and corrosion resistance and chemical compatibility; density and certification requirements.

Attributes which were binary, insignificant, aggregable and intangible were eliminated from consideration. Binary attributes are those which have only two relevant levels; either they are acceptible or they are not. Insignificant attributes are those which have only a trivial bearing on the decision making process. Aggregable attributes are those which can be lumped together since they all represent the same property in different forms. In this case only one of these attributes is necessary. Intangible attributes are those for which it is impossible to quantify the attribute levels. An example of this would be certification requirements.

After screening for these properties, six attributes remained and are listed below.

1. Maximum Operating Temperature: This attribute is important since it effects the thermodynamic efficiency of the engine.

2. Strength: This attribute is important because exhaust ducts experience significant thermally induced stresses, especially at points of attachment to the turbine section.

3. Toughness: Toughness is important because a reliable engine requires that its components be able to withstand impacts from external objects.

4. Thermal Expansion Mismatch: The cost of attaching the duct to the turbine section is affected by the need for complicated designs to deal with thermally induced stresses resulting from thermal expansion mismatch between the components.

5. Density: The density of the materials has a direct bearing on the weight of the component. Weight reduction is a major goal of aircraft designers since it would result in fuel cost savings and increased aircraft manueverability.

6. Cost: Cost is an important attribute since engine designers always prefer a lower cost component, all else being equal.

Initial ranges of acceptable levels of these attributes were also established from the responses to the preliminary survey and are listed in Table 16.

Table 16: Initial Ranges and Attribute Levels

	Attribute	Units	Minimum	Maximum
1.	Operating Temperature	°C	750	1500
2.	Strength	ksi	10	60
3.	Toughness	$MPa\sqrt{m}$	10	60
4.	CTE mismatch	10^{-6}in/in/°F	0	8
5.	Density	g/cc	1.8	9
6.	Cost	$	1000	10000

6.2. Questionnaire

The questionnaire used in the interview process consists of several sections. First, the interviewee is asked to verify the relevance of the attributes included and the ranges of values for each. This is followed by a practice session to acquaint the interviewee with evaluation technique used in the questionnaire. For this study, the lottery equivalent method discussed in Chapter 4, was used. This method was selected because it seemed to more closely represent the kinds of decisions engineers in the field often confront. Design engineers are often faced with choices among new alternatives each of which promises a different outcome if successful, or necessitates the use of the old, proven technology if not. This is analagous to the lottery equivalent method. The remainder of the questionnaire is concerned with evaluating the multiattribute utility function and providing a consistency check for the responses. Part A presents lotteries aimed at obtaining single attribute utility values for each attribute. Part B uses the same technique to determine the scaling factors. Part C asks the interviewee to make direct tradeoffs as a possible means of validating the multiattribute utility results. For a complete copy of the questionnaire, see Appendix E.

6.3. Questionnaire Responses and Results

The interview process resulted in responses of several types. Responses in parts A and B were in the form of probabilities which made the two lotteries equivalent. These are easily turned into single attribute utility values and scaling coefficients, and are all that is required to develop the multiattribute utility function. Part C responses were in the form of dollar amounts which the interviewee would pay for various attribute levels, and only serve as a possible way to corroborate the utility results.

A discussion of the results of this study, leading to the comparison of the alternatives also requires the knowledge of the specific levels of the attributes for each alternative. Table 17 shows these levels for investment cast superalloys, and SiC/SiC composites made by the slurry infiltration and the chemical vapor infiltration techniques.

Table 17: Attribute Levels for the Three Alternatives [33],[34],[35]

	Attribute	Investment Cast Superalloy	Slurry Infiltrated SiC/SiC	CVI SiC/SiC
1.	Operating Temperature (°C)	800	1100 (800)	1400 (1000)
2.	Strength (ksi)	100	14 (21.4)	22 (29)
3.	Toughness (MPa√m)	60	30	30
4.	CTE Mismatch (10^{-6} in/in/°F)	0	7	7
5.	Density (g/cc)	8.9	2.5	2.5
6.	Cost ($)	1000	4635	9291

For the operating temperature and strength for SiC/SiC composites made by both methods, alternate temperatures and the material strength at those temperatures are given in parentheses. These values were obtained from tensile tests done by the material supplier at various temperatures.

Perhaps as important as any of the formal responses were the discussions of the attributes and general engine design principles which took place during the interview. Discussion of risk behavior had a direct bearing on the selection of a form for the single attribute utility functions. While discussions of general engine design and the actual process engineers use to design and select materials were not directly used in the analysis, it provided great insight into the materials substitution problem. Therefore, summaries of those discussions, as well as the utility analysis results are presented in the following sections. For a complete listing of the raw data from the multiattribute utility study for all participants, see appendix F.

6.3.1. Subject #1

Subject #1 had a problem with the nature of the attributes. He was much more concerned with the time dependence of properties, *i.e.* vibrational effects, fatigue and crack growth. However, for the case of a short life engine, such as one for a missile, he agreed that time dependence was not as relevant.

Of all the attributes, subject #1 thought toughness was irrelevant. He said the real concerns were impact resistance and crack growth, and that material toughness was not an accurate way to represent this. Again he was more concerned with time dependence and the cyclic crack growth rate.

He also had a problem with what "strength" means as a requirement for the part. Which strength is important, ultimate tensile strength, creep strength of yield strength? Instead, he felt more comfortable dealing with what he termed a "limiting strength", which in the case of exhaust ducts for short lifetime missile engine applications was likely to be the tensile strength.

For the coefficient of thermal expansion mismatch, he thought it was equally important to consider the thermal conductivity and the elastic modulus, since both of these determine how large the thermally induced stresses will be. For the purpose of this study, it was assumed that these other factors were constant (and that the moduli mismatch was relatively large in the single attribute tradeoff, so as to accentuate the importance of CTE mismatch). After some consideration, it was decided that although he was concerned with elastic modulus, this would not be included in the study because it has two competing effects. On the one hand, a high elastic modulus is beneficial in helping to deal with vibrational problems and stiffness deflections. On the other hand, if there are large coefficient of thermal expansion mismatches, then high elastic moduli contribute to the thermally induced stresses.

Subject #1 had only a minor concern regarding the weight of the part, in that dense materials provide greater damping of vibrations. But overall, he still thought this was minor compared to the advantages of weight savings. However, an exhaust duct is such a small percent of the engine's total weight, this effect is minimal.

For cost, he was most concerned with the size of the project in terms of its overall cost. Each project is not an individual entity, but rather a learning experience for the next. On a small project he might be more willing to take a risk. This is because in this case the loss would be relatively small, but if it all worked, the payoff would be large since it would alloy him to be confident with the new design in a larger project where the savings would be substantial. On the other hand, for a large project, the cost associated with a new design which did not work would be tremendous and thus the risk too great. Overall, for the scale of projects he was accustomed to, he was willing to take chances except in the region nearest to the worst possible outcome.

Subject #1 also spoke at length about other issues of importance in engine design. In terms of costs, he was more concerned with the Life Cycle Cost rather than the sell price of a part. More importantly, he considered the business to be one of selling engine time, *i.e.* $/hr of engine operation. He was also concerned with the issue of recovery of development costs since government projects often get cut prematurely.

Another area of interest for Subject #1 was probabilistic design, such as the use of Monte Carlo methods for determining the flaw populations and thus the "real world" strength of materials. He is also interested in simulations of reliability to reflect a probabilistic assessment of the engine operating requirements. Furthermore, he is interested in integrated design issues.

Table 18 give Subject #1's single attribute utility and scaling coefficient data.

Table 18: Utility Results: Subject #1

	Attribute	Utility	k_i
1.	Operating Temperature	U(1000°C) = .8	.4
2.	Strength	U(15 ksi) = .7	.2
3.	CTE Mismatch	U(4x10^{-6}in/in/°F) = .3	.8
4.	Density	U(6 g/cc) = .7	.2
5.	Cost	U($5000) = .75 U($7500) = .5	.4

Discussions with Subject #1 also yielded clues concerning his risk behavior with respect to each attribute. This information, combined with his single attribute utility responses, led to the selection of mathematical forms for his single attribute utility functions. Table 19 shows his risk behavior and the form selected for his single attribute utility functions for each attribute. [25]

Table 19: Risk Behavior & Utility Functionality: Subject #1

	Attribute	Risk Form	Form of the Utility
1.	Operating Temperature	Risk Averse	$U(x) = h + k\ln(x + b)$
2.	Strength	Risk Averse	$U(x) = h + k\ln(x + b)$
3.	CTE Mismatch	Risk Positive	$U(x) = a - b\exp(-cx)$
4.	Density	Risk Averse	$U(x) = h + k\ln(x + b)$
5.	Cost	Risk Averse	$U(x) = a+bx+c\ln(d-x)$

See Appendix F for the coefficients.

Employing these single attribute utility expressions, utility values, scaling coefficients and the data given in Table 17, multiattribute utility values were determined for each alternative and are listed in Table 20.

Table 20: Utility Rankings: Subject #1

	Material Alternative	Utility
1.	Investment Cast Superalloys	.9887
2.	SiC/SiC Composite via Slurry Infiltration	.8410
3.	SiC/SiC Composite via CVI	.6774

The substantial differences among the part costs for each alternative are likely to have a major effect on the utility results. Consequently, it may be of value to look at the effect of cost on these values. Figure 14 shows the effect of cost reductions on the utilities of each alternative. Utilities for costs greater than those predicted by the technical cost models are not included. Rather the utility of the alternative at the current cost is used in this case as a basis for comparison with the other alternatives. Accordingly, the utility of superalloys is given as a constant horizontal line indicating its current level.

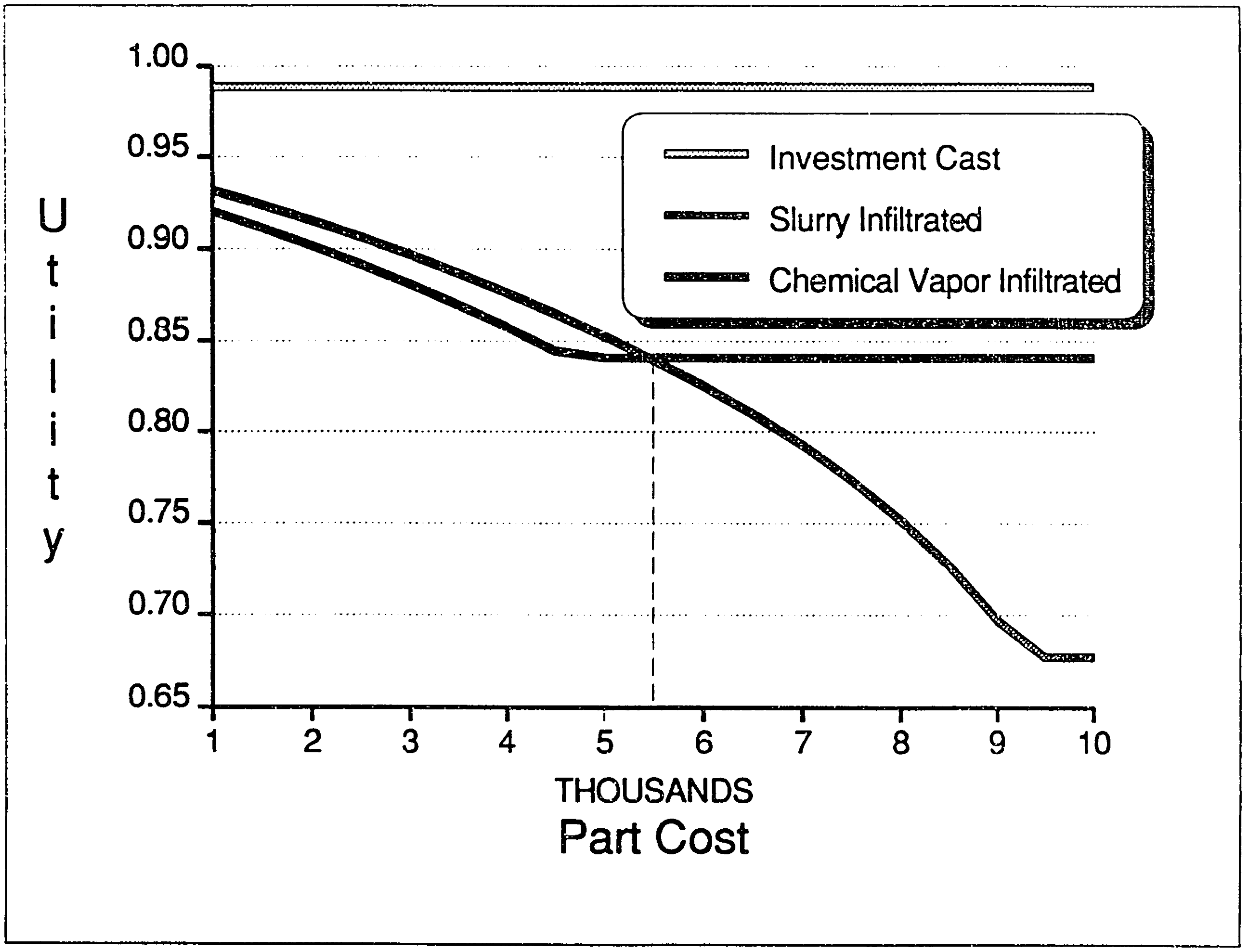


Figure 14: Utility as a Function of Cost: Subject #1

Figure 14 shows that regardless of the ability of ceramic matrix composite producers to lower their costs down to the minimum value included in this analysis, superalloys will still be the material of choice. This is most likely due to the problems encountered in dealing with thermal expansion mismatch between the new ceramic part and the superalloy component to which it must be attached. For example if there was no mismatch, the baseline utilities of slurry infiltrated and chemical vapor infiltrated SiC/SiC exhaust ducts would be .9787 and .9421, respectively, compared to their previous values of .8410 and .6774, respectively and .9887 for superalloys. This would make the ceramic matrix composite ducts more competitive with superalloy ducts. Subject #1 is concerned with the cost associated with attaching a ceramic matrix composite exhaust duct to a superalloy turbine section due to the high thermally induced stresses which would be present. In this case, ceramic matrix composite producers must not only introduce their product into the exhaust duct application, but also turbine applications. This may also require an extensive redesign of the engine.

While not necessarily able to surpass superalloys, the two ceramic matrix composites are equally desirable when the slurry infiltration composite costs $4635 and the chemical vapor infiltrated composite costs $5450. Part costs being equal, the chemical vapor infiltration technique is preferred to the slurry infiltration technique. It is only when the higher part cost associated with a chemical vapor infiltrated duct is included that a slurry infiltrated duct is preferred.

6.3.2. Subject #2

Interviews with subjects #2 and #3 occurred simultaneously, but each gave independent responses. However, it should be noted that the discussions and responses given by each participant affected the other's opinion, and accordingly, many, but not all, of their responses were identical.

Subject #2 felt a little uncomfortable dealing with exhaust ducts since most of his recent work concerned combustor liners. He thought combustor liners were another area where ceramic matrix composites held great promise. However, for the purpose of this study he limited his discussion to exhaust ducts, which he felt he was still qualified to analyze.

His main concern about all of the attributes was the duration of the application. He felt that a one time application with only a short lifetime (on the order of several hours) would have different requirements than a reusable or long duration engine. His responses all pertain to short life missiles.

He thought that strength requirements for the component would be very low since static components do not experience large stresses. Toughness also wasn't very important to him because he didn't see this component as critical.

In regards to thermal expansion mismatch, he expressed some concern with the effect of holes or gaps in the attachment. These could let cooler air into the hot section and cause large thermally induced stresses if there is a large CTE mismatch between the exhaust duct and the turbine section to which it is attached.

Density and weight reduction were important to Subject #2, but not absolutely critical. He was still much more concerned with operating at higher temperatures than reducing weight. This was mostly due to the engine size. For small engines, he did not consider engine weight to be substantial when compared to the weight of the missile's instrumentation.

Cost was considered to be the main driving factor, especially for expendable engines. He also considered reliability to be a factor in engine design.

Table 21 gives Subject #2's single attribute utility and scaling coefficient data.

Table 21: Utility Results: Subject #2

	Attribute	Utility	k_i
1.	Operating Temperature	U(1000°C) = .8	.8
2.	Strength	U(20 ksi) = .6	.4
3.	Toughness	U(15 MPa√) = .5	.1
4.	CTE Mismatch	U($4x10^{-6}$in/in/°F) = .4	.1
5.	Density	U(6 g/cc) = .6	.15
6.	Cost	U($5000) = .5 U($7500) = .3	.8

Subject #2's responses did not indicate a clear pattern of risk behavior. In some cases, such as operating temperature, strength and toughness, he was risk averse. For other attributes, such as CTE mismatch and density, he was risk positive (although only slightly risk positive in the case of CTE mismatch). Furthermore, when considering cost, his risk behavior varied across the range of values. Table 22 shows subject #2's risk behavior and the mathematical form used for his single attribute utility functions.

Table 22: Risk Behavior & Utility Functionality: Subject #2

	Attribute	Risk Form	Form of Utility
1.	Operating Temperature	Risk Averse	$U(x) = h + k\ln(x + b)$
2.	Strength	Risk Averse	$U(x) = h + k\ln(x + b)$
3.	Toughness	Risk Averse	$U(x) = h + k\ln(x + b)$
4.	CTE Mismatch	Risk Positive	$U(x) = a + b\exp(-cx)$
5.	Density	Risk Positive	$U(x) = a + b\exp(-cx)$
6.	Cost	Varying	$U(x) = a+bx+cx^2+dx^3$

See Appendix F for the coefficients.

The single attribute utility functions, scaling coefficients and material property data were used to determine subject #2's utility for each alternative. These results are given in Table 23.

Table 23: Utility Rankings: Subject #2

	Material Alternative	Utility
1.	Investment Cast Superalloys	.9551
2.	SiC/SiC Composite via CVI	.8929
3.	SiC/SiC Composite via Slurry Infiltration	.8853

Figure 17 shows the effect of cost on the utilities of each alternative. Utilities are only considered to vary with cost decreases from the baseline values determined using the technical cost models, since higher costs should not be necessary.

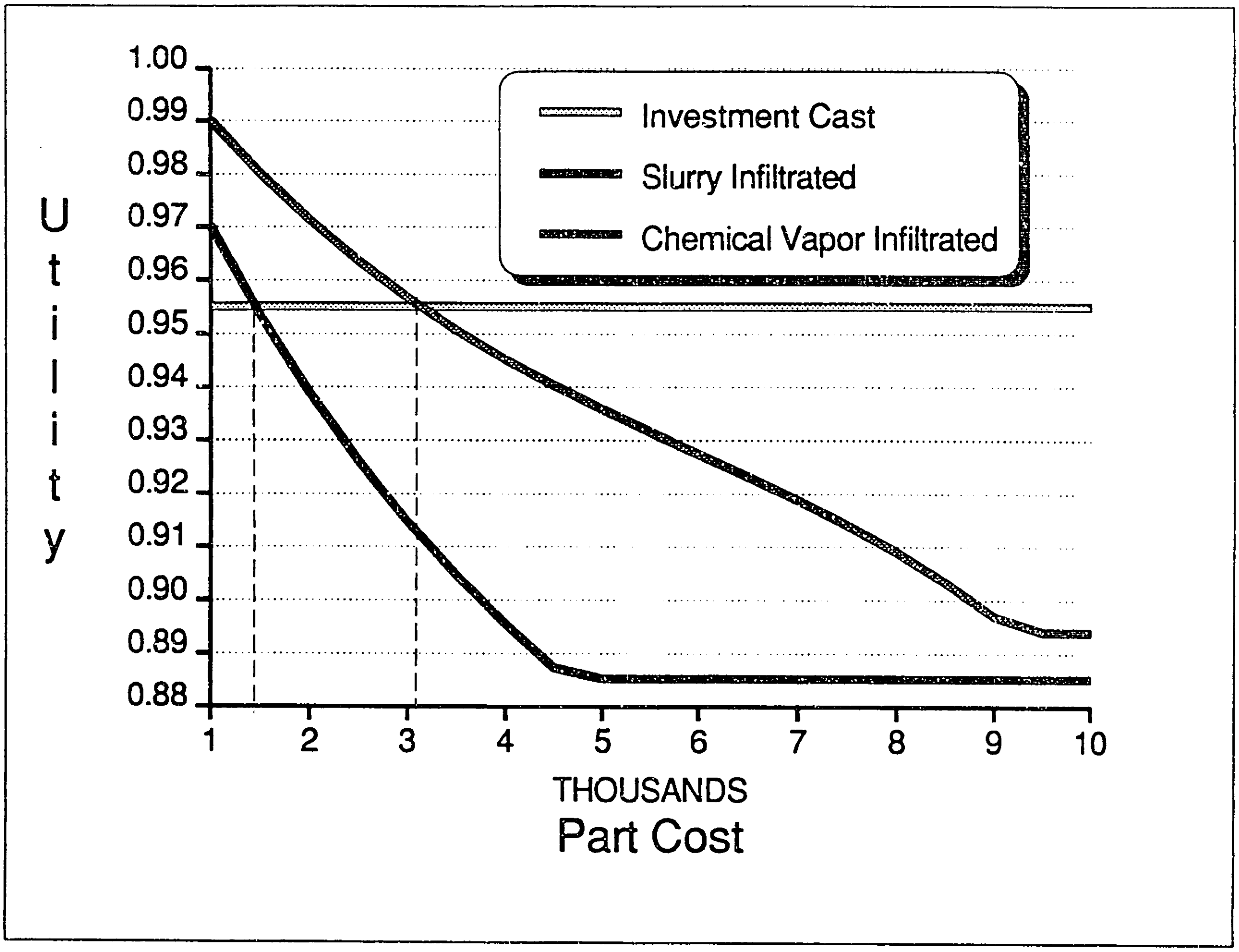


Figure 15: Utility as a Function of Cost: Subject #2

From Figure 15, costs at which the alternatives are equally valued can be determined. Slurry infiltrated SiC/SiC composites must cost no more than $1450 while chemical vapor infiltrated SiC/SiC composites can cost no more than $3180 in order to compete with the superalloy ducts currently available. Furthermore, unless the cost of producing an exhaust duct using the slurry infiltration technique can be reduced to $4150, they will not be competitive with those made by chemical vapor infiltration.

6.3.3. Subject #3

Subject #3 was also more familiar with other engine components, such as combustor lines, but still felt qualified to make decisions concerning exhaust ducts.

Subject #3 thought that operating temperature was a very important attribute due to its effect on the operating conditions of the engine. He also felt that cost was a major driving force in materials selection for any application. In addition, he said that it was important to specify other conditions which applied to the engine application. Engine life was considered to be important since short life engines have less stringent requirements. He also thought that vendor selection was a major issue since delays in the delivery of parts could be very costly.

He felt that toughness was not a very important attribute. If anything it should be used strictly as a tie breaker. He thought that the units of measuring toughness were meaningless. Furthermore, for certain materials, such as continuous fiber reinforced composites, toughness is a meaningless property. However, toughness might be relevant for whisker reinforced ceramic matrix composites.

Thermal expansion mismatch was considered to be little more than an annoyance. He said he valued zero mismatch. However, above that he would have to design an interface between the components. Although this is easily accomplished, there is a cost associated with this design. He did not feel that there was very much difference between designing for a small and large CTE mismatch, since the additional costs arise form the cost of making a new design, not the cost of implementation.

Subject #3 felt that density was important since engine design is often performance driven. However, for small engines, weight, and therefore density is often not critical.

Cost is another major consideration. He said that while many projects are performance driven, the engine still must be cost effective, especially in the case of missile applications where the engine is not reusable.

Table 24 gives Subject #3's single attribute utility and scaling coefficient data.

Table 24: Utility Results: Subject #3

	Attribute	Utility	k_i
1.	Operating Temperature	U(1000°C) = .7	.6
2.	Strength	U(20 ksi) = .6	.35
3.	Toughness	U(15 MPa√) = .5	.1
4.	CTE Mismatch	U(4x10^{-6}in/in/°F) = .4	.1
5.	Density	U(4 g/cc) = .6	.5
6.	Cost	U($5000) = .5 U($7500) = .2	.7

As was the case for Subject #2, Subject #3's responses did not indicate a single risk pattern. He was risk averse for the first three attributes (operating temperature, strength and toughness), but risk prone for the other three (CTE mismatch, density and cost). Table 25 shows Subject #3's risk behavior and the forms selected for his single attribute utility functions.

Table 25: Risk Behavior & Utility Functionality: Subject #3

	Attribute	Risk Form	Form of Utility
1.	Operating Temperature	Risk Averse	$U(x) = h + k\ln(x + b)$
2.	Strength	Risk Averse	$U(x) = h + k\ln(x + b)$
3.	Toughness	Risk Averse	$U(x) = h + k\ln(x + b)$
4.	CTE Mismatch	Risk Positive	$U(x) = a + b\exp(-cx)$
5.	Density	Risk Positive	$U(x) = a + b\exp(-cx)$
6.	Cost	Risk Positive	$U(x) = a+bx+cx^2+dx^3$

See Appendix F for the coefficients.

Once again property data from Table 17 were applied to the single attribute utility functions and the results were combined using the scaling coefficients to obtain multiattribute utility values for each alternative. These results are given in Table 26.

Table 26: Utility Rankings: Subject #3

	Material Alternative	Utility
1.	Investment Cast Superalloys	.9044
2.	SiC/SiC Composite via Slurry Infiltration	.8634
3.	SiC/SiC Composite via CVI	.8237

Figure 16 shows the utility of each alternative at varying cost levels. In all three cases, costs are assumed only to decrease from the levels predicted by the technical cost models. At higher costs, the current utility values are used.

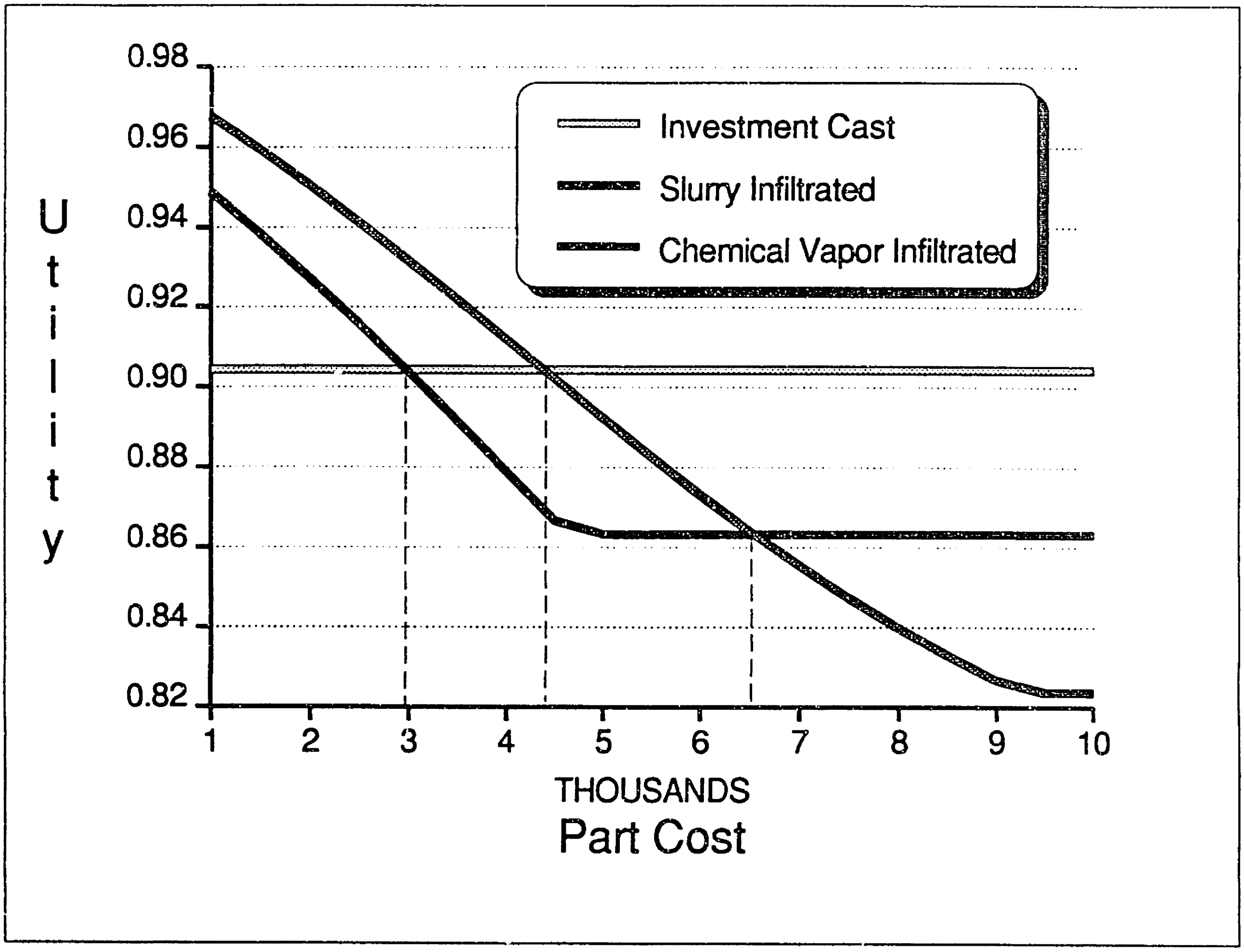


Figure 16: Utility as a Function of Cost: Subject #3

From Figure 16, crossover points, where alternatives are equally valued can be determined. A reduction in the cost of producing the duct from a SiC/SiC composite by the slurry infiltration technique to $2975 would make Subject #3 indifferent to the choice between it and the currently employed investment cast superalloy duct. Similarly, a cost reduction for the chemical vapor infiltrated composite to $4390 would also make Subject #3 indifferent to the choice between it and the current superalloy duct. The two ceramic matrix composite components are equally valued if the cost of the chemical vapor infiltrated part is reduced to $6550. Part costs being equal, the chemical vapor infiltration technique is preferred to the slurry infiltration technique. It is only when the higher part cost associated with a chemical vapor infiltrated duct is included that a slurry infiltrated duct is preferred.

6.3.4. Subject #4

Subject #4 thought that the tradeoffs asked about in the questionnaire were for the most part very reasonable. He stressed that while cost is a factor, usually design is performance driven. He thought toughness was an all or nothing issue, and therefore would not generally be traded unless some minimum is absolutely guaranteed. Instead, he thought this might be a tie breaker. This was reasonably well portrayed by his questionnaire responses, which gave toughness a relatively low scaling coefficient and also gave a single attribute utility function which was very steep at values of toughness just above the minimum. This was presumably because he would greatly value the added reliability of being a little above the minimum, but beyond that had no value for increased toughness.

Subject #4 also indicated that strength was not very important in this application, since exhaust ducts experience very little mechanical stress. He has some concern for low cycle fatigue, but this was not very great in the case of a missile engine, which is essentially a "one shot" deal.

He also spoke of the importance of reliability, and his desire to contract with several suppliers to ensure continued access to the best ducts. When he was told that for the purpose of this study, he was restricted to one supplier, he indicated his discomfort with the risk (*i.e.* risk aversion).

Table 27 gives subject #4's single attribute utility and scaling coefficient data.

Table 27: Utility Results: Subject #4

	Attribute	Utility	k_i
1.	Operating Temperature	U(1000°C) = .8	.6
2.	Strength	U(30 ksi) = .6	.7
3.	Toughness	U(30 MPa$\sqrt{}$) = .9	.4
4.	CTE Mismatch	U($4\text{x}10^{-6}$in/in/°F) = .6	.6
5.	Density	U(6 g/cc) = .6	.6
6.	Cost	U(\$5000) = .6	.6
		U(\$7500) = .4	

Subject #4's responses indicated that he was risk averse for all of the attributes. Furthermore, for all attributes except cost, he appeared to be decreasingly risk averse with increasing utility. That is to say, he was very unwilling to take a chance if the result could possibly be an extremely poor outcome. He was more willing to take risks, but still averse, if the possible negative outcome was not too bad. In the case of cost, an additional utility point was determined in order to get a more accurate picture of the shape of this utility function. While the subject indicated risk aversion over the entire range of value, the aversion did not change monotonically with utility. As a result, a third order polynomial was fitted to his responses to give a risk averse utility function that at some points showed increasing, and at other points showed decreasing risk aversion. Table 28 shows subject #4's risk behavior and the form of the mathematical expression fitted to his utility responses for each attribute.

Table 28: Risk Behavior & Utility Functionality: Subject #4

	Attribute	Risk Form	Form of Utility
1.	Operating Temperature	Risk Averse	$U(x) = h + k\ln(x + b)$
2.	Strength	Risk Averse	$U(x) = h + k\ln(x + b)$
3.	Toughness	Risk Averse	$U(x) = h + k\ln(x + b)$
4.	CTE Mismatch	Risk Averse	$U(x) = h + k\ln(x + b)$
5.	Density	Risk Averse	$U(x) = h + k\ln(x + b)$
6.	Cost	Risk Averse	$U(x) = a + bx + cx^2 + dx^3$

See Appendix F for the coefficients.

Incorporation of these functions and the scaling coefficients into a multiattribute utility function, combined with the use of the data given in Table 17 yielded utility values for each of the alternatives. These utility values are listed in Table 29.

Table 29: Utility Rankings: Subject #4

	Material Alternative	Utility
1.	Investment Cast Superalloys	.9846
2.	SiC/SiC Composite via CVI	.9339
3.	SiC/SiC Composite via Slurry Infiltration	.9059

Figure 17 shows the effect of cost reductions on the utilities of each alternative. Utilities for costs greater than those predicted by the cost models are not included. Rather, the utility of the alternative at the current cost is used as a basis for comparison with the other alternatives.

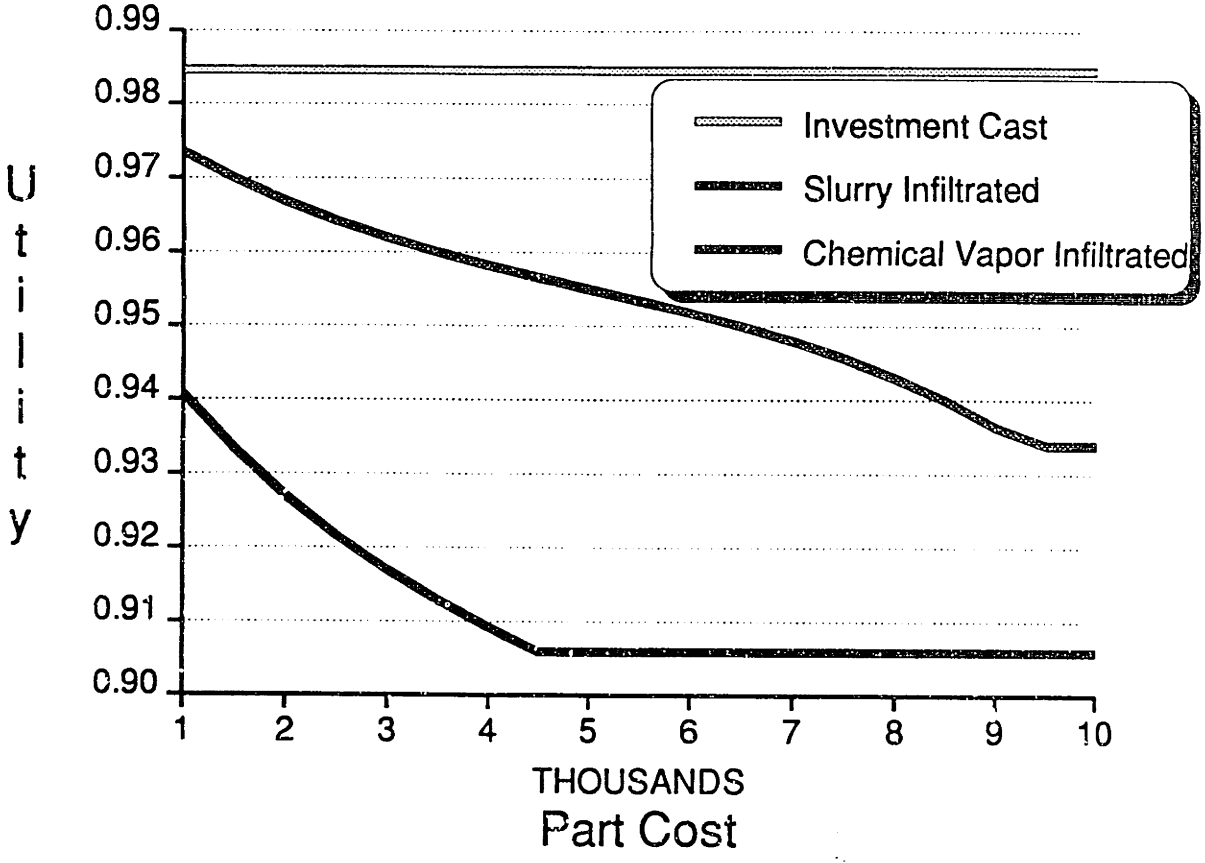


Figure 17: Utility as a Function of Cost: Subject #4

Figure 17 indicates that subject #4's ranking of the alternatives will remain regardless of any cost reductions with respect to the ceramic matrix composite technologies. This is due to the importance that he places on strength and CTE mismatch, the two attributes other than cost where superalloys have a substantial advantage over ceramic matrix composites. In the case of strength, his minimum acceptable value of 20 ksi eliminates the use of a slurry infiltrated SiC/SiC composite at 1100°C, since at this temperature its strength is only 14 ksi. However, at only 800°C, slurry infiltrated SiC/SiC composites have strengths of 22 ksi, above subject #4's minimum strength level. The alternate operating temperature and strength values given in Table 17 were used when calculating subject #4's utility for a slurry infiltrated SiC/SiC composite. Clearly this reduction in temperature played a major role in subject #4's utility results. One of the primary reasons for the consideration of ceramic matrix composites in engine components is their high temperature capabilities. In this case the ceramic matrix composite offers no significant advantage, at a large cost and significant reduction of other properties.

6.3.5. Subject #5

Subject #5 felt that the attributes selected represented some of his main considerations, but did not encompass a complete set of design criteria. Other attributes he expressed concern over were oxidation and chemical resistance, and the stage of development of the new material and its track record. The issues of track record and stage of development are not the focus of the multiattribute study, but will be touched upon in the next section of this study. It is inappropriate to consider either of these things in the multiattribute utility analysis since the goal of this technique is to produce a materials blind basis for comparing alternatives.

Subject #5 had difficulty responding to questions concerning the maximum operating temperature. He said that design was done for a specific temperature requirement, and, thus alternatives with lower temperature capabilities were unacceptable. However, when the question was rephrased to present a choice between a current acceptable duct and one in development with a chance of improved or diminished temperature capabilities, he was able to respond. This change in scenario involved a switch from the lottery equivalent to the certainty equivalent method. This change in measurement technique may introduce some inconsistencies. However, the results seemed to be consistent with the rest of the interview. He did not experience this same problem with any of the other attributes or when determining scaling coefficients. Consequently, the lottery equivalent method was used for the reminder of the interview.

Design considerations were thought to be important in evaluating part strength. He greatly valued small increased above the minimum acceptable level since this would allow for a great deal of design flexibility. Beyond that he did not value much extra strength.

Subject #5 considered toughness to be a critical parameter. Even though it is not used in component design, good material toughness gives the designer increased confidence in the component. He believed that it was important to limit the chances of a catastrophe occuring, although this consideration is not as crucial for exhaust ducts as it is for other engine components.

Thermal expansion mismatch was not considered to be very important, even for materials with a low thermal conductivity and a high elastic modulus which would exacerbate the thermally induced stresses. This is because he felt that thermal stress would probably not be too great. However, low thermal expansion mismatches reduce the need for complex attachment design and thus have a direct, if not somewhat limited, effect on cost.

Subject #5 considered density to be important because the resulting weight savings would decrease fuel consumption, reduce the need for support hardware and increase the maneuverability of the missile. A reduction in the need for support hardware would result in savings in production costs as well as additional weight savings and the accompanying fuel cost savings. Furthermore, he thought that density was an important consideration for medium and large engines, but not as critical for small engine applications.

As for cost, Subject #5 felt that there was a very real potential for cost decreases among the more expensive material alternatives, and thought this to be necessary in order for these materials to be competitive. along these lines, he said that hew was very unwilling to take risks which might result in substantial cost increases, thus indicating that he was risk averse with regard to cost.

Table 30 gives Subject #5's single attribute utility and scaling coefficient data.

Table 30: Utility Results: Subject #5

	Attribute	Utility	k_i
1.	Operating Temperature	$U(1000^\circ C) = .6$	.4
2.	Strength	$U(30\ \mathrm{ksi}) = .9$	.4
3.	Toughness	$U(30\ \mathrm{MPa}\sqrt{\ }) = .7$	.4
4.	CTE Mismatch	$U(4 \times 10^{-6} \mathrm{in/in/^\circ F}) = .8$	.4
5.	Density	$U(7\ \mathrm{g/cc}) = .6$	.4
6.	Cost	$U(\$9000) = .5$	.7

The discussion with Subject #5 and his utility responses indicated that he was risk averse for all of the attributes considered. Furthermore, he exhibited decreasing risk aversion with increasing utility for all of the attributes. Table 31 shows his risk behavior and the form of utility function chosen for each attribute.

Table 31: Risk Behavior & Utility Functionality: Subject #5

	Attribute	Risk Form	Functionality of Utility
1.	Operating Temperature	Risk Averse	$U(x) = h + k\ln(x + b)$
2.	Strength	Risk Averse	$U(x) = h + k\ln(x + b)$
3.	Toughness	Risk Averse	$U(x) = h + k\ln(x + b)$
4.	CTE Mismatch	Risk Averse	$U(x) = h + k\ln(x + b)$
5.	Density	Risk Averse	$U(x) = h + k\ln(x + b)$
6.	Cost	Risk Averse	$U(x) = h + k\ln(x + b)$

See Appendix F for the coefficients.

Once again, these utility functions were used along with the scaling coefficients and material property data given in Table 17 to determine utility values for each alternative. The alternatives and their utilities are listed in decreasing order in Table 32.

Table 32: Utility Rankings: Subject #5

	Material Alternative	Utility
1.	Investment Cast Superalloys	.9610
2.	SiC/SiC Composite via Slurry Infiltration	.9472
3.	SiC/SiC Composite via CVI	.9115

Figure 18 shows the effect of cost on the utilities of each attribute. At costs greater than those predicted by the technical cost models, the current cost estimate is used. This provides a basis for comparison with the other alternatives.

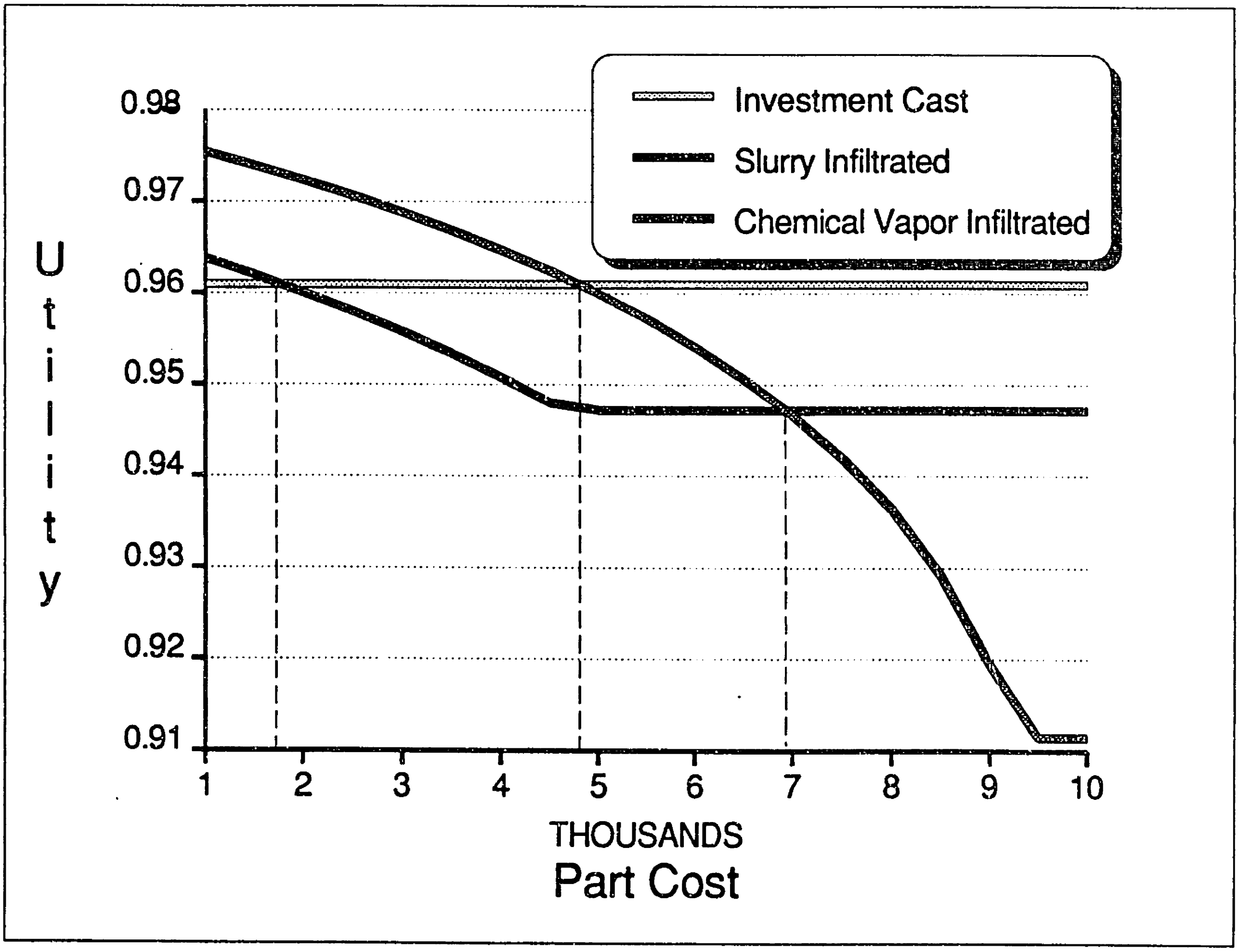


Figure 18: Utility as a Function of Cost: Subject #5

From Figure 18, costs at which the alternatives are equally valued can be determined. Slurry infiltrated SiC/SiC composite exhaust ducts must cost no more than $1750, while chemical vapor infiltrated SiC/SiC composite exhaust ducts can cost no more than $4800 in order to compete with the currently used superalloys. Furthermore, while still considered "inferior" to superalloys, the two ceramic matrix composites are equally desirable when the composite which was produced by the slurry infiltration technique costs $4635 and the one produced by the chemical vapor infiltration technique cost $6940.

6.3.6. Subject #6

Subject #6 was unwilling to complete a survey. He said that these kind of tradeoffs are not done when designing engines. Instead, there are specific requirements which must be met.

If offered an improved duct, which could be perfectly retrofitted for less money, he would be unwilling to switch. This is due to the costs of certification. He was very unwilling to ignore this cost, even just for the sake of argument. He was also unwilling to view the project as a new engine which still needed to be certified regardless of his choice of exhaust duct. He said that in this case, design criteria would be dictated by the requirements of the engine and the enabling technologies. This involves satisfying the most difficult materials requirement of the engine with a cutting edge material. From then on, the requirements for all other parts "are determined exactly by engineering calculations." Materials which can satisfy these requirements are then selected. No performance levels need to be traded, except possibly cost and weight, for a part which satisfies the performance requirements. However, he did agree that certain properties were not independent (utility dependent) and thus it was important to do the proper tradeoffs. The tradeoffs were based strictly on the properties of the material (*i.e.* in composite systems he would trade in-plane strength for interlaminar strength). He also recognized that several properties could be traded when considering the thermal shock properties of the part. In this case he indicated that the following properties were all important: maximum operating temperature, interlaminar strength, thickness, elastic modulus and thermal conductivity. These were especially important in the case of exhaust ducts because mechanical stresses are relatively small compared with thermally induced stresses.

Subject #6 also broke down engine projects into several classifications; commercial, military transports and trainers, military fighters and unmanned aircraft. He considered each of these to have different driving forces when designing an engine. For commercial applications, as well as military transports and trainers, the driving force is a life cycle cost. This includes not only the initial cost of the engine or engine part, but also the maintenance and operation costs. However, this is not true in the case of military fighters. While cost is important here, performance is still the biggest consideration. Unmanned aircraft (*i.e.* missiles) can be further broken down into two categories, tactical and strategic. Tactical missiles, those directly used in a battle situation, are designed to be low cost since their success is not critical. On the other hand, for strategic missiles, the overriding concern is reliability.

6.4. Multiattribute Conclusions and Limitations

The multiattribute utility analysis provided a quantitative evaluation of each of the three materials alternatives for each participant in this study. Some general trends were apparent from these results. Superalloys were preferred to the ceramic matrix composites by all five subjects. A more detailed discussion of these trends is given in Chapter 8.

The results obtained from the multiattribute utility analysis are based on the participant's trade-offs of the attributes investigated in this study. Attribute levels for each of the three material alternatives were then used to obtain multiattribute utility values. However, as was already discussed in Chapter 4, these attribute levels may not be valid, especially for new, unproven materials. In some cases, attribute levels in an application may vary widely from those reported in the laboratory. Also, engine designers simply may not have confidence in the reported attribute levels. Instead, they may base their material selection decisions on their own perceptions of what these attribute levels should be.

7. Subjective Probability Assessment

The results of the multiattribute utility study presented in chapter 6 indicate the value each engine designer places on each of three sets of attribute levels. If each set of attribute levels accurately represents the properties exhibited by a material used in the exhaust duct application, then the MAUA results also represent the value of each alternative. However, in some cases it is difficult to determine the exact levels of the attributes in the application of interest. Reported test values for materials may vary greatly from those experienced in practice. Furthermore, engine designers are aware of the discrepancies in property data and often take it into account when selecting a material. This being the case, the use of reported data in the multiattribute utility analysis will yield incorrect evaluations of the alternatives. Instead, the property values perceived by the designer should be used. The accuracy of these perceptions is irrelevant since it is these perceived attribute levels which the desginer uses when selecting a material. The problem then is how to determine these perceived attribute levels.

Subjective probability assessment can be used to determine the credibility which an engine designer places on the values reported for a given material. Instead of a single value, a probability distribution describing the likelihoods of the material possessing all values of a given attribute is obtained. Determination of these probability distributions for each relevant attribute for each alternative can achieved through the use of a questionnaire or interview.

7.1. Subjective Probability Assessment Technique

Subjective probability assessments were conducted interactively with the use of a questionnaire. Some interviews were conducted in person, while others took place on the telephone. The questionnaire considered only two of the three material alternatives investigated in this study, SiC/SiC composites via both the slurry infiltration and chemical vapor infiltration techniques. Probability distributions for attribute levels of investment cast superalloys were not determined since reliable data is available in this case. Furthermore, only three of the six attributes used in the multiattribute utility analysis were considered; operating temperature, strength and toughness. The coefficient of thermal expansion mismatch and the density of the material are both easily measured and do not vary with the application. Consequently, reported laboratory test values accurately represent these properties in applications. Cost was excluded because it is usually specified in a contract and is not subject to variations from the stated amount.

The questionnaire contained a brief description of the technique and the questions to be answered, followed by a section for each of the two material atlernatives. These sections contained a brief description of the material and the process by which it was made, followed by a list of its reported property data. Three questions were then asked to determine the probability distribution. The decision maker was asked to identify property values for which he thought there was a 10%, 50% and 90% chance of the alternative minimally possessing.

7.2. Data Analysis

Probability distribution curves were fitted to the three data points obtained for each attribute. Literature on subjective probability assessment did not give guidelines for appropriate probability distributions. Often data is left in raw form or used to produce histograms of results. However, in this case it was necessary to obtain a mathematical representation of the distribution in order to combine it with the results of the multiattribute utility analysis. Basic statistics arguments were used to choose a distribution which best represented the behavior of the subject. [36] A normal distribution provided the least biased interpretation of the data. However, in several cases, the mean was skewed away from the center of the distribution. To accommodate this assymmetry, the sum of two normal distributions was used. An equation describing this distribution is given below.

$$p(x) = 0.5*\exp[-((x-a)/b)^2] + 0.5*\exp[-((x-c)/d)^2]$$

where a, b, c, and d are undetermined coefficients to be fitted to the data. Figure 19 provides a schematic of the sum of two normal distributions.

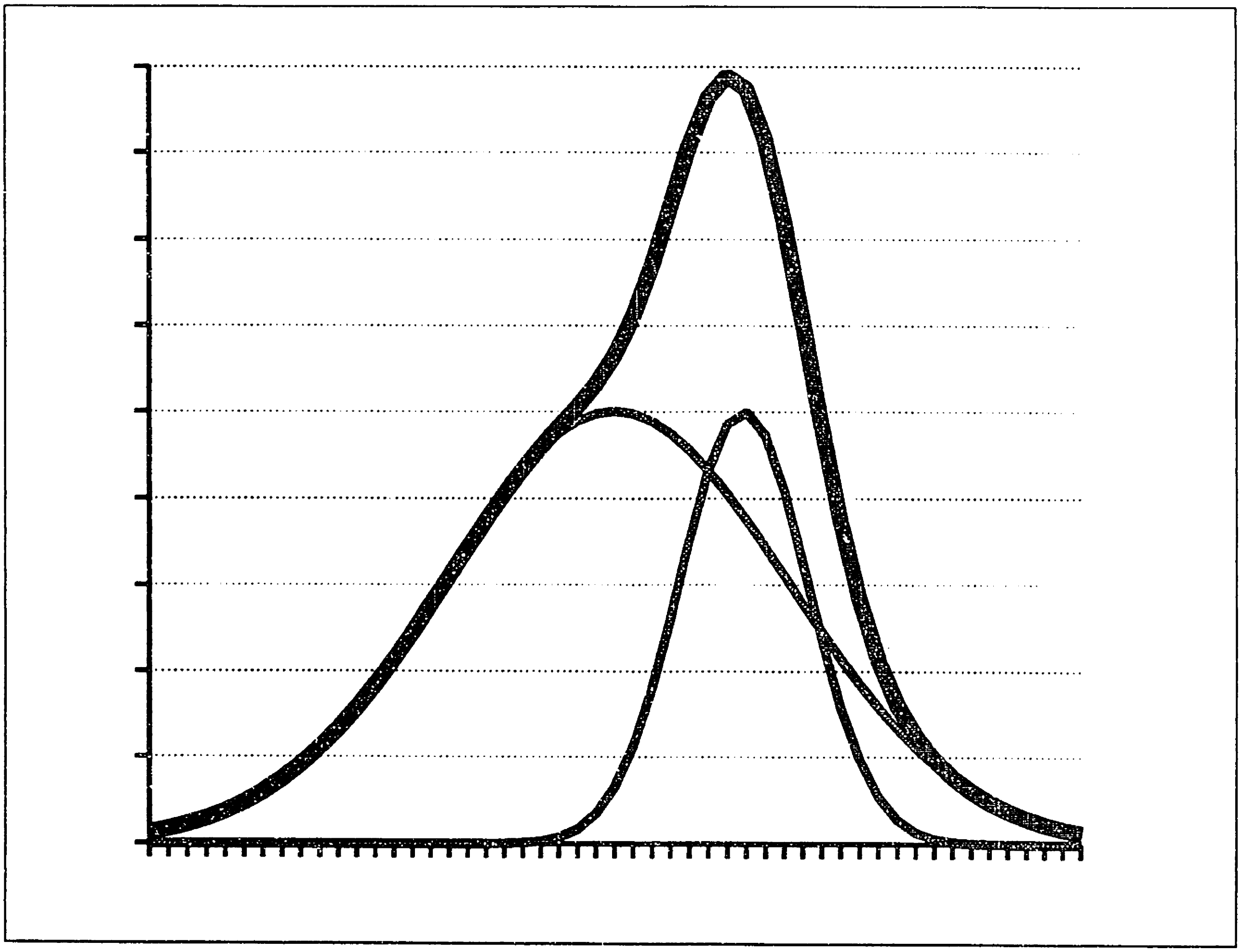


Figure 19: Sum of Two Normal Distributions

A normal distribution occurs when the 50% confidence value lies at the midpoint of the two extremes. In this case the coefficients a and c are identical and equal the mean. The coefficients b and d are also identical and can be determined exactly using standard normal probability distribution tables. [36] When the 50% confidence value does not coincide with the midpoint of the two extremes, no unique solution for the four undetermined coefficients exists. This is because only three data points have been found. Instead, an appropriate value for the coefficient a can be chosen and the other coefficients determined to fit the data. The selection of a is limited to certain values. The means of the two normal distributions must lie on opposite sides of both the midpoint between the two extremes and the 50% confidence value. Accordingly, the coefficient a cannot lie between these two values. Furthermore, it must be carefully chosed so that the resulting probability density function is not bimodal. If the means of the two normal distribution lie too far apart compared to their standard deviations, there will be a region in the middle of the distribution where the probabilities are uncharacteristicly low. While this is a valid distribution and satisfies the three data points, it in not representative of the perceptions of the decision maker. As a result, the coefficient "a" should be chosen close to the midpoint of the range of values in order to ensure a probability distribution which has only a single local maximum. Once the other coefficients are determined, the distribution should be checked to make certain that it is not bimodal.

Once the coefficient "a" is selected, the function can be solved numerically for the other coefficients. This was done using an interative technique described below.

Iterative Method of Solving for Undetermined Coefficients:

1. Choose "a" close to, but less than the midpoint of the extremes if the mean is greater than the midpoint (or close to, but more than the midpoint if the mean is less than the midpoint).

2. Find "b" such that the first data point is satisfied.

3. Find the areas under the probability distribution up to each of the other two data points.

4. Find "c" and "d" such that the area under the probability distribution up to the last two data points is now equal to their probability levels, 0.5 and 0.9.

5. Find the area under the probability distribution up to the first data point. If this equals the probability level of that data point, then the solution is found. If not, go to step #2 and repeat.

After finding the probability distribution functions, single attribute utilities were determined by integrating the product of the utility and the probability over the range of values for the attribute. These new utilities were then used in the multiattribute utility analysis instead of those based on the reported attribute levels. For a complete listing of the probability distributions for each participant in this study, see Appendix H.

7.3. Subjective Probability Assessment Responses and Results

Using the probability distributions and the resulting new single attribute utility values, new multiattribute utilities and rankings were found for each participant in the study. Furthermore, costs at which the alternatives are equally valued were determine given these new results. Only three of the five subjects in the original multiattribute utility study were used for this analysis. One participant was excluded because he no longer works in engine design, and now is employed by a material supplier. It was felt that his responses in this analysis would be reflective of his current position as a material supplier and not of an engine design engineer. Another subject felt that he was unable to answers questions concerning the SiC/SiC composites since his area of expertise was metallurgy and thus he was very unfamiliar with ceramic matrix composites.

7.3.1. Subject #1

Subject #1 felt that these questions were only relevant to two attributes; operating temperature and strength. He already eliminated toughness from consideration in the multiattribute portion of this study, and thus it was unnecessary to deal with it here. For the operating temperature and strength of both materials, he felt that there was little reason to disbelieve any of the reported values since they all seemed plausible. He did feel that there was some statistical chance of the values varying from the reported levels and his repsonses indicated the extent of these variations.

The incorporation of the subjective probability data into subject #1's multiattribute utility analysis resulted in relatively small changes in his overall utilities and consequently did not effect his ranking of the alternatives. This can be explained by the low scaling coefficients he assigned to the two attributes for which subjective probability data was collected (.4 for operating temperature and .2 for strength), as well was the fact that his single attribute utility functions in the region around the reported attribute levels are relatively flat. This means that small fluctuations in the attribute level will result in very small changes in utility. Furthermore, his single attribute utility values did not change very much since he found the reported values to be believable. Table 33 shows Subject #1's single attribute and multiattribute utilities for each ceramic matrix composite with and without the use of his subjective probability data.

Table 33: Utility Changes Due to Subjective Probability Data: Subject #1

		Slurry Infiltrated		Chemical Vapor Infiltrated	
	Attribute	with SPA	w/o SPA	with SPA	w/o SPA
1.	Operating Temperature	.8587	.8611	.9666	.9736
2.	Strength	.7239	.6529	.8551	.8884
	Overall	**.8146**	**.8410**	**.6731**	**.6774**

While these changes do not effect the current ranking of the alternatives, they do effect the costs at which the alternatives are equal. As before, investment cast superalloys are superior, regardless of cost savings by the ceramic matrix composite producers. However, SiC/SiC exhaust ducts produced by the chemical vapor infiltration technique experienced only a very small decrease in utility relative to that experienced by the SiC/SiC duct made by the slurry infiltration technique. In this case, the cost of a duct made by chemical vapor infiltration must only be reduced to $6300 in order to compete with ducts made by slurry infiltration. Figure 20 shows Subject #1's utility as a function of cost reductions for each of the alternatives when the subjective probability data is used.

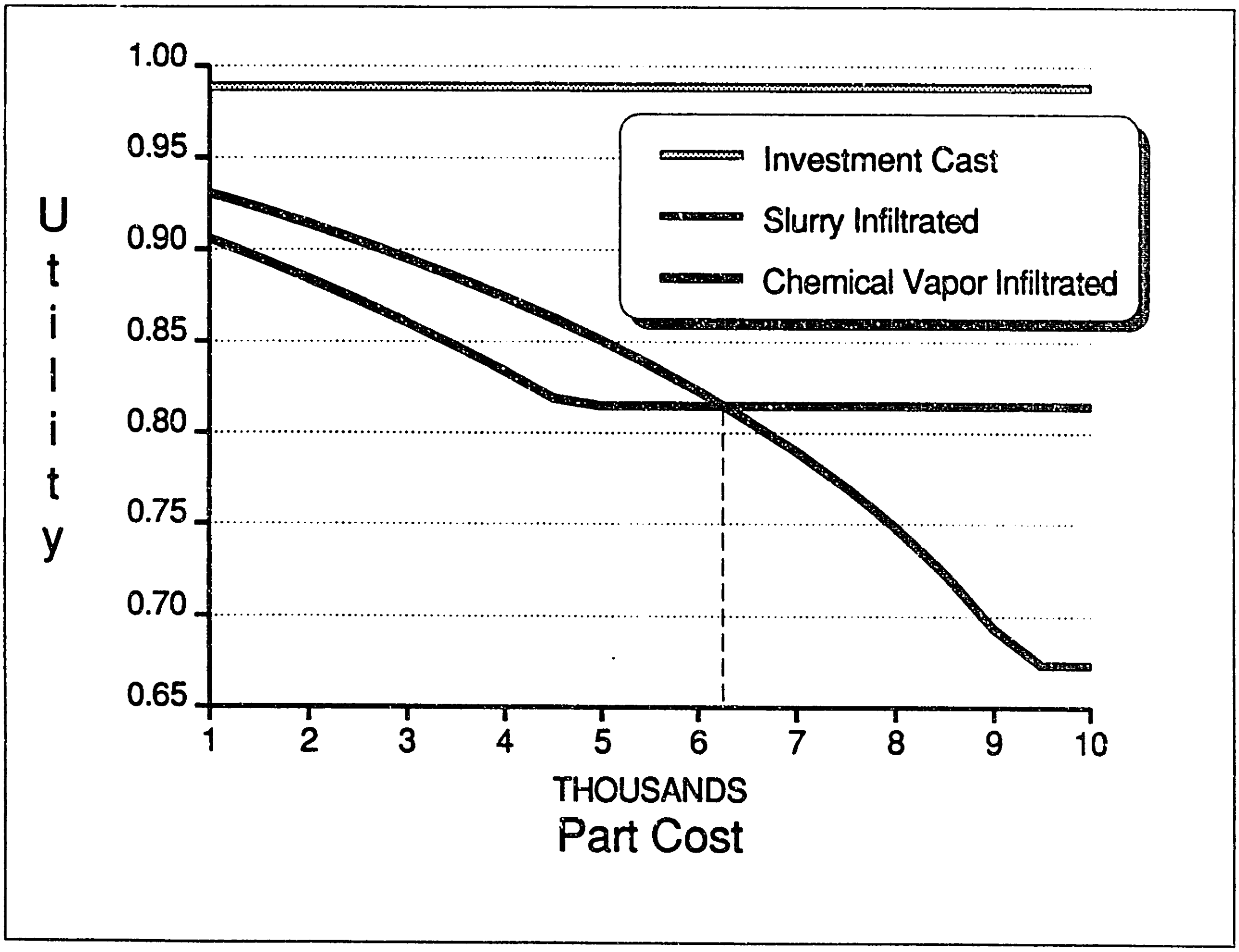


Figure 20: Utility vs. Cost with Subjective Probability Data: Subject #1

7.3.2. Subject #2

Subject #2 and #3 collaborated on their responses to the questions asked in the subjective probability assessment survey. However, because they displayed different preferences in the multiattribute utility analysis, their subjective probability assessment results have somewhat different consequences.

While both subjects felt that the information given for the operating temperature for both ceramic matrix composites were reasonable, they were not as comfortable with the data for strength and toughness. They thought the reported strength values were very low, especially in the case of the slurry infiltrated ceramic matrix composite. This was presumably caused by fiber damage during processing. They believed that, within a short period of time, materials suppliers would overcome some of the problems they are currently experiencing and would achieve higher strengths, even at elevated temperatures. This was well represented by their responses which placed a mean value for strength at 30 ksi for slurry infiltrated and 32 ksi for chemical vapor infiltrated SiC/SiC composites. For toughness they thought the values were possible but somewhat optimistic, and gave both ceramic matrix composites only a 50% chance of having the reported 30 $MPa\sqrt{m}$ in a given component.

The use of single attribute utility data obtained from subject #2's probability distribution not only affected his single and multiattribute utilities for the two composite materials, but also altered his ranking of them. Now at the projected cost, slurry infiltrated SiC/SiC exhaust ducts are preferred to those made by chemical vapor infiltration. For both alternatives, his single attribute utilities for strength increased greatly. This is because he felt confident that the material supplier could easily improve upon the current strength.

On the other hand, for toughness his single attribute utilities dropped for both alternatives. This was mostly due to the fact that the reported values were at the uppper limit of the utility scale and the probabilistic increases in toughness are of no additional value, while probabilistic decreases will result in lower utility. Furthermore, he believed the reported data to be somewhat inflated and thus his utility is lower.

His single attribute utility for operating temperature showed a slight decrease for both alternatives. This is due to the shape of his utility curve, which is very steep initially. Consequently, the small probability of the composite only achieving a low operating temperature has a greater effect on the utility than the same small probability of obtaining a very high operating temperature.

Overall, his multiattribute utility increased slightly after the incorporation of the subjective probability data. This is due to the large change in expected strength compared to the other attributes. Table 34 contains Subject #2's single attribute and multiattribute utilities for the attributes investigated in the subjective probability assessment portion of this study, both with and withough the use of this additional informtation.

Table 34: Utility Changes Due to Subjective Probability Data: Subject #2

		Slurry Infiltrated		Chemical Vapor Infiltrated	
	Attribute	with SPA	w/o SPA	with SPA	w/o SPA
1.	Operating Temperature	.8398	.8611	.9666	.9739
2.	Strength	.8511	.2763	.8993	.6912
3.	Toughness	.8490	1.0000	.8490	1.0000
	Overall	.9124	.8853	.9025	.8929

Not only do these changes affect subject #2's ranking of the three alternatives, they also change the costs at which the alternatives are equally values. Figure 21 shows the variation of the three multiattribute utility curves with cost reductions when the subjective probability data is included. Slurry infiltrated SiC/SiC composite exhaust ducts costing $2010 and chemical vapor infiltrated SiC/SiC composite exhaust ducts costing $3575 are equally valued with the current superalloy duct. In addition, at costs below $8475, the chemical vapor infiltrated duct is preferred to the slurry infiltrated duct at its current cost of $4635. Without the inclusion of the subjective probability data, slurry infiltrated ducts costing $1450 and chemical vapor infiltrated ducts costing $3180 are equally valued with the current superalloy duct. Also, chemical vapor infiltrated ducts are preferred to slurry infiltrated ducts at their current costs. The use of the subjective probability data improved the competitive position of both ceramic matrix composites compared to superalloys. Furthermore, slurry infiltrated ceramic matrix composites saw a larger increase than their chemical vapor infiltration counterpart when the subjective probability data is incorporated.

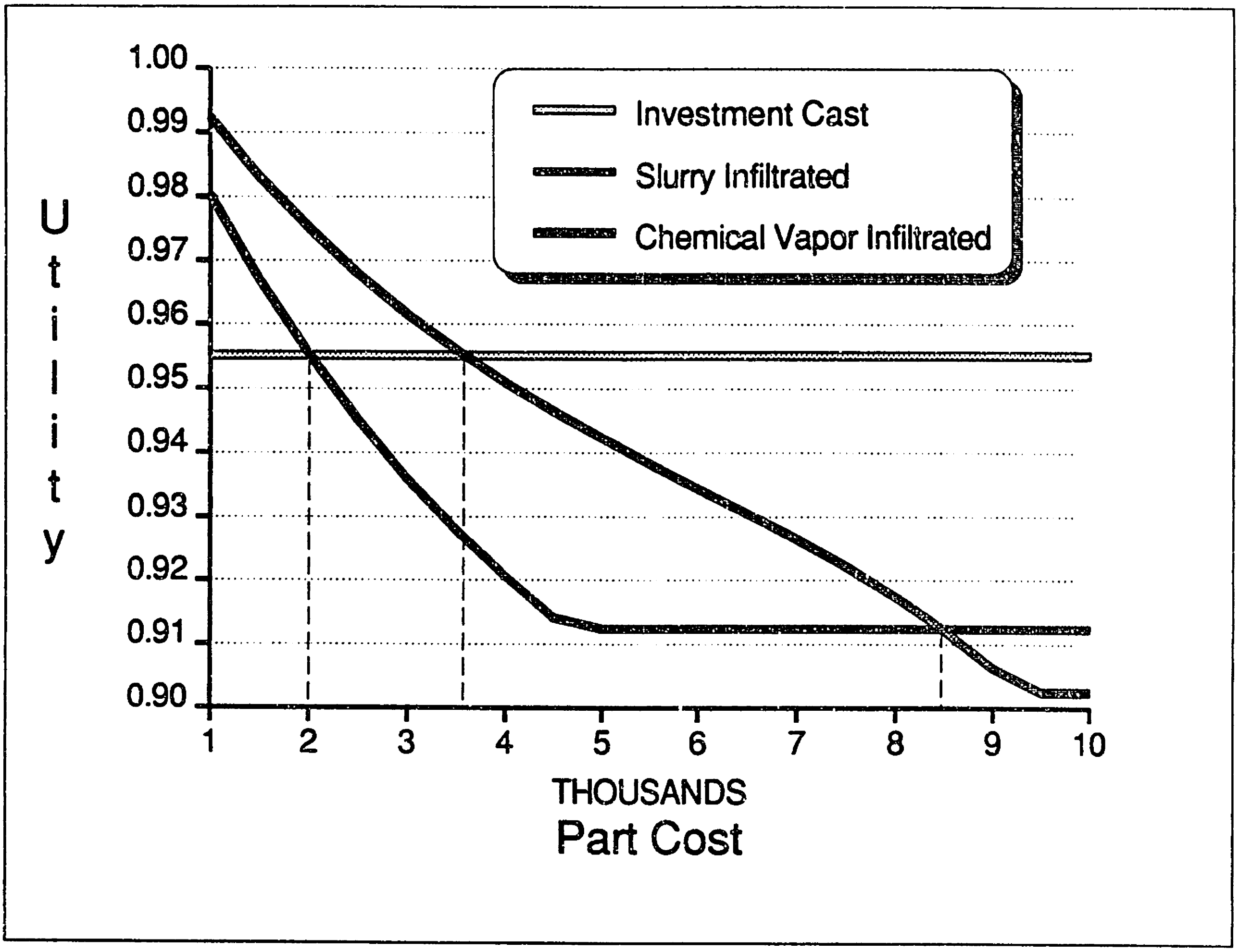


Figure 21: Utility vs. Cost with Subjective Probability Data: Subject #2

7.3.3. Subject #3

Subject #3's probability assessments were the same as Subject #2's, and consequently the effect on his utilities was similar. There was a slight decrease in his single attribute utility for operating temperature, a somewhat larger decrease for toughness and a very large increase for strength. Once again this resulted in an overall increase in utility for both materials. Table 33 shows these results.

Table 35: Utility Changes Due to Subjective Probability Data: Subject #3

		Slurry Infiltrated		Chemical Vapor Infiltrated	
	Attribute	with SPA	w/o SPA	with SPA	w/o SPA
1.	Operating Temperature	.7474	.7534	.8182	.8521
2.	Strength	.8186	.2763	.8993	.6912
3.	Toughness	.8214	1.0000	.8214	1.0000
	Overall	**.8955**	**.8634**	**.8320**	**.8237**

Subject #3's ranking of the alternatives remained the same, but the costs at which the alternatives are equal changed. Figure 22 shows his utility curves for each attribute as its cost drops from its currently predicted level to the minimum level considered in this study, $1000. Slurry infiltrated and chemical vapor infiltrated SiC/SiC exhaust ducts are considered equally desirable as the current superalloy duct at costs of $4195 and $4665 respectively. Furthermore, chemical vapor infiltrated ducts will compete with slurry infiltrated ducts if their costs are reduced to $5140 compared to $4635 for the slurry infiltrated component.

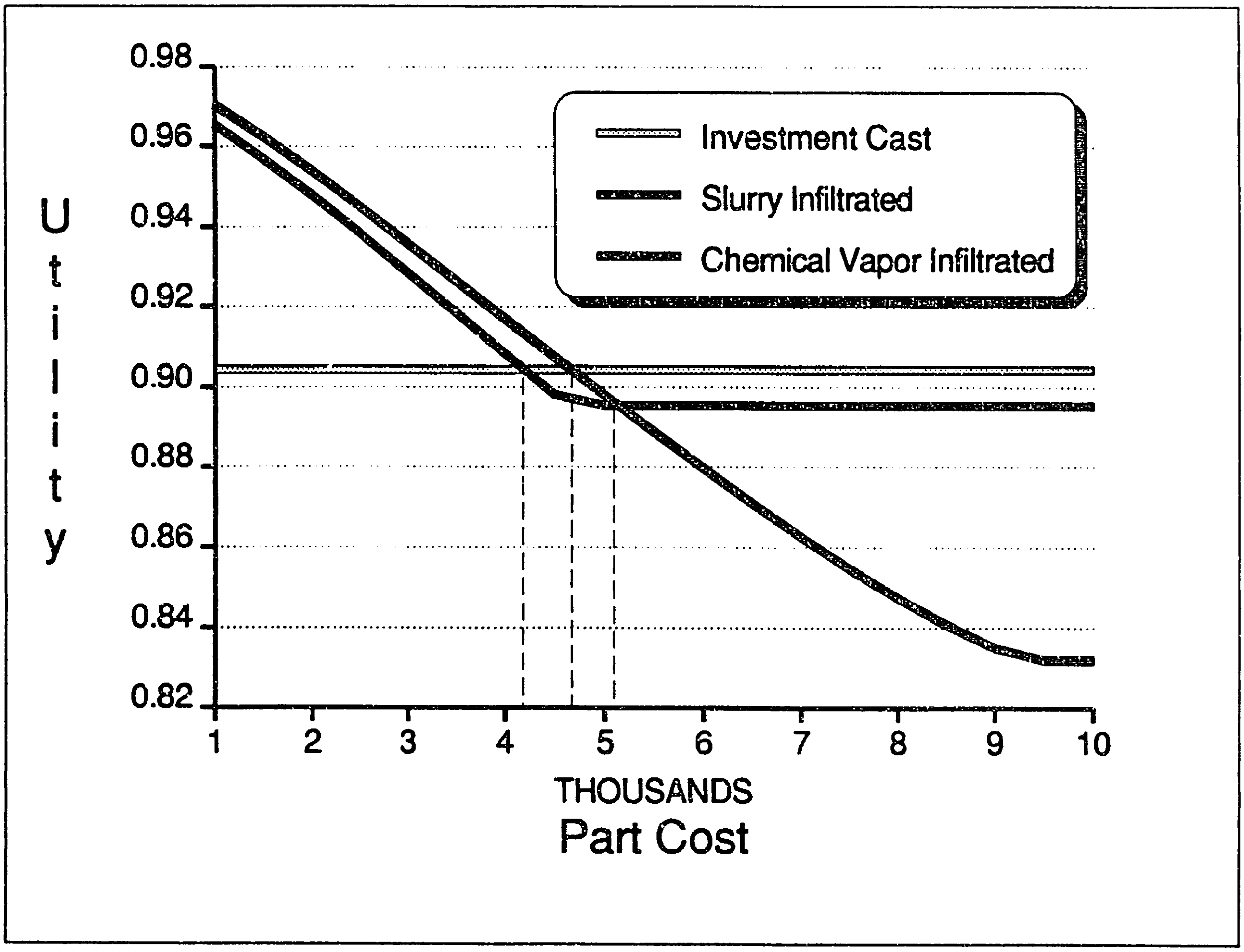


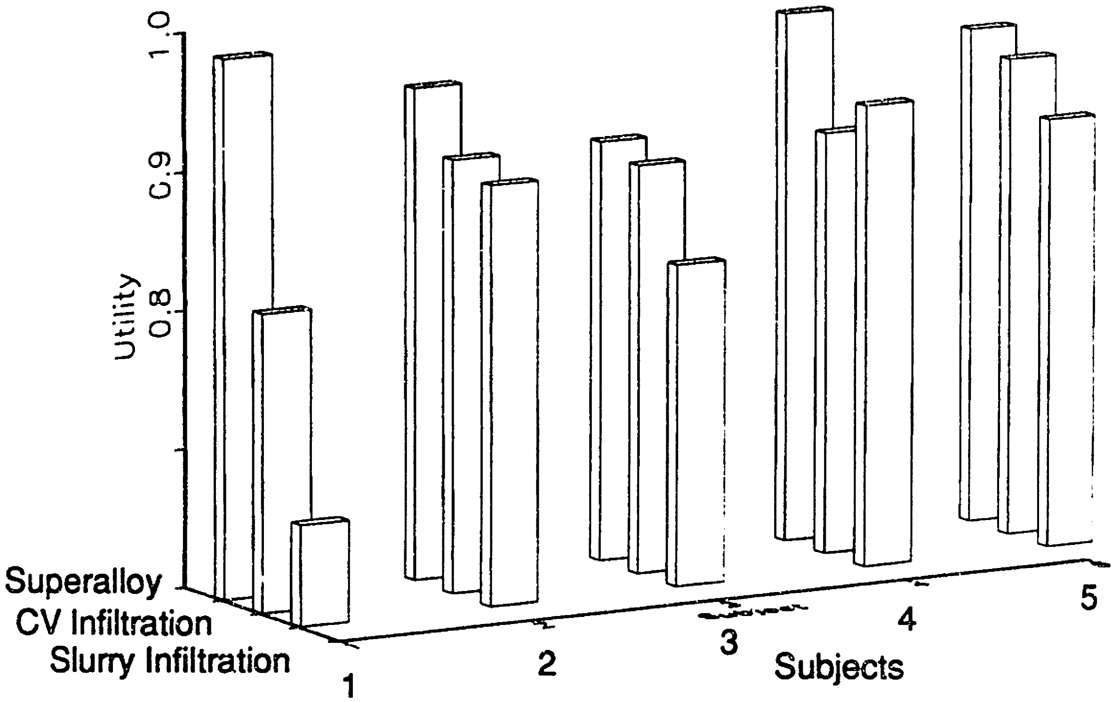
Figure 22: Utility vs. Cost with Subjective Probability Data: Subject #3

8. Comparison of Materials Alternatives

Up until this point this study has explored the preferences of each engine designer for various attributes, and, consequently for the three materials being considered for use in this exhaust duct applications. This still leaves the questions of what, if any, general trends there are for materials selection in this application and what can materials suppliers do to improve the competitiveness of their product.

8.1. Rankings of the Alternatives

A definite trend emerged among the respondents in the ranking of the alternatives. All five participants ranked investment cast superalloys first, and four of the five ranked slurry infiltrated SiC/SiC composite ducts second. This is the same ranking which came out of the technical cost model results and is an indication of the importance of cost to each of the engine designers. However, the performance advantages associated with the more expensive alternatives dramatically narrowed the gap between the alternatives. Figure 23 shows the utility levels of the alternatives for each respondent. The costs determined by the technical cost models were used, and subjective probability data was included when available.



Subject	**1**	**2**	**3**	**4**	**5**
Superalloy	0.9887	0.9551	0.9044	0.9846	0.9610
Slurry Infiltration	0.8146	0.9124	0.8955	0.9059	0.9472
CV Infiltration	0.6730	0.9025	0.8320	0.9339	0.9115

Figure 23: Utility of the Materials Alternatives

Only in the case of Subject #4 do exhaust ducts made by the chemical vapor infiltration process outrank those made by the slurry infiltration technique. Subject #4 felt that there was a relatively high minimum strength requirement for the material, 20 ksi. The slurry infiltrated duct, if used at elevated temperatures, could not meet this requirement. As a result, it would be limited to lower temperatures. For this reason, his ranking of a slurry infiltrated duct was low. The other four engineers had lower minimum requirements for strength which the slurry infiltrated duct could achieve at elevated temperatures (1100°C). Consequently, these four subjects ranked the slurry infiltrated duct above the chemical vapor infiltrated duct. In the case of Subject #2, it was only after the application of his subjective probability data that slurry infiltrated ducts surpassed chemical vapor infiltrated ducts. He placed some importance on strength and a great deal of importance on operating temperature, both which give an advantage to the chemical vapor infiltrated product. However, in the subjective probability phase of the study he indicated that he thought that the slurry infiltration technique could be used to make ducts with significantly higher strengths at even higher temperatures than the reported values. His mean expected value for temperature and strength of a slurry infiltrated component were 1250°C and 30 ksi respectively compared to the reported values of 1100°C and 14 ksi respectively. This resulted in a higher utility for the slurry infiltrated SiC/SiC composite ducts than for the chemical vapor infiltrated component. However, ceramic matrix composite ducts are still not valued as highly as their superalloy counterparts. Several approaches can be taken to remedy this situation. These involve cost reductions, a variety of performance improvements, or both.

8.2. Cost Equivalents

One obvious way for the ceramic matrix composites to become more competitive is through cost reductions. For the exhaust duct application, three of the five participants in this study indicated a preference for the ceramic matrix composites if their costs were the same as that of a superalloy duct, $1000. This means that strictly on a performance basis, these three engine designers prefer the ceramic matrix composite ducts to superalloy ducts.

Table 36 shows the costs at which each of the ceramic matrix composite alternatives are equally desirable as a superalloy and the cost at which a duct produced by the chemical vapor infiltration technique competes with one produced by the slurry infiltration technique, for all five participants. In each case the comparison is made to the material alternative at the cost predicted by the technical cost models, $1000 for superalloy ducts and $4635 for slurry infiltrated SiC/SiC composite ducts. In addition, subjective probability data is used for the first three respondents.

Table 36: Cost at which the Utility of the Alternatives are Equal

Subject	Slurry Infiltration vs. Superalloys	CVI vs. Superalloys	CVI vs. Slurry Infiltration
#1:	below $1000	below $1000	$7980
#2:	$2010	$3575	$8475
#3:	$4195	$4665	$4845
#4:	below $1000	below $1000	above $9291
#5:	$1750	$4800	$6940

Table 36 indicates that significant cost reductions are required if either of the ceramic matrix composite processes are going to compete with superalloys in this application. Four of the five respondents require that SiC/SiC ducts produced by the slurry infiltration technique cost less than $2010 in order to be preferred to a superalloy duct. This is a significant reduction from the currently estimated cost of $4635. For one participant only a modest cost reduction to $4195 is needed. All five of the subjects require large cost reductions for SiC/SiC composite ducts produced by the chemical vapor infiltration process before they consider them to be of equal value as a superalloy duct. In the best case, a chemical vapor infiltrated duct would have to cost only $4800 compared to the currently estimated cost of $9291.

The cost at which the two ceramic matrix composites have the same utility varies widely. At one extreme, a chemical vapor infiltrated duct could cost only slightly more than a slurry infiltrated duct. At the other extreme, Subject #4 prefers the chemical vapor infiltrated duct at its current cost of $9291 even though it costs more than twice as much as the slurry infiltrated component. Again, Subject #4 had a higher minimum strength requirement for the duct than the other respondents. This resulted in an extremely low evaluation of this alternative since it also affected its maximum operating temperature. Small improvements in the strength of the slurry infiltrated duct at 1100°C would result in a considerably higher utility for this alternative, above that of the chemical vapor infiltrated duct.

8.3. Recommendations for Materials Suppliers

While superalloys are the material of choice in current exhaust duct applications, changing performance requirements and the emergence of new materials have created potential competition in these components. Cost still remains a substantial advantage for superalloys. However, as continued research and development aimed at new materials results in cost reductions, and the performance requirements of aircraft gas turbine engines become increasely stringent, the competitive advantage of superalloys is likely to decrease. The question remains, what must each material supplier do to improve (or in the case of superalloys, maintain) its competitiveness?

8.3.1. Investment Cast Superalloys

The major advantages to using superalloys in this application are their low cost, good mechanical properties (*i.e.* strength and toughness) and proven track record. In the past these issues have dominated material selection. However, the push for weight reduction in aircraft engines promise to make the high density of superalloys a significant drawback. Furthermore, as new turbine materials are developed, engine operating temperatures, and thus exhaust gas temperatures, are likely to rise. While superalloys can be used at elevated temperatures, there are still limitations. It is possible to produce superalloys which can withstand temperatures up to about 2000°F (1150°C). The processing techniques necessary to achieve these higher temperatures are more complicated than ordinary investment casting and are likely to be more costly. [8] However, at 2000°F , and all other properties being as before, superalloys at a cost of as much as $2750 for Subject #3 to above $10,000 for Subjects #1 and #4, would have the same utility as the current ceramic matrix composite ducts. More importantly, lower costs, from less than $2150 for Subject #1 to less than $5150 for Subject #5 are worth paying for the improved service temperature since this will result in a multiattribute utility higher than the current superalloy. These results are shown in Table 37.

Table 37: Cost at which 2000°F Service Temperature Superalloy Ducts have the Same Utility as the Current Ceramic Matrix Composite and Superalloy Ducts

Subject	Maximum Cost for Same Utility as CMC	Maximum Cost for Improved Superalloy Utility
# 1	above $10,000	$2150
# 2	$6500	$2640
# 3	$2750	$2415
# 4	above $10,000	$3800
# 5	$7180	$5150

The need for higher temperature materials in exhaust ducts will likely reduce the cost advantage held by superalloys. Furthermore, it may also have the effect of changing the way engine designers trade operating temperature for other attributes. This may also diminish the competitive position of superalloys in this application.

The main focus of research for superalloy suppliers should be to improve on specialized casting techniques with an eye towards cost reductions. While the use of directional solidification and single crystal casting techniques can result in components with good mechanical properties at elevated temperatures, the cost may be too great.

8.3.2. Slurry Infiltrated SiC/SiC Composites

Other than cost, the main area in which slurry infiltrated SiC/SiC composites need improvement is strength at elevated temperatures. While strength was not generally considered to be a major concern when designing exhaust ducts, the reported strength of a SiC/SiC composite produced by this technique was near the bottom of the utility scale for most of the participants in this study, and was even below the minimum for one.

Fortunately for ceramic matrix composite producers using this process, the subjective probability portion of this study indicated that engineers involved in the materials selection process believed that slurry infiltrated ceramic matrix composites should exhibit much higher strengths. As a result, suppliers of this product should focus on improving the strength of their material. However, this must be done without any large cost increase which would offset the benefits of the improved mechanical properties. For strengths of 30 ksi and all other properties as before, slurry infiltrated SiC/SiC composite exhaust ducts costing as much as $5000, which is above its currently estimated cost, for Subject #3, down to below $1000 for Subjects #1 and #4, will have the same utility as the current superalloy duct. Table 38 shows the costs which would give slurry infiltrated ducts the same utility, given a strength of 30 ksi, as the current superalloy duct.

Table 38: Cost Evaluation for 30 ksi Strength Slurry Infiltrated Duct

Subject	Competitive Cost 30 ksi Strength	Baseline Competitive Cost
# 1	below $1000	below $1000
# 2	$2550	$2010
# 3	$5000	$4195
# 4	below $1000	below $1000
# 5	$3375	$1750

Another consideration is the operating temperature. Cost reductions for the chemical vapor infiltration process could eliminate the competitive advantage that the slurry infiltration technique holds between the two ceramic matrix composite processes. Also, innovative superalloy castings have the potential to be used at temperatures even higher than those of slurry infiltrated ceramic matrix composites. [8] This would eliminate the need for the slurry infiltrated composites. Improving the temperature capabilities of the slurry infiltrated composite would help to maintain this competitive advantage. Improving the service temperature is closely related to the issue of strength since it is the mechanical properties at elevated temperatures which limit the operating temperature.

At 1400°C, and all other properties being as before, slurry infiltrated SiC/SiC composite exhaust ducts costing as much as $3850 for Subject #5 down to below $1000 for Subject #1 would have the same utility as the current superalloy duct. For Subject #4, the slurry infiltrated material would also need to see an improved strength. Table 39 shows the cost which would give slurry infiltrated ducts the same utility, given a service temperature of 1400°C as the current operating temperature.

Table 39: Cost for which a 1400°C Operating Temperature Slurry Infiltrated Duct has the Same Utility as the Current Superalloy Duct.

Subject	Competitive Cost 1400°C	Baseline Competitive Cost
# 1	below $1000	below $1000
# 2	$2310	$2010
# 3	$3600	$4195
# 4	------	below $1000
# 5	$3850	$1750

Also important to ceramic matrix composite suppliers should be the thermal expansion mismatches between the exhaust duct and the turbine section. Currently, turbine sections are composed of superalloys, and thus, a superalloy exhaust duct holds an advantage over ceramic matrix composite ducts in that there is no thermal expansion mismatch problem. However, the use of ceramic matrix composites throughout an engine would not only eliminate the disadvantage to ceramic matrix composites, but might even make their low coefficient of thermal expansion a selling point in applications with tight geometric tolerances.

If the thermal expansion mismatch is eliminated with the incorporation of ceramic matrix composites into the turbine section of the engine, slurry infiltrated SiC/SiC composite exhaust ducts costing as much as $6100 for Subject #5 down to below $1000 for Subject #4 would have the same utility as the current superalloy duct. Table 40 shows the cost which would give slurry infiltrated ducts with no thermal expansion mismatch the same utility as the current superalloy duct.

Table 40: Cost for which a Slurry Infiltrated Duct with No Thermal Expansion Mismatch has the Same Utility as the Current Superalloy Duct

Subject	Competitive Cost No Thermal Expansion Mismatch	Baseline Competitive Cost
# 1	$1950	below $1000
# 2	$2315	$2010
# 3	$4850	$4195
# 4	below $1000	below $1000
# 5	$6100	$1750

Furthermore, engines are currently designed based on the use of superalloys in many applications, including exhaust ducts. The introduction of ceramic matrix composites into engine components should be accompanied by a redesign of the entire engine to accommodate the new material, not just the new component. For these reasons, it may be beneficial for ceramic matrix composite suppliers to work towards putting their product in a number of applications in order to make overall engine redesign feasible and cost effective, as well as to address problems associated with thermal expansion mismatch between components.

Finally, a combination of these improvements would lead to an even better competitive position for slurry infiltrated exhaust ducts. A duct with a strength of 30 ksi at 1400°C and no thermal expansion mismatch (density and toughness at their baseline values) costing as much as $8500 for Subject #4 down to $3700 for Subject #1 would have the same utility as the current superalloy duct. The best case cost found in Chapter 5 is $2407 which is below all of these values. This indicates the possibility for slurry infiltrated SiC/SiC composite exhaust ducts to compete with superalloy ducts. The key for suppliers of this material is to not only cut costs as much as possible, but also to improve its properties.

8.3.3. Chemical Vapor Infiltrated SiC/SiC Composites

Ceramic matrix composites made by the chemical vapor infiltrated technique are the high cost, high performance materials being looked at for this application. Unfortunately, while performance is valued, it is not valued enough to offset such large costs. Cost reduction is clearly what is needed to make these materials competitive in this application. There is still some room for improvement in material properties, specifically strength, and in the long term, operating temperature.

Strength increases to 30 ksi would improve the competitiveness of chemical vapor infiltrated composites as it did for slurry infiltrated composites. At this strength, and all other properties remaining the same as before, chemical vapor infiltrated exhaust ducts costing as much as $5485 for Subject #3 down to below $1000 for Subjects #1 and #4 would have the same utility as the current superalloy duct. Table 41 shows the cost which would give chemical vapor infiltrated ducts the same utility as the current superalloy ducts given a strength of 30 ksi and for the current strength.

Table 41: Cost for which a 30 ksi Strength Chemical Vapor Infiltrated Duct has the Same Utility as the Current Superalloy Duct

Subject	Competitive Cost 30 ksi Strength	Baseline Competitive Cost
# 1	below $1000	below $1000
# 2	$4310	$3575
# 3	$5485	$4665
# 4	below $1000	below $1000
# 5	$5210	$4800

Like slurry infiltrated ducts, the elimination of thermal expansion mismatches between the exhaust duct and the turbine section will also result in an improved competitive position for chemical vapor infiltrated ducts. In this case, a slurry infiltrated SiC/SiC composite exhaust duct costing as much as $7950 for Subject #5 down to $3000 for Subject #4 would have the same utility as the superalloy duct. Table 42 shows the cost which would give chemical vapor infiltrated ducts with no theraml expansion mismatch the same utility as the current superalloy duct.

Table 42: Cost for which a Chemical Vapor Infiltrated Duct with No Thermal Expansion Mismatch has the Same Utility as the Current Superalloy Duct

Subject	Competitive Cost No Thermal Expansion Mismatch	Baseline Competitive Cost
# 1	$3500	below $1000
# 2	$4250	$3575
# 3	$5375	$4665
# 4	$3000	below $1000
# 5	$7950	$4800

Also, a combination of these improvements would lead to an even better competitive position for chemical vapor infiltrated exhaust ducts. A duct with a strength of 30 ksi and no thermal expansion mismatch, all other properties remaining as before, could cost from as much as $8500 for Subject #4 down to $3700 for Subject #1. The best case cost for chemical vapor infiltrated ducts found in Chapter 5 is $3647 which is below all of these values. This indicates the possibility for chemical vapor infiltrated SiC/SiC composite exhaust ducts to compete with superalloy ducts. Again, chemical vapor infiltrated composite suppliers must focus on cost reduction, but the property improvements previously discussed will make the necessary cost reductions more realistic.

Furthermore, the same issues concerning engine redesign and the introduction of ceramic matrix composites into more than on component apply here as well. More importantly, ceramic matrix composite producers using this technique should look towards other engine applications, where there is a higher premium placed on performance. These potential applications may range from those with relatively easy mechanical requirement, such as combustor liners, to mechanically demanding applications such as turbine components.

9. Recommendations and Future Work

The increasingly stringent performance requirements demanded of components in many aerospace applications have led to a proliferation of new materials. Many of these materials have the potential to be used in numerous applications. Unfortunately, only limited progress has been made towards widespread use of these new materials in non-critical applications. Aerospace engineers often design with an already proven material in mind unless specific requirements necessitate a change. This can result in suboptimal materials choices and gives no indication of the shortcomings of new materials. This thesis provides a systematic framework for evaluating new alternatives in an ever changing market for new advanced materials. The methodology not only considers component cost through the use of technical cost modeling, but also performance tradeoffs through multiattribute utility analysis and some less tangible issues such as the design engineer's expectations regarding new materials through the use of subjective probability assessments. The result is a quantitative ranking of the materials alternatives.

Additional work on this subject is needed in two areas. Methodological refinement and updates are needed to improve upon the accuracy of the results and to encompass other issues concerning the materials selection process. Also, additional case studies can be conducted to address the materials competition in other high temperature aerospace applications. It might be beneficial to look into applications which exploit the strengths of each of the material alternatives. These might include combustor liners, which have high temperature requirements with relatively low mechanical requirements. Furthermore, while this study focused only on superalloys and ceramic matrix composites, studies involving other components could involve a variety of other materials such as advanced alloys, metal matrix composites, monolithic ceramics and intermetallic matrix composites.

In the past, material selection decisions were made by a number of methods which often led to suboptimal choices. These methods are discussed in Chapter 4. The methodology established in this study provides a systematic approach to the materials selection problem. This methodology was applied to the case study of exhaust ducts for medium sized, non-man rated engines. The results of this study have already been presented in Chapters 5 through 8. The results not only provided a basis for comparison of the material alternatives, but also shed some light on the strong points and limitations of the methodology.

9.1. Technical Cost Modeling

Technical cost modeling was used to estimate the cost of producing an exhaust duct from the three alternatives. Cost estimates were based on anticipated versions of scaled up production for the ceramic matrix composite processing techniques. In this way, technical cost modeling was very effective as a means of estimating costs which would otherwise be unavailable. These models provide a better basis for cost comparison with investment cast superalloys, which are currently produced on a mass production scale.

Despite the advantages of using technical cost modeling, there are limitations in this application. Values for process yields are only estimates. Cost estimates are sensitive to the process yields, especially for the two ceramic matrix composite processes, and thus only as accurate as the yield inputs. Furthermore, the ceramic matrix composite cost models involved assumptions concerning the scale up and automation of the process, which do not represent actual manufacturing practices. Results from these models must be viewed in this light. Future work is needed to establish the validity of the way these processes were scaled up, as well as to obtain accurate values for process yields and other inputs. Furthermore, technical cost models need to be continually revised to represent the current technology being employed in practice. Inputs must also be updated to reflect current materials, labor and equipment costs.

9.2. Multiattribute Utility Analysis

Multiattribute utility analysis was used to measure the trade-offs that engine designers make when selecting a material. This provided a materials blind basis for comparing the alternatives and eliminated some of the biases often encountered in selecting a material.

Multiattribute utility analysis also has limitations for use in this type of application. The interview process can often be difficult and requires some experience in order to get accurate results. The interview approach is necessary because it would be extremely difficult to get results representative of the attribute trade-offs without an interactive questionnaire. Furthermore, some participants in the study were resistant to the techniques employed in questionnaire since these do not always represent the way they make decisions. While great effort was taken to make the questionnaire closely resemble situations encountered by engine designers, the scenarios did not always match the engine designer's personal experiences. On designer praised the questionnaire for presenting exactly the kind of decisions he often faces. On the other hand, another engine designer refused to respond to the questionnaire, since he felt that it was totally irrelevant to the way he does engine design. Usually, the decision makers were more comfortable with the questionnaire when it was explained that the techniques employed were simply ways of measuring the attribute trade-offs and did not represent the way decisions are actually made.

Problems also arose with regard to the scenarios presented in questionnaire. Some engine designers thought that the scenarios presented were not accurate portrayals of the situations they experienced in practice. They often wanted to hedge against risks by seeking multiple component suppliers. The questionnaire did not allow for this. The use of additional measuring techniques should be explored in order to find methods which may not be so awkward for the decision maker. Also, different scenarios, which more closely reflect situations encountered by engine designers, should be employed.

9.3. Subjective Probability Assessment

Subjective probability assessment was used to account for discrepancies between reported attribute levels and those perceived by the engine designers for new material alternatives. In this study, participants were only asked to indicate expected values for the few attributes for which material supplier laboratory test results were considered to be suspect. Another use of this technique might be to investigate a decision maker's possible reluctance to switch to a new unproven material. Also other evaluation techniques for subjective probability assessment might be tried in order to improve upon the accuracy of the results. The certainty or lottery equivalent methods employed in the multiattribute utility analysis portion of this study might yield more accurate results. Also, subjective probabilities must be periodically updated to account for the changing perceptions of the decision maker towards new materials. As new materials become more familiar to engine designers, their evaluation of the performance levels are likely to change.

APPENDIX A:

Investment Casting Technical Cost Model

Investment Casting Model
Materials Systems Laboratory

PRODUCTION INPUTS

	Units	Value	Override
Production Volume	parts per year	2400	
CLA(1) or Gravity(0)		1	
Length	inch	8	
Width	inch	25	
Thickness	inch	0.375	
What Alloy (see menu)		6	
Volume of part	cubic inch	75	
Core	(1=yes,0=no)	0	
Core Price	$/core	$0.00	
Recoverable Core?	(1=yes,0=no)	0	
Cored Volume	cubic inch	0	0
Outer Surface Area	square inch	424.75	0
Cored Area	square inch	0	0
Surface Area	square inch	424.75	0
Ratio-Total Vol/Cored Vol	#	NA	0
Number per configuration	#	1	0
What Wax (see menu)		13	
Final Weight of Part	lbs	24.09	0
Lifetime of Product	yrs	3	
Dedicated Equipment	(1=yes,0=no)	0	

Processing Specifications

	Units	Value	Override
MOLD WAX PIECES			
Cavities per injection die	#	8	
Percent of wax makeup		50%	
Tooling cost		$50,000	
Tooling life	yrs	5	
ASSEMBLE WAX PATTERN			
Radius of runner	inch	1	
Length of gates	inch	0.5	
Length of runner	inch	20	
Volume of runner	cubic inch	60	
Max runner volume permitted	cubic inch	3840	

Wax density	lbs/cubic inch	0.036	
Total wax volume	cubic inch	135	
Total surface area	square inch	544.75	
Time to attach one piece	seconds	10	

SLURRY DIP AND DRY

Number of robots	#	2	
Number of dips required	#	9	
Number of manual dips	#	2	
Number of robot dips	#	7	
Number of trees on robot	#	3	
Number of grades of slurry	#	2	

First Dip:

Refractory	9	0.42	0
Binder	10	0.45	0
Sand	9	0.42	0

Second Dip and subsequent dips:

Refractory	7	0.10	
Binder	11	0.60	
Sand	7	0.10	

Time for manual dip	mins	1	
Time for robot cycle (includes pick-up,slurry,stucco and hang)	mins	2	
Equivalent robot labor rate		$39.30	

INSPECTION

Shell inspection cycle time	hrs	0.017	
Percent requiring repair		5%	
Average time for repair	hrs	0.083	

FIRING AND PREHEAT

Time needed to fire shell	hrs	3	
Shell density	lbs/cubic inch	0.09	
Shell thickness after firing	inch	0.25	
Shell weight	lbs	12.75	
Weight of shell and wax	lbs	17.62	
Weight of shell with metal	lbs	55.95	

FINAL MACHINING

Time to machine	hrs	15	
Machining Equipment Cost	$	$5,000	

SPECIFIC CALCULATED INPUTS

	Units	Value	Override
Surface area of part	square inch	424.75	0
Density of part alloy	lbs/cubic inch	0.32	0
Price of alloy	$/lb	$6.00	0
Price of Scrap	$/lb	$2.00	0

EXOGENOUS INPUTS

	Units	Value	
Skilled Wage	$/hr	$15.00	
Unskilled Wage	$/hr	$10.00	0
Benefits	%	30%	
Electricity	$/kWh	0.067	
Work Days per Year		180	
Shifts per Day		3	
Equipment Accounting Life	yrs	6	
Opportunity Cost of Capital		12.0%	

CAPITAL COST PARAMETERS

Amortization Period (all other capital)	10
Maintenance (% of capital investment)	30.0%
Building Cost (per square foot)	$50
Period for Amortizing Building Cost (yrs)	30
Typical area of greenfield facility - ftç	25000

CALCULATION OF PARTS NECESSARY

	Scrap Rate	Units	Number
Number necessary to start		pieces	4395
Mold wax pattern	1.00%	pieces	4351
Assemble wax pattern	0.50%	trees	4329
Slurry dip and dry	2.00%	trees	4242
Steam dewax	0.00%	trees	4242
Cleaning and inspection	1.00%	trees	4199
Firing	0.00%	trees	4199
Melt and Pour	1.00%	trees	4157
Shakeout and Blast	0.00%	trees	4157
Cut-off and grinding	5.00%	parts	3949
Final Machining	20.00%	parts	3159
Visual Inspection	20.00%	parts	2527
Final Inspection, X-ray	5.00%	parts	2400

MATERIALS DATABASE

Material Type		Material	$/lb	Scrap $/lb	Density
ALLOYS					
	1	Carbon Steel	$0.25	$0.05	0.283
	2	Alloy Steel	$0.39	$0.05	0.283
	3	Aluminum based alloys	$1.00		0.100
	4	Copper based alloys	$1.00		0.323
	5	Titanium			0.100
	6	Nickel based superalloys	$6.00	$2.00	0.320

Material Type		Material	$/lb	Density(g/cc)
REFRACTORIES				
	7	Alumino Silicates	$0.10	3.250
	8	Fused Silica	$0.35	2.200
	9	Zircon Sand and Flours	$0.42	4.560
BINDERS				
	10	Water based Colloidal Silica	$0.45	
	11	Ethyl Silicate	$0.60	
	12	Colloidal Alumina	$0.75	
WAXES				
	13	Waxes	$1.00	
	14	Wax Extrusions	$0.65	
	15	Reclaimed Wax	$0.40	

EQUIPMENT DATABASE

ITEM			COST	CYCLE TIME
Wax Injection Presses	Clamping Pressure			
	0	12.5	$40,000	10.0 secs
	13.5	18	$50,000	10.0 secs
	19	37.5	$60,000	10.0 secs
	38.5	40	$65,000	10.0 secs
	41	50	$70,000	10.0 secs
	51	100	$75,000	10.0 secs
	101			
Robot Systems For Dipping (including necessary conveyors)				
	Capacity(lbs)			
	0	140	$250,000	4.0 mins
	141	250	$270,000	4.0 mins
	251	450	$300,000	4.0 mins
	451	800	$330,000	4.0 mins
	801	1500	$360,000	4.0 mins
	1501			

Barrel Sanders

Opening Size(")		
0	18	$3,000
19	24	$3,500
25	30	$4,000
31	36	$4,500
37	42	$5,000
43	48	$5,500
49	60	$6,000
61		

Fluidbeds, Blowers

Chamber Depth	Chamber Diameter		
26	0	24	$4,000
26	25	30	$4,500
26	31	36	$5,000
26	37	42	$5,500
	43		

Rainfall Sanders

Work Diameter	Work Depth	
30	42	$4,000

Autoclave Dewaxing Systems		
	$50,000	0.25 hrs
Wax Reclaiming System	$100,000	
Pattern Wash Recovery Still Systems	$20,000	

Firing & preheat "pusher" furnace

CSA	Length gas	
4	50	$300,000

Melting Furnace

	Alum Cap	Gas	
0	10	120000	
11	16	150000	
17	30	220000	
31	70	300000	
71	150	450000	
151	250	600000	
251	400	800000	$110,000
401	600	1200000	
601	850	1400000	
851	900	1500000	
901	1000	1700000	
1001			

Knock Out Equipment

Load Area(cubic feet)	
3.375	$2,000
8	$3,000

Grit Blasters (incl. necessary dust collectors)

Hanging	1	$120,000	2.0 mins
Barrel	2	$100,000	2.0 mins

EQUIPMENT AND PRODUCTION RATE EVALUATION

THE PLANT:

Total time per year	4320
Total processing time per year	3456
Total processing time per day	19.2

Calculation of time to process job (slurry dip & dry):

Number of robots	2
Time of robot cycle	0.033
Number of robot dips	7
Number of trees per robot	3
Time for one tree	0.039
Number of trees	4329
Utilization of the Plant	0.049

SLURRY ROOM:

Production Rate(trees/hr)	1.00
Volume(trees/day)	19.24

MOLD WAX PATTERN

Cycle Time of Equipment	hrs	0.000347
Wax Density	lbs/cu.in.	0.036
Wax Volume per tree	cu.in.	135.00
Wax Price	$/lb	$0.75
Number of Pieces	#	4395
Parts per tree	#	1
Proportion of Plant Required	#	0.0004
Number of Machines	#	1
Workers per Molding Machine	#	0.333
Number of Workers	#	0.333
Wage (including benefits)	$/hr	$13.00
Production Rate	pieces/hr	1.02
Tooling Cost	$	$50,000
Tool Usefulness Life	years	3
Injection Molding Machine Cost	$	$60,000
% Maintenance		30%

MATERIAL	Wax	$16,069
DIRECT LABOR		$730
EQUIPMENT	Tooling	$20,817
	Maintenance	$877
Wax Injectors		$711
TOTAL ANNUAL COST		$39,204

ASSEMBLE WAX PATTERN

Production Rate	pieces/hr	1.01
Cycle Time (/part)	hrs	0.0028
Number of pieces	#	4351
Wage (including benefits)	$/hr	$13.00
Proportion of Plant Required for One Worker		0.003
Number of Workers Used	#	1
Energy		
Equipment		

DIRECT LABOR	$2,189
EQUIPMENT	$0
Total Annual Cost	$2,189

SLURRY DIP AND DRY

Cycle Time for Manual Dip (/tree)		hrs	0.017
Cycle Time for Robot Dip (/tree)		hrs	0.033
Time for One Tree		hrs	0.039
Total Number of Trees		#	4329
Production Rate		trees/hr	1.00
Number of Trees per Robot		#	3
Total Number of Dips		#	9
Number of Manual Dips		#	2
Number of Robot Dips		#	7
Number of Robots		#	2
Number of Workers		#	2
Weight of Shell and Wax		lbs	17.62
Weight of Wax		lbs	4.87
Weight of Shell		lbs	12.75
Material Price		$/lb	$0.25
Wage (including benefits)		$/hr	$19.50
% Maintenance			30.0%
Proportion of Plant Required			0.049
Equipment Cost:	Slurry Tank	$5,000	$244
	Robot Dipper	$250,000	$12,178
	Parts Hanger	$20,000	$974
	Rainfall Sander	$20,000	$974
	Fluid Bed	$20,000	$974
Total Equipment Cost			$15,344
MATERIAL	Slurry		$13,796
DIRECT LABOR			$6,566
EQUIPMENT			
	Total Dip Room		$7,464
	Maintenance		$9,207
TOTAL ANNUAL COST			$37,032

STEAM DEWAX

Cycle Time		hrs	0.25
Number of Trees		#	4242
Production Rate		trees/hr	0.98
Required Trees per Autoclave		#	7
Maximum Trees per Autoclave	?????	#	100
Number of Autoclaves		#	1
Number of Workers		#	1
Wage (including benefits)		$/hr	$13.00
Cost of Steam Autoclave		$	$50,000
Maintenance			30.0%
Proportion of Plant Required	(One Tree/Autoclave)		0.307
Proportion of Plant Required	(Max Trees/Autoclave)		0.003

DIRECT LABOR		$2,189
EQUIPMENT	Steam Autoclave	$592
	Maintenance	$731
TOTAL ANNUAL COST		$3,512

CLEANING & INSPECTION

Cycle Time for Inspection	hrs	0.017
Percent Requiring Repair	%	5.0%
Time for Repair	hr	0.083
Total Average Cycle Time	hr	0.021
Number of Trees	#	4242
Production Rate	trees/hr	0.982
Number of Workers	#	1
Wage (including benefits)	$/hr	19.5
Equipment Cost	$	$1,000
Maintenance		30.0%
Proportion of Plant Required (1 worker)		0.026

DIRECT LABOR		$3,283
EQUIPMENT	Equipment rent	$12
	Maintenance	$15
TOTAL ANNUAL COST		$3,309

FIRING AND PREHEAT

Time to Fire	hrs	3
Number of Trees	#	4199
Production Rate	trees/hr	0.97
Tree Length	ft	1.67
Furnace Length	ft	50
Tree Radius	in	1.50
Furnace Radius	in	4
Trees per Furnace	#	60
Trees per Firing Cycle	#	3
Proportion of Furnaces Used		0.050
Number of Furnaces	#	2
Workers per Furnace	#	2
Number of Workers	#	4
Wage (including benefits)	$/hr	$19.50
Furnace Cost	$	$300,000
Maintenance		30.0%

DIRECT LABOR		$13,131
EQUIPMENT	Furnace	$7,109
	Maintenance	$8,768
TOTAL ANNUAL COST		$29,008

MELT AND POUR

Cycle Time	hrs	0.1
Number of Trees	#	4199
Production Rate	trees/hr	0.97
Parts per Tree	#	1
Volume per Part	cu. in.	75.00
Density of Alloy	lbs/cu.in.	0.32
Alloy Price	$/lb	$6.00
Number of Lines	#	3
Workers per Line	#	3
Number of Workers	#	9
Wage (including benefits)	$/hr	$19.50
Cost of Inductotherm	$	$150,000
Cost of CLA	$	$150,000
Maintenance		30.0%
Proportion of Plant Required (for one line)		0.121

MATERIAL	Charge Cost	$665,122
	Scrap Credit	$0
DIRECT LABOR		$36,932
INDIRECT CAPITAL	Inductotherm	$5,332
	C.L.A.	$5,332
	Maintenance	$13,152
TOTAL ANNUAL COST		$725,869

SHAKEOUT AND BLAST

Cycle Time	hrs	0.004
Number of Trees	#	4157
Production Rate	trees/hr	0.96
Parts per Tree	#	1
Volume per Part	cu. in.	75.00
Density of Alloy	lbs/cu.in.	0.32
Scrap Price	$/lb	$2.00
Number in Parallel	#	1
Unit Cost of Equipment	$	$2,000
Number of Laborers	#	1
Wage (including benefits)	$/hr	$13.00
Maintenance		30.0%

Proportion of Plant Required (for one line)	0.005

DIRECT LABOR		$2,736
EQUIPMENT	Knockout	$24
	Maintenance	$29

Weight of Scrap Generated	0.00
Value of Scrap	$0

TOTAL ANNUAL COST	$2,789

BLASTING CUT-OFF AND GRINDING

Number of Trees	4157
Production Rate	0.96

BLASTING	Cycle Time	# in Parallel	Cost
Grit Blaster	2 min	1	$100,000
Hanging Grit Blaster	2 min	1	$120,000
Number of Laborers			1
Wage (including benefits)			$13.00
CUT-OFF			
Saws	5 min	3	$2,000
Grinding Wheels	10 sec	1	$1,000
Number of Laborers			4
Wage (including benefits)			$13.00
MOLTEN SALT CLEANING			
Salt Bath	5 min	1	$80,000
Trees per Salt Bath			4
Number of Laborers			1
Wages (including benefits)			$13.00
BLASTING			
Grit Blaster	2 min	1	$100,000
Number of Laborers			1
Wages (including benefits)			$13.00

DIRECT LABOR		$19,150
EQUIPMENT	Saws	$71
	Grinding Wheels	$12
	Grit Blasters	$2,370
	Hanging Blasters	$0
	Molten Salt Bath	$948
	Maintenance	$4,194

Weight of Scrap Generated	5010.72
Value of Scrap	$10,021

TOTAL ANNUAL COST	$16,723

FINAL MACHINING

Number of Parts	#	3949
Time to Machine	hrs	15
Production Rate	parts/hr	1.14
Number of Workers	#	352
Wage (including benefits)	$/hr	$19.50
Machining Equipment Cost	$	$5,000
Number of Lines	#	352
Maintenance	%	30.0%
Scrap Price	$/lb	$2.00
Proportion of Plant Required (for one worker)		17.14
DIRECT LABOR		$1,444,443
EQUIPMENT		$20,853
	Maintenance	$25,720
Weight of Scrap Generated		19031.10
Value of Scrap		$38,062
TOTAL COST		$1,452,954

VISUAL INSPECTION

Cycle Time	secs	10
Number of Parts	#	3949
Production Rate	parts/hr	0.91
Number of Workers	#	1
Wage (including benefits)	$/hr	$19.50
Scrap Price	$/lb	$2.00
Proportion of Plant Required (for one worker)		0.003
DIRECT LABOR		$4,104
Weight of Scrap Generated		15224.88
Value of Scrap		$30,450
TOTAL COST		($26,346)

FINAL INSPECTION & X-RAY

Cycle Time	hrs	0.0042
Number of Parts	#	2527
Production Rate	parts/hr	0.58
Number of Workers	#	1
Wage (including benefits)	$/hr	$19.50
Scrap Price	$/lb	$2.00
Equipment Rental	$	$150,000
Maintenance		30.0%
Proportion of Plant Required (for one worker)		0.003

DIRECT LABOR		$4,104
EQUIPMENT	X-ray, Magna-flux & NDT	$1,777
	Maintenance	$2,192

Weight of Scrap Generated	3059.43
Value of Scrap	$6,119
TOTAL COST	$1,954

SUMMARY OF EXPENSES

Facilities	$7,559	$3.15	0.33%
Mold Wax Pattern	$39,204	$16.33	1.71%
Assemble Wax Core	$2,189	$0.91	0.10%
Slurry Dip and Dry	$37,032	$15.43	1.61%
Steam Dewax	$3,512	$1.46	0.15%
Cleaning and Inspection	$3,309	$1.38	0.14%
Firing	$29,008	$12.09	1.26%
Melt and Pour	$725,869	$302.45	31.62%
Shakeout	$2,789	$1.16	0.12%
Blasting, Cut-off & Grinding	$16,723	$6.97	0.73%
Final Machining	$1,452,954	$605.40	63.29%
Visual Inspection	($26,346)	($10.98)	-1.15%
Final Inspection, X-ray	$1,954	$0.81	0.09%
	$2,295,755	$956.56	100.00%

COST BREAKDOWN BY FUNCTION

	TOTAL COST	COST/PART	PERCENT
FACILITIES	$7,559	$3.15	0.33%
LABOR	$1,539,554	$641.48	67.06%
TOOLING	$20,817	$8.67	0.91%
EQUIPMENT	$52,606	$21.92	2.29%
MATERIALS	$610,334	$254.31	26.59%
MAINTENANCE	$64,885	$27.04	2.83%
	$2,295,755	$956.56	100.00%

COST BREAKDOWN BY UNIT OPERATION (material costs removed)

	TOTAL COST	COST/PART	PERCENT
Material	$610,334	$254.31	26.59%
Facilities	$7,559	$3.15	0.33%
Mold Wax Pattern	$23,135	$9.64	1.01%
Assemble Wax Core	$2,189	$0.91	0.10%
Slurry Dip and Dry	$23,237	$9.68	1.01%
Steam Dewax	$3,512	$1.46	0.15%
Cleaning and Inspection	$3,309	$1.38	0.14%
Firing	$29,008	$12.09	1.26%
Melt and Pour	$60,747	$25.31	2.65%
Shakeout	$2,789	$1.16	0.12%
Blasting, Cut-off & Grinding	$26,744	$11.14	1.16%
Final Machining	$1,491,016	$621.26	64.95%
Visual Inspection	$4,104	$1.71	0.18%
Final Inspection, X-ray	$8,073	$3.36	0.35%
	$2,295,755	$956.56	100.00%

APPENDIX B:

Slurry Infiltration Technical Cost Model

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--------------------------------------------------------------------
                         Slurry Infiltration Model
                         Materials Systems Laboratory

                         June 25, 1991
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PRODUCTION INPUTS
_________________________

                                             Units            Value
                          ----------------------------------------
Production Volume           PRODUCT    parts per year          2400
Length                       LENGTH         inch                  8
Width                        WIDTH          inch                 25
Thickness                    THICK          inch              0.375
Fiber Material (see menu)    FIBER                                2
Matrix Material              MATRIX                               1
Slurry Material              SLURRY                               1
Part Volume                  VOLUME      cubic inch              75
Ply Thickness               PLYTHICK        inch             0.0125
Ply per Part                PLYPART                              30
Volume Fraction of Fibers     VF                                0.5
Final Weight of Part         WEIGHT         lbs                9.73
Product Lifetime              LIFE         years                  3
Part Geometry             (part fits in a box this size)
        Effective Length                    inch                 10
        Effective  Width                    inch                 10
        Effective Height                    inch                 10
--------------------------------------------------------------------

Processing Specifications
_________________________
                                             Units            Value
                          ----------------------------------------
Fiber Desizing
-------------------------

Time to Desize One Ply                       hrs                  2
Desizing Furnace                              $             $20,000
Fiber Cloth Width                           inch                 30
Furnace Width                               inch                 60
Furnace Length                              inch                 60
Workers per Furnace                           #                 0.2
Fiber Coating?                            1=yes,0=no              0
Fiber Coating Cost                        $/sq meter         $1,500
```

Slurry Preparation

Slurry Composition		
Percent Precursor	%	20%
Percent Ceramic	%	80%
Precursor Density	g/cc	0
Ceramic Density	g/cc	3.98
Percursor Cost	$/lb	$0.20
Ceramic Cost	$/lb	$0.50
Alumina Feeder Cost	$	$10,500
Metering System Cost	$	$10,000
Tank Cost	$	$6,500
Transfer Pump Cost	$	$5,500
Freezer Cost	$	$1,700
Work Bench Cost	$	$700
Cabinet Cost	$	$650
Material Tester Cost	$	$2,000
Workers per Line	#	0.2
Mixer Rate	cu in/hr/mixer	1386
Space Requirement	sq ft	25

Infiltration

Prepreggor Cost	$	$500,000
Storage Refrigerator Cost	$	$35,000
Test Equipment Cost	$	$10,000
Workers per Slurry Bath	#	0.2
Prepreggor Rate	ft/min	5
Prepreggor Length	inch	60
Prepreggor Width	inch	30
Mylar Film Cost	$/sq ft	$0.12

Tacking

Is Tacking Necessary?	(1=yes,0=no)	0
Time to Tack	hrs	4
Humidity Cabinet Cost	$	$1,000
Width of Humidity Cabinet	inch	60
Workers per Humidity Cabinet	#	0.1

Blank Cutting

Cutting Machine Cost	$	$10,000
Workers per Cutting Machine	#	0.2
Time to Cut	hr	0.05
Mylar Film Cost	$/sq ft	$0.12

Ply Cutting

Ultrasonic Knife Cost	$	$10,000
Manual Cutting Tables	$	$75,000
Cutter Width	inch	30
Workers per Cutting Machine	#	1
Template Design Cost	$/life	$10,000
Cutter Rate	ft/min	3
Template Life	plys/tool	1000000

Load into Mold

Mold Cost	$	$5,000
Mold Life	parts/mold	20
Bench Cost	$	$12,500
Time to Load One Ply	hr/ply	0.5
Is Bleeder Cloth Necessary?	(1=yes,0=no)	1
Bleeder Cloth Cost	$/sq ft	$0.12
Release Film Cost	$/sq ft	$0.51
Workers per Line	#	1

Autoclave

Time to Bag	hr/part	1
Workers to Bag	#	1
Time to Autoclave	hr/part	1
Workers per Autoclave	#	1
Autoclave Length	inch	84
Autoclave Diameter	inch	36
Autoclave Cost	$	$150,000
Autoclave Pressure	psi	200
Bag Cost	$/sq ft	$0.15
Sealant Tapes	$/sq ft	$0.86
Gas Cost	$/cubic meter	$0.50

Remove from Mold

Time to Remove	hr/part	0.01
Workers to Remove	#	1

Post Cure Heat Treatment

Furnace Length	inch	60
Furnace Diameter	inch	60
Time to Cure	hr	1
Workers per Furnace	#	1
Furnace Cost	$	$50,000

Machining

Time to Machine	hr	8
Workers to Machine	#	1
Drill Cost	$	$10,000
Saw Cost	$	$20,000

Quality Control

Is QC Equipment Dedicated?	(1=yes,0=no)	1
Ultrasonic Scanner Cost	$	$2,200,000
Ultrasound Inspection Rate	ft/min	5
Workers per Ultrasound	#	1
Thermographic Test Unit Cost	$	$75,000
Thermographic Inspection Rate	parts/line-hr	0.75
Workers per Thermograph	#	1
Radiographic Test Unit Cost	$	$800,000
Radiographic Inspection Rate	parts/line-hr	0.75
Workers per Radiograph	#	1

Inspection Rates:		
Thermographic	%	100.0%
Radiographic	%	50.0%
Ultrasonic	%	10.0%
Space Requirement	sq ft	100

Exogenous Inputs

		Units	Value
Equipment Dedicated	DEDICATE	(1=yes,0=no)	0
Wage	WAGE	$/hr	$15.00
Benefits	BENEFIT	%	30.0%
Work Days per Year	DAYS	#	180
Shifts per Day	SHIFTS	#	3
Total Time per Year	TIME	hrs	4320
Percent Downtime		%	1
Processing Time per Year	PROCTIME	hrs	4320
Equipment Accounting Life	ACCTLIFE	yrs	5
Opportunity Cost Capital	OPCOST	%	0.12
Maintenance	MAINT	%	30.0%
Facilities Cost	FCOST	$/sq ft	$50

Calculation of Parts Necessary

	Scrap Rate	Units	Number
Number to Start		plys	106928
Fiber Desizing	0.0%	plys	106928
Slurry Preparation		-----	------
Infiltration	1.0%	plys	105858
Tack Fabric	0.0%	plys	105858
Cut Blanks	0.0%	plys	105858
Ply Cutting	2.0%	plys	103740
Load into Mold	5.0%	parts	3285
Autoclave	5.0%	parts	3120
Remove from Mold	0.0%	parts	3120
Post Cure Heat Treatment	10.0%	parts	2808
Machining	10.0%	parts	2527
Quality Control	5.0%	parts	2400
		Total parts	2400

Materials Database

Material Type	Material	$/sq.ft.	Scrap $/lb	Density g/cc
Fiber Cloth				
	1 Alumina	$25.00	$0.00	3.98
	2 Silcon Carbide	$30.00	$0.00	3.21
		$/lb		
Matrices				
	1 Alumina	$0.50	$0.00	3.98
Slurries				
	1	$0.20	$0.10	

Fiber Desizing

Effective Production	plys/yr	106928
Production Rate	plys/hr	24.75
Time to Desize	hrs/ply	2
Fiber Cloth Width	inch	30
Furnace Width	inch	60
Furnace Length	inch	60
Pull Rate	inch/hr	30
Lines per Furnace	#	2
Plys per Furnace	#	15.00
Ply Desizing Rate	plys/furnace-hr	7.50
Number of Furnaces	#	3.30
Workers per Furnace	#	0.2
Number of Workers	#	0.66
Wage (including benefits)	$/hr	$19.50
Part Length	inch	8
Part Width	inch	25
Part Thickness	inch	0.375
Ply Thickness	inch	0.0125
Ply Cross Section	sq in	200
Fiber Cloth Cost	$/sq in	$0.21
Fiber Scrap Price	$/lb	$0.00
Desizing Furnace Cost	$	$20,000
Maintenance	%	30.0%
Fiber Coating Cost	$/sq in.	$0.00
Total Coating Cost	$	$0
Space Requirement	sq ft	267.32

Material		$5,346,400
Labor		$55,603
Equipment		$18,310
	maintenance	$19,801
Facilities		$13,366
Value of Scrap		$0
TOTAL ANNUAL COST		$5,453,480

Slurry Preparation

Effective Production	plys/yr	106928
Fiber Cloth Width	inch	30
Part Length	inch	8
Length of Cloth Pulled	inch	855424
Infiltrated Cloth Area	sq in.	25662720
Ply Thickness	inch	0.0125
Infiltrated Cloth Volume	cu in.	320784
Volume Fraction of Fibers		0.5
Volume of Matrix Needed	cu in.	160392
Required Mixing Rate	cu in./hr	37.13
Total Slurry Volume	cu in.	220539
Slurry Composition		
Percent Polymer Precursor	%	20%
Percent Matrix	%	80%
Precursor Volume	cu in.	44107.8
Matrix Volume	cu in.	176431.2
Precursor Cost	$/lb	$0.20
Matrix Cost	$/lb	$0.50
Precursor Weight	lbs.	0
Matrix Weight	lbs.	25346
Alumina Feeder Cost	$	$10,500
Metering System	$	$10,000
Tank Cost	$	$6,500
Transfer Pump Cost	$	$5,500
Freezer Cost	$	$1,700
Work Bench Cost	$	$700
Cabinet Cost	$	$650
Material Tester Cost	$	$2,000
Workers per Line	#	0.2
Actual Mixing Rate	cu in./hr/mixer	1386
Number of Lines	#	0.03
Number of Workers	#	0.01
Wage (including benefits)	$/hr	$19.50
Maintenance	%	30.0%
Space Requirement	sq ft	0.66969296

Material		$12,673
Labor		$621
Equipment		$279
	maintenance	$302
Facilities		$33
Value of Scrap		$0

TOTAL ANNUAL COST	$13,908

Infiltrate the Fabric

Effective Production	plys/yr	106928
Production Rate	plys/hr	24.75
Prepreggor Cost	$	$500,000
Storage Refrigerator Cost	$	$35,000
Test Equipment Cost	$	$10,000
Length of Prepreggor	inch	60
Width of Prepreggor	inch	30
Fiber Cloth Width	inch	30
Part Length	inch	8
Total Ply Area	sq ft	178213.333
Mylar Film Requirement	sq ft	356426.666
Mylar Film Cost	$/sq ft	$0.12
Lines per Prepreggor	#	1
Prepreggor Rate	ft/hr	300
Ply Infiltration Rate	plys/bath-hr	450
Number of Prepreggors	#	0.06
Workers per Prepreggor	#	0.2
Number of Workers	#	0.01
Wage (including benefits)	$/hr	$19.50
Maintenance	%	30.0%
Space Requirement	sq ft	3.21774074

Material		$42,771
Labor		$927
Equipment		$8,316
	maintenance	$8,993
Facilities		$161
Value of Scrap		$0
TOTAL ANNUAL COST		$61,168

Tacking

Is Tacking Necessary?	(1=yes,0=no)	0
Effective Production	plys/yr	105858
Production Rate	plys/hr	24.50
Pull Rate	inch/hr	30
Time to Tack	hr	4
Fiber Cloth Width	inch	30
Width of Humidity Cabinet	inch	60
Length of Humidity Cabinet	inch	120
Lines per Humidity Cabinet	#	2
Plys per Humidity Cabinet	#	30
Ply Tacking Rate	plys/cabinet-hr	7.5
Number of Cabinets	#	3.27
Workers per Cabinet	#	0.1
Number of Workers	#	0.33
Wage (including benefits)	$/hr	$19.50
Humidity Cabinet Cost	$	$1,000
Maintenance	%	30.0%

Material	$0
Labor	$0
Equipment	$0
Facilities	$0

TOTAL ANNUAL COST	$0

Blank Cutting

Effective Production	plys/yr	105858
Production Rate	plys/hr	24.50
Time to Cut	hr	0.05
Blank Cutting Rate	blanks/cutter-hr	20
Number of Cutters	#	1.23
Workers per Cutter	#	0.2
Number of Workers	#	0.25
Wage (including benefits)	$/hr	$19.50
Cutting Machine Cost	$	$10,000
Maintenance	%	30.0%
Fiber Cloth Width	inch	30
Blank Length	inch	8
Total Ply Area	sq ft	176430
Mylar Film Requirement	sq ft	176430
Mylar Film Cost	$/sq ft	$0.12
Ply Thickness	inch	0.0125
Blank Volume	cu. in	3
Fiber Volume Fraction	%	0.5
Fiber Density	lbs/cu.in.	0.12
Fiber Scrap Price	$/lb	$0.00
Matrix Density	lbs/cu.in.	0.14
Matrix Scrap Price	$/lb	$0.00
Space Requirement	sq ft	39.8192708

Material		$21,172
Labor		$20,642
Equipment		$3,399
	maintenance	$3,676
Facilities		$1,991
Value of Scrap		$0
TOTAL ANNUAL COST		$50,879

Ply Cutting

Effective Production	plys/yr	105858
Production Rate	plys/hr	24.50
Cutter Rate	ft/hr	3
Cutter Width	inch	30
Lines per Cutter	#	1
Ply Cutting Rate	plys/cutter-hr	4.5
Number of Cutters	#	5.45
Template Life	#	1000000
Total Template	#/life	1
Template Cost	$/yr	$4,163
Workers per Cutter	#	1
Number of Workers	#	5.45
Template Design Cost	$	$10,000
Ultrasonic Knife	$	$10,000
Manual Cutting Table Cost	$	$75,000
Part Length	inch	8
Part Width	inch	25
Ply Thickness	inch	0.0125
Ply Volume	cu in.	2.5
Blank Volume	cu in.	3
Scrap Volume	cu in.	58224
Fiber Volume Fraction	%	0.5
Wage (including benefits)	$/hr	$19.50
Maintenance	%	30.0%
Fiber Density	lbs/cu.in.	0.12
Fiber Scrap Price	$/lb	$0.00
Matrix Density	lbs/cu.in.	0.14
Matrix Scrap Price	$/lb	$0.00
Space Requirement	sq ft	165.18

Material		$0
Labor		$458,718
Equipment		$128,401
	template cost	$4,163
	maintenance	$138,857
Facilities		$8,259
Value of Scrap		$0
TOTAL ANNUAL COST		$738,398

Load into Mold

Effective Production	parts/yr	3458
Production Rate	parts/hr	0.80
Plys per Part	#	30
Bench Cost	$	$12,500
Is Bleeder Cloth Necessary?	(1=yes,0=no)	1
Bleeder Cloth Cost	$/sq ft	$0.12
Release Film Cost	$/sq ft	$0.51
Part Cross Section	sq ft	1.39
Time to Load One Ply	hr/ply	0.5
Time per Part	hr/part	16.5
Part Loading Rate	parts/line-hr	0.06
Number of Lines	#	13.21
Total Molds	#/life	519
Mold Cost	$	$5,000
Mold Life	parts/mold	20
Workers per Line	#	1
Part Volume	cu in.	75
Fiber Volume Fraction	%	0.5
Wage (including benefits)	$/hr	$19.50
Maintenance	%	30.0%
Fiber Density	lbs/cu.in.	0.12
Fiber Scrap Price	$/lb	$0.00
Matrix Density	lbs/cu.in.	0.14
Matrix Scrap Price	$/lb	$0.00
Space Requirement	sq ft	374.95

Material		$4,899
Labor		$1,112,612
Equipment		$45,799
	molds	$1,080,426
	bleeder cloth	$576
	maintenance	$49,529
Facilities		$18,748
Value of Scrap		$0
TOTAL ANNUAL COST		$2,312,588

Autoclave

Effective Production	parts/yr	3285
Production Rate	parts/hr	0.76
Time to Bag	hr/part	1
Part Bagging Rate	parts/line-hr	1
Workers to Bag	#	1
Time to Cure	hr	1
Part Curing Rate	part/autoclave-h	72
Workers per Autoclave	#	1
Autoclave Length	inch	84
Autoclave Diameter	inch	36
Parts per Autoclave	#	72
Number of Autoclaves	#	0.01
Autoclave Cost	$	$150,000
Wage (including benefits)	$/hr	$19.50
Maintenance	%	30.0%
Autoclave Pressure	psi	200
Gasses Used (ambient pressure)	cubic meter	74.72
Gas Cost	$/cubic meter	$0.50
Bag Cost	$/sq ft	0.15
Sealant Tape Cost	$/sq ft	0.86
Area of Bag & Sealant	sq ft	9689.60937
Number of Autoclave Cycles	#	46
Part Volume	cubic inch	75
Fiber Volume Fraction	%	0.5
Fiber Density	lbs/cu.in.	0.12
Fiber Scrap Price	$/lb	$0.00
Matrix Density	lbs/cu.in.	0.14
Matrix Scrap Price	$/lb	$0.00
Space Requirement	sq ft	0.81322337

Material		$11,505
Labor		$64,947
Equipment		$439
	maintenance	$475
Facilities		$41
Value of Scrap		$0
TOTAL ANNUAL COST		$77,408

Remove from Mold

Effective Production	parts/yr	3120
Production Rate	parts/hr	0.72
Time to Remove	hr/part	0.01
Part Removal Rate	parts/line-hr	100
Workers per Line	#	1
Number of Lines	#	1
Number of Workers	#	1
Wage (including benefits)	$/hr	$19.50
Part Volume	cubic inch	75
Fiber Volume Fraction	%	0.5
Fiber Density	lbs/sq.in.	0.12
Fiber Scrap Price	$/lb	$0.00
Matrix Density	lbs/sq.in.	0.14
Matrix Scrap Price	$/lb	$0.00
Space Requirement	sq ft	28.39

Material	$0
Labor	$608
Equipment	$0
Facilities	$1,419
Value of Scrap	$0
TOTAL ANNUAL COST	$2,028

Post Cure Heat Treatment

Effective Production	parts/yr	3120
Production Rate	parts/hr	0.72
Furnace Length	inch	60
Furnace Width	inch	60
Parts per Furnace	#	216
Time to Cure	hr	1
Part Curing Rate	parts/hr	216
Number of Furnaces	#	0.00
Workers per Furnace	#	1
Furnace Cost	$	$50,000
Wage (including benefits)	$/hr	$19.50
Maintenance	%	30.0%
Part Volume	cubic in.	75
Space Requirement	sq ft	0.27083333

Material		$0
Labor		$282
Equipment		$46
	maintenance	$50
Facilities		$14
Value of Scrap		$0

TOTAL ANNUAL COST	$392

Machining

Effective Production	parts/yr	2808
Production Rate	parts/hr	0.65
Time to Machine	hr	8
Workers per Line	#	1
Part Machining Rate	parts/machine-hr	0.125
Number of Machining Lines	#	5.20
Number of Workers	#	5.20
Drill Cost	$	$10,000
Saw Cost	$	$20,000
Wage (including benefits)	$/hr	$19.50
Maintenance	%	30.0%
Part Volume	cubic in.	75
Space Requirement	sq ft	147.62
Material		$0
Labor		$438,048
Equipment		$43,276
	maintenance	$46,800
Facilities		$7,381
Value of Scrap		$0
TOTAL ANNUAL COST		$535,505

Quality Control

Effective Production	parts/yr	2527
Production Rate	parts/hr	0.58
Is QC Equipment Dedicated?	(1=yes,0=no)	1
Ultrasonic Scanner Cost	$	$2,200,000
Ultrasound Capacity	ft/hr	300
Ultrasound Inspection Rate	parts/line-hr	450
Workers per Ultrasound	#	1
Thermographic Test Unit Cost	$	$75,000
Thermographic Inspection Rate	parts/line-hr	0.75
Workers per Thermograph	#	1
Radiographic Test Unit Cost	$	$800,000
Radiographic Inspection Rate	parts/line-hr	0.75
Workers per Radiograph	#	1
Inspection Rates:		
Thermographic	%	100.0%
Radiographic	%	50.0%
Ultrasonic	%	10.0%
Parts to be Inspected		
Thermographic	parts	2527
Radiographic	parts	1264
Ultrasonic	parts	253
Number of Ultrasounds	#	1.00
Number of Thermographic Units	#	1.00
Number of Radiographic Units	#	1.00
Wage (including benefits)	$/hr	$19.50
Maintenance	%	30.0%
Part Volume	cubic in.	75
Fiber Volume Fraction	%	0.5
Fiber Density	lbs/sq.in.	0.12
Fiber Scrap Price	$/lb	$0.00
Matrix Density	lbs/sq.in.	0.14
Matrix Scrap Price	$/lb	$0.00
Space Requirement	sq ft	100

Material		$0
Labor		$98,577
Equipment		$853,035
	maintenance	$922,500
Facilities		$5,000
Value of Scrap		$0

TOTAL ANNUAL COST		$1,879,112

SUMMARY OF EXPENSES

	TOTAL COST	COST/PART	PERCENT
Fiber Desizing	$5,453,480	$2,272.28	49.0%
Slurry Preparation	$13,908	$5.79	0.1%
Infiltration	$61,168	$25.49	0.5%
Tack Fabric	$0	$0.00	0.0%
Cut Blanks	$50,879	$21.20	0.5%
Ply Cutting	$738,398	$307.67	6.6%
Load into Mold	$2,312,588	$963.58	20.8%
Autoclave	$77,408	$32.25	0.7%
Remove from Mold	$2,028	$0.84	0.0%
Post Cure Heat Treatment	$392	$0.16	0.0%
Machining	$535,505	$223.13	4.8%
Quality Control	$1,879,112	$782.96	16.9%
TOTAL	$11,124,865	$4,635.36	100.0%

COST BREAKDOWN BY FUNCTION

	TOTAL COST	COST/PART	PERCENT
Materials	$5,439,420	$2,266.42	48.9%
Labor	$2,251,584	$938.16	20.2%
Equipment	$2,186,466	$911.03	19.7%
Maintenance	$1,190,983	$496.24	10.7%
Facilities	$56,412	$23.51	0.5%
TOTAL	$11,124,865	$4,635.36	100.0%

COST BREAKDOWN BY UNIT OPERATION (material costs removed)

	TOTAL COST	COST/PART	PERCENT
Material	$5,439,420	$2,266.42	48.9%
Fiber Desizing	$107,080	$44.62	1.0%
Slurry Preparation	$1,235	$0.51	0.0%
Infiltration	$18,397	$7.67	0.2%
Tack Fabric	$0	$0.00	0.0%
Cut Blanks	$29,708	$12.38	0.3%
Ply Cutting	$738,398	$307.67	6.6%
Load into Mold	$2,307,689	$961.54	20.7%
Autoclave	$65,903	$27.46	0.6%
Remove from Mold	$2,028	$0.84	0.0%
Post Cure Heat Treatment	$392	$0.16	0.0%
Machining	$535,505	$223.13	4.8%
Quality Control	$1,879,112	$782.96	16.9%
TOTAL	$11,124,865	$4,635.36	100.0%

APPENDIX C:

Chemical Vapor Infiltration Technical Cost Model

Chemical Vapor Infiltration Model
Materials Systems Laboratory

March 11, 1991

PRODUCTION INPUTS

		Units	Value
Production Volume	PRODUCT	parts per year	2400
Length	LENGTH	inch	8
Width	WIDTH	inch	25
Thickness	THICK	inch	0.375
Fiber Material (see menu)	FIBER		2
Matrix Material	MATRIX		1
Part Volume	VOLUME	cubic inch	75
Ply Thickness	PLYTHICK	inch	0.0125
Ply per Part	PLYPART		30
Volume Fraction of Fibers	VF		0.5
Final Weight of Part	WEIGHT	lbs	269.25
Product Lifetime	LIFE	years	3
Part Geometry			
Effective Length		inch	10
Effective Width		inch	10
Effective Height		inch	10

Processing Specifications

	Units	Value
Fiber Desizing		
Time to Desize One Ply	hrs	2
Desizing Furnace	$	$20,000
Fiber Cloth Width	inch	40
Furnace Width	inch	60
Furnace Length	inch	60
Workers per Furnace	#	0.2
Fiber Coating?	1=yes,0=no	0
Fiber Coating Cost	$/sq meter	$1,500
Blank Cutting		
Cutting Machine Cost	$	$10,000
Workers per Cutting Machine	#	0.2
Time to Cut	hr	0.05

Ply Cutting

Cutting Machine Cost	$	$50,000
Workers per Cutting Machine	#	1
Template Cost	$	$10,000
Time to Cut	hr/ply	0.02

Layup

Time to Layup	hr	2.5
Workers per Line	#	1

Infiltration

Number of Infiltration Steps Required	#	2
Time to Infiltrate (1st pass)	hrs/part	2000
Time to Infiltrate (2nd pass)	hrs/part	1500
Form of Infiltration Time Function: (1=exponential, 2=linear, 3=constant)		1
Workers per Line	#	1
Gas Flow Rate	cubic ft/hr	0.1
Gas Composition		2
Gas #1 (see menu)		1
Gas #2 (see menu)		2
Gas #3 (see menu)		0
Percent Gas #1	%	50.0%
Percent Gas #2	%	50.0%
Percent Gas #3	%	0.0%
Infiltration Chamber Cost	$	$1,000,000
Infiltration Chamber Length	inch	84
Infiltration Chamber Diameter	inch	48

Machining

Time to Machine	hrs/part	8
Workers per Line	#	1
Machine Cost	$	$400
Space Requirement	sq ft	100

Final Machining

Time to Machine	hr	4
Workers per Line	#	1
Machine Cost	$	$1,000

Final Coating

Time to Coat	hr	24
CVD Unit	$	$1,000,000
Workers per Line	#	1
CVD Chamber Length	inch	84
CVD Chamber Diameter	inch	48

Quality Control

Is QC Dedicated?	(1=yes,0=no)	1
Ultrasonic Scanner Cost	$	$2,200,000
Ultrasonic Scanner Capacity	ft/hr	300
Workers per Ultrasonic Scanner	#	1
Ultrasound Space Requirement	sq ft	50
Thermographic Test Unit Cost	$	$75,000
Thermographic Inspection Rate	parts/line hr	0.75
Workers per Thermograph	#	1
Thermograph Space Requirement	sq ft	25
Radiographic Test Unit Cost	$	$800,000
Radiographic Inspection Rate	parts/line hr	0.75
Workers per Radiograph	#	1
Radiograph Space Requirement	sq ft	25
Inspection Rates:		
Thermographic	%	100%
Radiographic	%	50%
Ultrasonic	%	10%
Space Requirement	sq ft	100

Exogenous Inputs

		Units	Value
Dedicated Equipment	DEDICATE	(1=yes,0=no)	1
Wage	WAGE	$/hr	$15.00
Benefits	BENEFIT	%	30.0%
Work Days per Year	DAYS	#	180
Shifts per Day	SHIFTS	#	3
Total Time per Year	TIME	hrs	4320
Percent Downtime		%	1
Processing Time per Year	PROCTIME	hrs	4320
Equipment Accounting Life	ACCTLIFE	yrs	5
Opportunity Cost Capital	OPCOST	%	12.0%
Maintenance	MAINT	%	30.0%
Facility Cost	FCOST	$/sq ft	$50

Calculation of Parts Necessary

	Scrap Rate	Units	Number
Number to Start		plys	108327
Fiber Desizing	0.0%	plys	108327
Cut Blanks	1.0%	plys	107243
Cut Plys	1.0%	plys	106170
Layup	0.0%	parts	3539
Infiltration (first step)	1.0%	parts	3503
:			:
:			:
Machining (last step)	10.0%	parts	2808
Final Machining	10.0%	parts	2527
Final Coating	0.0%	parts	2527
Quality Control	5.0%	parts	2400
		Total parts	2400

```
    Number of Interations                   2

    INFILTRATION                                              99.0%
  1                           0.0%         0.99               3503
  2                           0.0%         0.99               3120
  3                           0.0%           NA                 NA
  4                           0.0%           NA                 NA
  5                           0.0%           NA                 NA
  6                           0.0%           NA                 NA
  7                           0.0%           NA                 NA
  8                           0.0%           NA                 NA
  9                           0.0%           NA                 NA
 10                           0.0%           NA                 NA

    MACHINING                                                 90.0%
  1                           0.0%          0.9               3152
  2                           0.0%          0.9               2808
  3                           0.0%           NA                 NA
  4                           0.0%           NA                 NA
  5                           0.0%           NA                 NA
  6                           0.0%           NA                 NA
  7                           0.0%           NA                 NA
  8                           0.0%           NA                 NA
  9                           0.0%           NA                 NA
 10                           0.0%           NA                 NA
                                                              2808
```

Materials Database

Material Type		Material	$/sq.ft.	Scrap $/lb	Density g/cc
Fiber Cloth					
	1	Alumina	$25.00	$0.00	3.98
	2	Silcon Carbide	$30.00	$0.00	3.2
			$/lb		
Matrices					
	1	Alumina	$0.50	$0.10	3.98
	2	Silicon Carbide			
			$/cu.ft.		
Gases	1	CH3SiCl3	$0.20		
	2	H2	$0.10		
	3	AlCl3	$0.20		
	4	CO2	$0.05		
	5	Al(CH3)3	$0.20		
	6	O2	$0.05		
	7	Al[OCH(CH3)2]3	$0.20		
	8	Al(OC2H5)3	$0.20		
Gas Systems			Gas #1	Gas #2	Gas #3
	1	Alumina #1	3	2	4
		percentage	50.0%	25.0%	25.0%
	2	Alumina #2	5	6	
		percentage	50.0%	50.0%	
	3	Silicon Carbide #1	1	2	
		percentage	50.0%	50.0%	

Fiber Desizing

Effective Production	plys/yr	13543
Production Rate	plys/hr	3.13
Time to Desize	hrs/ply	2
Fiber Cloth Width	inch	40
Furnace Width	inch	60
Furnace Length	inch	60
Pull Rate	inch/hr	30
Lines per Furnace	#	1.5
Plys per Furnace	#	11.25
Ply Desizing Rate	plys/furnace-hr	5.625
Number of Furnaces	#	1
Workers per Furnace	#	0.2
Number of Workers	#	0.2
Wage (including benefits)	$/hr	$19.50
Part Length	inch	8
Part Width	inch	25
Part Thickness	inch	0.375
Ply Thickness	inch	0.1
Ply Cross Section	sq in	200
Fiber Cloth Cost	$/sq in	$0.21
Fiber Scrap Price	$/lb	$0.00
Desizing Furnace	$	$20,000
Maintenance	%	30.0%
Fiber Coating Cost	$/sq in.	$0.00
Total Coating Cost	$	$0
Space Requirement	sq ft	81

Material		$902,867
Labor		$9,390
Equipment		$5,548
	maintenance	$6,000
Facilities		$4,050
Value of Scrap		$0
TOTAL ANNUAL COST		$927,855

Blank Cutting

Effective Production	plys/yr	13543
Production Rate	plys/hr	3.13
Time to Cut	hr	0.05
Blank Cutting Rate	blanks/cutter-hr	20
Number of Cutters	#	1.00
Workers per Cutter	#	0.2
Number of Workers	#	0.20
Wage (including benefits)	$/hr	$19.50
Cutting Machine Cost	$	$10,000
Maintenance	%	30.0%
Fiber Cloth Width	inch	40
Blank Length	inch	8
Ply Thickness	inch	0.1
Blank Volume	cu in.	32
Space Requirement	sq ft	36.67

Material		$0
Labor		$2,641
Equipment		$2,774
	maintenance	$3,000
Facilities		$1,833

TOTAL ANNUAL COST	$10,248

Ply Cutting

Effective Production	plys/yr	13407
Production Rate	plys/hr	3.10
Time to Cut	hr/ply	0.02
Ply Cutting Rate	ply/cutter-hr	50
Number of Cutters	#	1.00
Number of Lines	#	1
Tools per Line	#/life	1
Tool Cost	$/yr	$4,163
Workers per Cutter	#	1
Number of Workers	#	1
Template Design Cost	$	$10,000
Cutting Machine Cost	$	$50,000
Part Length	inch	8
Part Width	inch	25
Ply Thickness	inch	0.1
Ply Volume	cu. in.	20
Blank Volume	cu. in.	32
Scrap Volume	cu. in.	163584
Fiber Volume Fraction	%	0.5
Wage (including benefits)	$/hr	$19.50
Maintenance	%	30.0%
Fiber Density	lb/cu. in.	0.12
Fiber Scrap Price	$/lb	$0.00
Space Requirement	sq ft	34.22
Material		$0
Labor		$5,229
Equipment		$13,870
	maintenance	$15,000
Facilities		$1,711
Value of Scrap		$0
TOTAL ANNUAL COST		$35,810

Layup

Effective Production	parts/yr	3539
Production Rate	parts/hr	0.82
Time to Layup	hrs	2.5
Part Layup Rate	parts/line-hr	0.4
Workers per Line	#	1
Number of Lines	#	3
Number of Workers	#	3
Wage (including benefits)	$/hr	$19.50
Fiber Volume Fraction	%	0.5
Fiber Density	lb/cu in	0.12
Fiber Scrap Price	$/lb	0
Part Volume	cu in	75
Space Requirement	sq ft.	85.17

Material	$0
Labor	$172,526
Equipment	$0
Facilities	$4,258
Value of Scrap	$0

TOTAL ANNUAL COST	$176,785

Infiltration

Form of Infiltration Time Function: (1=exponential, 2=linear, 3=constant)			1
Time to Infiltrate (1st pass)		hrs/part	2000
Time to Infiltrate (2nd pass)		hrs/part	1500
Infiltration Function Parameters			
Exponential			-0.14384103
Linear: Slope			0
Intercept			0
Gas Flow Rate		cubic ft/hr	0.1
Gas Composition			2
$\mathrm{Al(CH_3)_3}$	50.0%		
$\mathrm{O_2}$	50.0%		
Gas Cost		$/cu.ft.	$0.13
Workers per Infiltration Chamber		#	1
Wage (including benefits)		$/hr	$19.50
Infiltration Chamber Cost		$	$1,000,000
Chamber Length		inch	84
Chamber Diameter		inch	48
Parts per Infiltration Chamber		#	112
Maintenance		%	30.0%
Space Requirement per Chamber		sq ft	88

	Effective Production	Time to Infiltrat	Labor Cost	Material Cost	Number of Machines	Scrap Volume
Step 1	3503	2000.000	$1,232,330	$88,475	15	2700
2	3120	1500.000	$914,846	$65,681	11	2400
3	NA	NA	$0	$0	0	0
4	NA	NA	$0	$0	0	0
5	NA	NA	$0	$0	0	0
6	NA	NA	$0	$0	0	0
7	NA	NA	$0	$0	0	0
8	NA	NA	$0	$0	0	0
9	NA	NA	$0	$0	0	0
10	NA	NA	$0	$0	0	0
11	NA	NA	$0	$0	0	0
12	NA	NA	$0	$0	0	0
13	NA	NA	$0	$0	0	0
14	NA	NA	$0	$0	0	0
15	NA	NA	$0	$0	0	0
16	NA	NA	$0	$0	0	0
17	NA	NA	$0	$0	0	0
18	NA	NA	$0	$0	0	0
19	NA	NA	$0	$0	0	0
20	NA	NA	$0	$0	0	0
			$2,147,176	$154,156	26	5126

Material		$154,156
Labor		$2,147,176
Equipment		$7,212,653
	maintenance	$7,800,000
Facilities		$114,400
Value of Scrap		$0
TOTAL ANNUAL COST		$17,428,386

Machining

Time to Machine	hrs/part	8
Workers per Line	#	1
Machine Cost	$	$400
Wage (including benefits)	$/hr	$19.50
Maintenance	%	30.0%
Space Requirement per Line	sq ft	28.39

	Effective Production	Labor Cost	Number of Lines	Scrap Volume
Step 1	3152	$546,468	7	26325
2	2808	$486,720	6	23400
3	NA	$0	0	0
4	NA	$0	0	0
5	NA	$0	0	0
6	NA	$0	0	0
7	NA	$0	0	0
8	NA	$0	0	0
9	NA	$0	0	0
10	NA	$0	0	0
11	NA	$0	0	0
12	NA	$0	0	0
13	NA	$0	0	0
14	NA	$0	0	0
15	NA	$0	0	0
16	NA	$0	0	0
17	NA	$0	0	0
18	NA	$0	0	0
19	NA	$0	0	0
20	NA	$0	0	0
		$1,033,188	13	49725

Material		$0
Labor		$1,033,188
Equipment		$1,443
	maintenance	$1,560
Facilities		$18,453
Value of Scrap		$0
TOTAL ANNUAL COST		$1,054,643

Final Machining

Effective Production	parts/yr	2808
Production Rate	parts/hr	0.65
Time to Machine	hr	4
Part Machining Rate	parts/line-hr	0.25
Workers per Line	#	1
Number of Machines	#	3
Machine Cost	$	$1,000
Wage (including benefits)	$/hr	$19.50
Maintenance	%	30.0%
Part Volume	cubic inch	75
Space Requirement	sq ft.	85.17

Material		$0
Labor		$219,024
Equipment		$832
	maintenance	$900
Facilities		$4,258
Value of Scrap		$0

TOTAL ANNUAL COST	$225,015

Final Coating

Effective Production	part/yr	2527
Production Rate	part/hr	0.58
Time to Coat	hr	24
Chamber Length	inch	84
Chamber Diameter	inch	48
Parts per CVD Chamber	#	112
Part Coating Rate	parts/line-hr	4.67
Number of Coating Machines	#	1
Workers per Line	#	1
Coating Machine Cost	$	$1,000,000
Gas Flow Rate	cu ft/hr	0.1
Gas Cost	$/cu ft	$0.13
Wage (including benefits)	$/hr	$19.50
Maintenance	%	30.0%
Part Volume	cubic inch	75
Space Requirement	sq ft	88.00
Material		$0
Labor		$10,559
Equipment		$277,410
	maintenance	$300,000
Facilities		$4,400
TOTAL ANNUAL COST		$592,369

Quality Control

Effective Production	parts/yr	2527
Production Rate	parts/hr	0.58
Is QC Equipment Dedicated?	(1=yes,0=no)	1
Ultrasonic Scanner Cost	$	$2,200,000
Ultrsonic Scanner Capacity	ft/hr	300
Ultrasonic Inspection Rate	parts/line hr	450
Workers per Ultrasound	#	1
Ultrasound Space Requirement	sq ft	50
Thermographic Test Unit Cost	$	$75,000
Thermographic Inspection Rate	parts/line hr	0.75
Workers per Thermograph	#	1
Thermograph Space Requirement	sq ft	25
Radiographic Test Unit Cost	$	$800,000
Radiographic Inspection Rate	parts/line hr	0.75
Workers per Radiograph	#	1.00
Radiograph Space Requirement	sq ft	25
Inspection Rates:		
Thermographic	%	100%
Radiographic	%	50%
Ultrasonic	%	10%
Parts to be Inspected		
Thermographic	parts	2527
Radiographic	parts	1264
Ultrasonic	parts	253
Number of Ultrsonic Scanners	#	1
Number of Thermographic Units	#	1
Number of Radiographic Units	#	1
Wage (including benefits)	$/hr	$19.50
Maintenance	%	30.0%
Total Space Requirements	sq ft	100

Material		$0
Labor		$72,291
Equipment		$853,035
	maintenance	$922,500
Facilities		$5,000
Value of Scrap		$0

TOTAL ANNUAL COST	$1,847,826

Summary of Expenses

	TOTAL COST	COST/PART	PERCENT
Fiber Desizing	$927,855	$386.61	4.16%
Blank Cutting	$10,248	$4.27	0.05%
Ply Cutting	$35,810	$14.92	0.16%
Layup	$176,785	$73.66	0.79%
Infiltration	$17,428,386	$7,261.83	78.16%
Machining	$1,054,643	$439.43	4.73%
Final Machining	$225,015	$93.76	1.01%
Final Coating	$592,369	$246.82	2.66%
Quality Control	$1,847,826	$769.93	8.29%
	$22,298,937	$9,291.22	100.00%

COST BREAKDOWN BY FUNCTION

	TOTAL COST	COST/PART	PERCENT
Materials	$1,057,023	$440.43	4.74%
Labor	$3,672,024	$1,530.01	16.47%
Equipment	$8,367,565	$3,486.49	37.52%
Maintenance	$9,048,960	$3,770.40	40.58%
Facilities	$153,364	$63.90	0.69%
	$22,298,937	$9,291.22	100.00%

COST BREAKDOWN BY UNIT OPERATION (material costs removed)

	TOTAL COST	COST/PART	PERCENT
Materials	$1,057,023	$440.43	4.74%
Fiber Desizing	$24,988	$10.41	0.11%
Blank Cutting	$10,248	$4.27	0.05%
Ply Cutting	$35,810	$14.92	0.16%
Layup	$176,785	$73.66	0.79%
Infiltration	$17,274,229	$7,197.60	77.47%
Machining	$1,054,643	$439.43	4.73%
Final Machining	$225,015	$93.76	1.01%
Final Coating	$592,369	$246.82	2.66%
Quality Control	$1,847,826	$769.93	8.29%
	$22,298,937	$9,291.22	100.00%

APPENDIX D:

MAUA Preliminary Survey

Table I:

	Characteristic	Relevant	
1.	Operating Temperature	Yes	No
2.	Part Weight	Yes	No
3.	Cost	Yes	No
4.	____________________		
5.	____________________		
6.	____________________		

Table 2:

Characteristic	Typical	Minimum	Maximum
1. Operating Temperature (°C)	1000	700	1500
corrected values:	________	________	________
2. Part Weight (lbs.)	20	5	25
corrected values:	________	________	________
3.			
4.			
5.			
6.			

Questions/Comments:

APPENDIX E:

MAUA Questionnaire

Multi-Attribute Utility Analysis

QUESTIONNAIRE

High Temperature Aircraft Gas Turbine Applications
Exhaust Ducts

Richard Roth

Materials Systems Laboratory
Massachusetts Institute of Technology

INTRODUCTION

This questionnaire is designed to explore your preferences briefly for different performance characteristics of exhaust ducts. This format may be limiting in some ways, so please feel free to comment on its content and format. The procedures used in this questionnaire, known collectively as Multi-attribute Utility Analysis, have been validated in theory and in practice, but their use in this form is experimental.

The purpose of this questionnaire is not to model the decision-making environment, but rather to provide insight into how you, the decision-maker, view the necessary trade-offs associated with material selection for exhaust ducts. It is designed to acquire an understanding of your expert professional judgment. As such, there are no right or wrong answers to these questions. Rather, the purpose of this session is to learn, through your answers, how you value the various performance attributes of an exhaust duct.

Questionnaire Structure

This questionnaire is directed toward an engineer or manager involved with the design of an aircraft gas turbine engine. It is especially intended for an engineer determining the engineering performance criteria used to make exhaust duct material selection decisions in medium size engines (approximately 1000 lbs. of thrust).

The questionnaire is based on the following scenario. Consider yourself to be heading a design team responsible for developing a missile engine. Most of the work is complete; the only remaining decision is which of two duct manufacturers will supply the part. At your request, your engineers have gathered some initial data to aid your decision. I will present scenarios which ask you to make a selection decision based on this data.

Explanation

This questionnaire is primarily composed of specific questions regarding your preference between pairs of options, called lotteries. Each lottery will be expressed as a current condition, and explicit probability **p** of improving to a future state, and an implicit probability **1-p** of remaining in the current state. For the first option, the probability of improvement will be fixed at 50%. In the second option, you will be asked to adjust the probability **p** of improvement, using a technique called bracketing, until the two lotteries are equivalent; that is, until you value the two options equally. Graphically, the uncertain situation appears as follows:

Current Situation	50%	--->	Future Option #1
	- OR -		
Current Situation	p	--->	Future Option #2

In a few moments, we will go through a practice scenario to acquaint you further with this type of procedure.

I recognize that be expressing decision problems in this way I am asking you to react to an artificial situation. However, please bear with me and try to answer the questions as completely and as thoroughly as you can.

Exhaust Ducts

Through preliminary discussions, I have selected several characteristics of exhaust ducts which are considered when choosing a material/process for part fabrication (Table 1).

TABLE 1 - Relevance of Characteristics

Characteristic	**Relevance**	
1. Maximum Operating Temperature	Yes	No
2. Strength	Yes	No
3. Toughness	Yes	No
4. Coefficient of Thermal Expansion	Yes	No
5. Density (Weight)	Yes	No
6. Cost	Yes	No

In order to provide a quantitative basis for evaluation, several reference points must be established for each attribute. Table 2 contains approximate typical, maximum and minimum values for each attribute. Do you agree with these assessments?

TABLE 2 - Attribute Values

Characteristic	Units	Minimum	Intermediate	Maximum
1. Maximum Operating Temperature	°C	750	1000	1500
2. Tensile Strength	ksi	10	30	60
3. Fracture Toughness	$\mathrm{MPa}\sqrt{\mathrm{m}}$	10	30	60
4. CTE Mismatch	10^{-6} in/in/°F	0	4	8
5. Density (Weight)	g/cc	1.8	6	9
6. Cost	$	1000	5000	10000

PRACTICE SCENARIO

At this point, it is instructive to go through a practice example that is illustrative of the use of Multi-attribute Utility Analysis. The practice session will examine the trade-off between hypothetical amounts of two familiar quantities: annual salary and vacation time. The questions would be posed as follows.

PART A:

Practice: Salary (single attribute)

Suppose that you have two job offers, one from Company A and the other from Company B. Each job has the same starting salary of $35,000. Based on your own knowledge and information from a contact within Company A, you estimate that there is 50% chance that the salary would soon increase to $50,000.

Your are aware that Company B has a history of offering larger pay raises than Company A, to $60,000. This pay raise, however is less likely than at Company A. As far as you can determine, all other aspects of the two companies are identical.

What probability **p** of a pay raise from $35,000 to $60,000 at Company B would be necessary to make this offer indifferent to the 50% probability of a pay raise from $35,000 to $50,000 at Company A?

$35,000	50%	--->	$50,000
	- OR -		
$35,000	**p**	--->	$60,000

Practice: Vacation (single attribute)

Now imagine two unrelated job offers, this time from Companies C and D. Both firms allow 10 paid vacation days per year. You estimate that after one year with Company C, the chance of an increase to 15 days is 50%.

Company D is less likely to offer an increase in paid vacation days at the end of one year. This increase, however, is expected to bring the total to 20 days. All other aspects of Companies C and D are identical.

What probability **p** of an increase in vacation days from 10 to 20 at Company D would make the offer comparable to the 50% probability of the increase from 10 to 15 days at Company C?

10 days 50% ---> 15 days

- OR -

10 days **p** ---> 20 days

PART B:

Practice: Salary (scaling coefficient)

You have accepted one of the job offers previously mentioned. Your starting salary is $35,000 with 10 days of paid vacation. The company is small, and there exists the possibility for rapid advancement, depending on how your manager views your work habits.

If you are conservative, you figure that there is a 50% probability of being promoted, with a new salary of $60,000 and 10 vacation days. There is, however, a 50% chance that your actions will not sit well with your new manager, and that you will remain in your current position until your next job review.

On the other hand, you might adopt a more aggressive stance in your new job. The result would be a lower probability of being awarded a promotion to a new position, paying $60,000 with 20 days of vacation.

What probability of being offered the promotion to $60,000 with 20 days of vacation would make you indifferent to the 50% chance of a promotion to $60,000 with 10 days vacation.

$35,000 10 days	50%	--->	$60,000 10 days
	- OR -		
$35,000 10 days	**p**	--->	$60,000 20 days

Practice: Vacation (scaling coefficient)

You have instead accepted a different one of the job offers previously mentioned. Again, your beginning salary is $35,000 with 10 days of paid vacation.

You figure that a conservative stance will result in a 50% probability of being promoted to a new position, still paying $35,000, but with 20 vacation days. There is, however, a 50% chance that your actions will not sit well with your new manager, and that you will remain in your current position until your next job review.

On the other hand, you might adopt a more aggressive stance in your new job. The result in this case would be a lower probability of being awarded a promotion to a new position, paying $60,000 with 20 days of vacation.

What probability of being offered the promotion to $60,000 with 20 days of vacation would make you indifferent to the 50% chance of a promotion to $35,000 with 20 days?

$35,000 10 days	50%	--->	$35,000 20 days
	- OR -		
$35,000 10 days	p	--->	$60,000 20 days

PART C:

Practice: Direct Trade-off

This final question of the practice session considers a direct trade-off between the two attributes: salary and vacation days. In general, these questions will be worded as follows:

How much of attribute A would you be willing to sacrifice (gain) for a given improvement (decline) in attribute B?

Suppose that you currently have 15 days of vacation, with a salary of $50,000. How much of a salary increase would you need in order to settle for 12 days of vacation? 10 days? How much of a salary cut would you take to increase you vacation to 18 days? 20 days?

Vacation Days	Salary
10	
12	
15	$50,000
18	
20	

MULTI-ATTRIBUTE UTILITY ANALYSIS

PART A:

Recall the questionnaire's scenario: you are heading a design team responsible for developing a missile engine. Your only remaining decision is which of two manufacturers will supply the exhaust duct. Your engineers have gathered some initial data, in the form of probabilities, to aid you selection.

I will present situations which ask that you make a selection decision based on these data.

MAXIMUM OPERATING TEMPERATURE

You have decided to contract with one of two manufacturers to be your duct supplier. Both firms' ducts are limited to environments under 750°C. The ducts are similarly identical in all other aspects. Both manufacturers hope to offer ducts with improved performance sometime in the near future.

Based on part performance and the data collected by your engineers, you estimate that there is a 50% chance that **Firm A** will eventually develop a duct capable of operating at 1000°C. If they cannot, you will continue to use their current duct.

Alternatively, you expect that **Firm B** might develop a duct capable of operating at 1500°C. If they cannot, you would again continue to use their current duct.

At what probability **p** of **Firm B's** success in developing the improved duct would you consider the two options equivalent?

A: 750°C 50% ---> 1000°C

- OR -

B: 750°C **p** ---> 1500°C

STRENGTH

For a different project, you have again decided to contract with one of two manufacturers to be your duct supplier. Both firms' ducts have tensile strengths of 10 ksi and are identical in all other aspects. Both manufacturers hope to offer ducts with improved performance sometime in the near future.

Based on past performance and the data collected by your engineers, you estimate that there is a 50% chance that **Firm A** will eventually develop a duct with a tensile strength of 30 ksi. If they cannot, you will continue to use their current duct.

Alternatively, you expect that **Firm B** might develop a duct with a tensile strength of 60 ksi. If they cannot, you would again continue to use their current duct.

At what probability **p** of **Firm B's** success in developing the improved duct would you consider the two options equivalent?

A:	10 ksi	50%	--->	30 ksi
		- OR -		
B:	10 ksi	**p**	--->	60 ksi

TOUGHNESS

For a different project, you have again decided to contract with one of two manufacturers to be your duct supplier. Both firms' ducts have minimally acceptable toughness characteristics of 10 MPa√m and are identical in all other aspects. Both manufactures hope to offer ducts with improved performance sometime in the near future.

Based on past performance and the data collected by your engineers, you estimate that there is a 50% chance that **Firm A** will eventually develop a duct with a toughness of 30 MPa√m. If they cannot, you will continue to use their current duct.

Alternatively, you expect that **Firm B** might develop a duct with a toughness of 60 MPa√m. If they cannot, you would again continue to use their current duct.

At what probability **p** of **Firm B's** success in developing the improved duct would you consider the two options equivalent?

A: 10 MPa√m 50% ---> 30 MPa√m

- OR -

B: 10 MPa√m **p** ---> 60 MPa√m

COEFFICIENT OF THERMAL EXPANSION

For a different project, you have again decided to contract with one of two manufactures to be your duct supplier. Both firms' ducts have coefficients of thermal expansion mismatch of 8×10^{-6} in/in/°F and are identical in all other aspects. Both manufacturers hope to offer ducts with improved performance sometime in the near future.

Based on past performance and the data collected by your engineers, you estimate that there is a 50% chance that **Firm A** will eventually develop a duct with a CTE mismatch of 4×10^{-6} in/in/°F. If they cannot, you will continue to use their current duct.

Alternatively, you expect that **Firm B** might develop a duct with a CTE mismatch of 0 in/in/°F. If they cannot, you would again continue to use their current duct.

At what probability **p** of **Firm B's** success in developing the improved duct would you consider the two options equivalent?

A:	8×10^{-6} in/in/°F	50%	--->	4×10^{-6} in/in/°F
		- OR -		
B:	8×10^{-6} in/in/°F	**p**	--->	0 in/in/°F

DENSITY (WEIGHT)

For a different project, you have again decided to contract with one of two manufacturers to be your duct supplier. Both firms' ducts have densities of 9 g/cc and are identical in all other aspects. Both manufacturers hope to offer ducts with improved performance sometime in the near future.

Based on past performance and the data collected by your engineers, you estimate that there is a 50% chance that **Firm A** will eventually develop a duct with a density of 6 g/cc. If they cannot, you will continue to use their current duct.

Alternatively, you expect that **Firm B** might develop a duct with a density of 1.8 g/cc. If they cannot, you would again continue to use their current duct.

At what probability **p** of **Firm B's** success in developing the improved duct would you consider the two options equivalent?

A:	9 g/cc	50%	--->	6 g/cc
		- OR -		
B:	9 g/cc	**p**	--->	1.8 g/cc

COST

For a different project, you have again decided to contract with one of two manufacturers to be your duct supplier. Both firms' ducts are expensive, costing $10,000. The ducts are identical in all other aspects as well. Both manufacturers hope to offer less expensive ducts sometime in the near future.

Based on past performance and the data collected by your engineers, you estimate that there is a 50% chance that **Firm A** will eventually develop a duct costing only $5000. If they cannot, you will continue to use their current duct.

Alternatively, you expect that **Firm B** might develop a $1000 duct. If they cannot, you would again continue to use their current duct.

At what probability **p** of **Firm B's** success in developing the inexpensive duct would you consider the two options equivalent?

A: $10,000 50% ---> $5,000

- OR -

B: $10,000 **p** ---> $1,000

COST

For a different project, you have again decided to contract with one of two manufacturers to be your duct supplier. Both firms' ducts are expensive, costing $10,000. The ducts are identical in all other aspects as well. Both manufacturers hope to offer less expensive ducts sometime in the near future.

Based on past performance and the data collected by your engineers, you estimate that there is a 50% chance that **Firm A** will eventually develop a duct costing only $7500. If they cannot, you will continue to use their current duct.

Alternatively, you expect that **Firm B** might develop a $1000 duct. If they cannot, you would again continue to use their current duct.

At what probability **p** of **Firm B's** success in developing the inexpensive duct would you consider the two options equivalent?

A: $10,000 50% ---> $7,500

- OR -

B: $10,000 **p** ---> $1,000

PART B:

The questions in this part are similar to those in part A, with the exception that all of the attributes are considered together. For all cases, the first section discussing Firm 1's improvement will be the same; it is included for completeness.

MAXIMUM OPERATING TEMPERATURE

As in part A, you are again selecting one of two manufacturers to supply the exhaust duct. Both ducts are identical, although the potential for change is not. The two manufacturers both hope to come out with improved versions in the near future. Keep in mind that the contract you sign will bind you to one firm or the other and, thus, to the selected firm's new design in addition to their current one.

Firm A promises a 50% chance that the new design will be improved, but **only in maximum operating temperature.** If the improvements do not occur, the current duct will continue to be used.

Firm B is less likely to offer an improvement, but it will be in **all areas.** If the improvements do not come through, then the current duct will continue to be used.

At what probability of **Firm B's** improvement to the "wonder duct" would you consider the two alternatives equal?

A:	750°C	50%	--->	**1500°C**
	10 ksi			10 ksi
	10 MPa$\sqrt{m}$			10 MPa$\sqrt{m}$
	8×10^{-6} in/in/°F			8×10^{-6} in/in/°F
	9 g/cc			9 g/cc
	$10,000			$10,000

- OR -

B:	750°C	**p**	--->	**1500°C**
	10 ksi			**60 ksi**
	10 MPa$\sqrt{m}$			**60 MPa$\sqrt{m}$**
	8×10^{-6} in/in/°F			**0 in/in/°F**
	9 g/cc			**1.8 g/cc**
	$10,000			**$1,000**

STRENGTH

You are again selecting one of two manufacturers to supply exhaust ducts. Both ducts are identical, although the potential for change is not. The two manufacturers both hope to come out with improved versions in the near future.

Firm A promises a 50% chance that the new design will be improved, but **only in strength**. If the improvement does not occur, the current duct will continue to be used.

Firm B is less likely to offer an improvement, but it will be in **all areas**. If the improvements do not come through, then the current duct will continue to be used.

At what probability of **Firm B's** improvement to the "wonder duct" would you consider the two alternatives equal?

A:	750°C	50%	--->	750°C
	10 ksi			**60 ksi**
	10 MPa$\sqrt{m}$			10 MPa$\sqrt{m}$
	8 x 10^{-6} in/in/°F			8 x 10^{-6} in/in/°F
	9 g/cc			9 g/cc
	\$10,000			\$10,000

- OR -

B:	750°C	**p**	--->	**1500°C**
	10 ksi			**60 ksi**
	10 MPa$\sqrt{m}$			**60 MPa$\sqrt{m}$**
	8 x 10^{-6} in/in/°F			**0 in/in/°F**
	9 g/cc			**1.8 g/cc**
	\$10,000			**\$1,000**

TOUGHNESS

You are again selecting one of two manufacturers to supply exhaust ducts. Both ducts are identical, although the potential for change is not. The two manufacturers both hope to come out with improved versions in the near future.

Firm A promises a 50% chance that the new design will be improved, but **only in toughness**. If the improvement does not occur, the current duct will continue to be used.

Firm B is less likely to offer an improvement, but **it will be in all areas**. If the improvements do not come through, then the current duct will continue to be used.

At what probability of **Firm B's** improvement to the "wonder duct" would you consider the two alternatives equal?

A:	750°C	50%	--->	750°C
	10 ksi			10 ksi
	10 MPa$\sqrt{m}$			**60 Mpa$\sqrt{m}$**
	8×10^{-6} in/in/°F			8×10^{-6} in/in/°F
	9 g/cc			9 g/cc
	\$10,000			\$10,000

- OR -

B:	750°C	p	--->	**1500°C**
	10 ksi			**60 ksi**
	10 MPa$\sqrt{m}$			**60 MPa$\sqrt{m}$**
	8×10^{-6} in/in/°F			**0 in/in/°F**
	9 g/cc			**1.8 g/cc**
	\$10,000			**\$1,000**

COEFFICIENT OF THERMAL EXPANSION

You are again selecting one of two manufacturers to supply exhaust ducts. Both ducts are identical, although the potential for change is not. The two manufacturers both hope to come out with improved versions in the near future.

Firm A promises a 50% chance that the new design will be improved, but **only in coefficient of thermal expansion**. If the improvement does not occur, the current duct will continue to be used.

Firm B is less likely to offer an improvement, but it will be in **all areas**. If the improvements do not come through, then the current duct will continue to be used.

At what probability of **Firm B**'s improvement to the intermediate level would you consider the two alternatives equal?

A:	750°C	50%	--->	750°C
	10 ksi			10 ksi
	10 $\text{MPa}\sqrt{\text{m}}$			10 $\text{MPa}\sqrt{\text{m}}$
	8×10^{-6} in/in/°F			**0 in/in/°F**
	9 g/cc			9 g/cc
	$10,000			$10,000

- OR -

B:	750°C	**p**	--->	**1500°C**
	10 ksi			**60 ksi**
	10 $\text{MPa}\sqrt{\text{m}}$			**60 $\text{MPa}\sqrt{\text{m}}$**
	8×10^{-6} in/in/°F			**0 in/in/°F**
	9 g/cc			**1.8 g/cc**
	$10,000			**$1,000**

DENSITY (WEIGHT)

You are again selecting one of two manufacturers to supply exhaust ducts. Both ducts are identical, although the potential for change is not. The two manufacturers both hope to come out with improved versions in the near future.

Firm A promises a 50% chance that the new design will be improved, but **only in density**. If the improvements do not occur, the current duct will continue to be used.

Firm B is less likely to offer an improvement, but it will be in **all areas**. If the improvements do not come through, then the current duct will continue to be used.

At what probability of **Firm B's** improvement to the intermediate level would you consider the two alternatives equal?

A:	750°C	50%	--->	750°C
	10 ksi			10 ksi
	10 MPa√m			10 MPa√m
	8×10^{-6} in/in/°F			8×10^{-6} in/in/°F
	9 g/cc			**1.8 g/cc**
	$10,000			$10,000

- OR -

B:	750°C	p	--->	**1500°C**
	10 ksi			**60 ksi**
	10 MPa√m			**60 MPa√m**
	8×10^{-6} in/in/°F			**0 in/in/°F**
	9 g/cc			**1.8 g/cc**
	$10,000			**$1,000**

COST

You are again selecting one of two manufacturers to supply exhaust ducts. Both ducts are identical, although the potential for change is not. The two manufacturers hope to come out with improved versions in the near future.

Firm A promises a 50% chance that the new design will be improved, but **only in cost**. If the improvement does not occur, the current duct will continue to be used.

Firm B is less likely to offer an improvement, but it will be in **all areas**. If the improvements do not come through, then the current duct will continue to be used.

At what probability of **Firm B's** improvement to the intermediate level would you consider the two alternatives equal?

A:	750°C	50%	--->	750°C
	10 ksi			10 ksi
	10 MPa√m			10 MPa√m
	8×10^{-6} in/in/°F			8×10^{-6} in/in/°F
	9 g/cc			9 g/cc
	$10,000			**$1,000**

- OR -

B:	750°C	p	--->	**1500°C**
	10 ksi			**60 ksi**
	10 MPa√m			**60 MPa√m**
	8×10^{-6} in/in/°F			**0 in/in/°F**
	9 g/cc			**1.8 g/cc**
	$10,000			**$1,000**

PART C:

The final part of this survey considers a direct trade-off between pairs of attributes. In this scenario, maximum operating temperature, strength, toughness, coefficient of thermal expansion and density will each be compared to cost.

MAXIMUM OPERATING TEMPERATURE

Suppose that you have an exhaust duct that can be operated at **1000°C** and costs **$2500**. How much more would you be willing to pay to increase the maximum operating temperature to **1250°C**? To **1500°C**? How much less would you need to pay to compensate for a loss in operating temperature to **875°C**? To **750°C**?

Maximum Operating Temperature	Cost
750°C	
875°C	
1000°C	$2500
1250°C	
1500°C	

STRENGTH

Suppose that you have an exhaust duct with a tensile strength of **30 ksi** and costs **$2500**. How much more would you be willing to pay to increase the tensile strength to **45 ksi**? To **60 ksi**? How much less would you need to pay to compensate for a loss in tensile strength to **20 ksi**? To **10 ksi**?

Tensile Strength	Cost
10 ksi	
20 ksi	
30 ksi	$2500
45 ksi	
60 ksi	

TOUGHNESS

Suppose that you have an exhaust duct with a toughness of **30 MPa√m** and costs **$2500**. How much more would you be willing to pay to increase the toughness to **45 MPa√m**? To **60 MPa√m**? How much less would you need to pay to compensate for a loss in toughness to **20 MPa√m**? To **10 MPa√m**?

Toughness	Cost
10 MPa√m	
20 MPa√m	
30 MPa√m	$2500
45 MPa√m	
60 MPa√m	

COEFFICIENT OF THERMAL EXPANSION

Suppose that you have an exhaust duct with a coefficient of thermal expansion mismatch of 4 x 10^{-6} in/in/°F and costs **$2500**. How much more would you be willing to pay to decrease the mismatch to **2 x 10^{-6}** in/in/°F? To **0 in/in/°F**? How much less would you need to pay to compensate for an increase in CTE mismatch to **6 x 10^{-6}** in/in/°F? To **8 x 10^{-6}** in/in/°F?

CTE Mismatch	Cost
0 x 10^{-6} in/in/°F	
2 x 10^{-6} in/in/°F	
4 x 10^{-6} in/in/°F	$2500
6 x 10^{-6} in/in/°F	
8 x 10^{-6} in/in/°F	

DENSITY (WEIGHT)

Suppose that you have an exhaust duct with a density of **6 g/cc** and costs **$2500**. How much more would you be willing to pay to decrease the density to **4.5 g/cc**? To **3 g/cc**? How much less would you need to pay to compensate for an increase in density to **7.5 g/cc**? To **9 g/cc**?

Density	Cost
3 g/cc	
4.5 g/cc	
6 g/cc	$2500
7.5 g/cc	
9 g/cc	

APPENDIX F:

Multiattribute Utility Analysis Data

Subject #1

	Attribute	Lottery
1.	Operating Temperature	(750,.5;1000)=(750,.4;1500)
2.	Strength	(10,.5;15)=(10,.35,30)
3.	CTE Mismatch	$(8x10^{-6},.5;4x10^{-6})=(8x10^{-6},.15;0)$
4.	Density	(9,.5;6)=(9,.35;1.8)
5.	Cost	(10000,.5;5000)=(10000,.375;1000)
		(10000,.5;7500)=(10000,.25;1000)

Utility Functions

Operating Temperature	Strength
b = -746.8	b = -9.778
h = -0.2154	h = 0.3338
k = 0.1835	k = 0.2216

CTE Mismatch	Density	Cost
a = -0.225	b = 9.588	a = -3.670
b = -1.225	h = 0.2054	b = 0.000
c = 0.2118	k = 0.3871	c = 0.5046
		d = 11500

Subject #2

	Attribute	Lottery
1.	Operating Temperature	(750,.5;1000)=(750,.4;1500)
2.	Strength	(10,.5;20)=(10,.3,30)
3.	Toughness	(3,.5;15)=(3,.25;30)
4.	CTE Mismatch	$(8x10^{-6},.5;4x10^{-6})=(8x10^{-6},.2;0)$
5.	Density	(9,.5;4)=(9,.3;1.8)
6.	Cost	(10000,.5;5000)=(10000,.25;1000)
		(10000,.5;7500)=(10000,.1;1000)

Utility Functions

Operating Temperature	Strength	Toughness
b = -746.8	b = 5.6811	b = 45
h = -0.2154	h = -3.348	h = -8.674
k = 0.1835	k = 1.216	k = 2.241

CTE Mismatch	Density	Cost
a = -0.8000	a = -0.7405	a = 1.222
b = -1.8000	b = -2.155	b = -0.2494
c = 0.1014	c = 0.1187	c = 0.02931
		d = -0.001658

Subject #3

	Attribute	Lottery
1.	Operating Temperature	(750,.5;1000)=(750,.35;1500)
2.	Strength	(10,.5;20)=(10,.3,30)
3.	Toughness	(3,.5;15)=(3,.25;30)
4.	CTE Mismatch	(8x10^{-6},.5;4x10^{-6})=(8x10^{-6},.2;0)
5.	Density	(9,.5;4)=(9,.3;1.8)
6.	Cost	(10000,.5;5000)=(10000,.25;1000) (10000,.5;7500)=(10000,.15;1000)

Utility Functions

Operating Temperature	Strength	Toughness
b = -746.8	b = 5.6811	b = 45
h = -0.1885	h = -3.348	h = -8.674
k = 0.1605	k = 1.216	k = 2.241

CTE Mismatch	Density	Cost
a = -0.8000	a = -0.7405	a = 1.099
b = -1.8000	b = -2.155	b = -0.08944
c = 0.1014	c = 0.1187	c = -0.1008
		d = 0.0008034

Subject #4

	Attribute	Lottery
1.	Operating Temperature	(750,.5;1000)=(750,.4;1500)
2.	Strength	(20,.5;30)=(20,.3,50)
3.	Toughness	(10,.5;30)=(10,.45;60)
4.	CTE Mismatch	$(6x10^{-6},.5;4x10^{-6})=(6x10^{-6},.3;0)$
5.	Density	(9,.5;6)=(9,.3;1.8)
6.	Cost	(10000,.5;5000)=(10000,.3;1000)
		(10000,.5;7500)=(10000,.2;1000)

Utility Functions

Operating Temperature	Strength	Toughness
b = -746.8	b = -19.025	b = -9.995
h = -0.2154	h = 0.007334	h = 0.5730
k = 0.1835	k = 0.2891	k = 0.1092

CTE Mismatch	Density	Cost
b = 6.682	b = 11.01	a = 1.0195
h = 0.1677	h = -0.4587	b = -0.2244
k = 0.4382	k = 0.6570	c = 0.03619
		d = -0.00212

Subject #5

	Attribute	Lottery
1.	Operating Temperature	(1000)=(750,.6;1500)
2.	Strength	(10,.5;30)=(10,.45,60)
3.	Toughness	(10,.5;30)=(10,.35;60)
4.	CTE Mismatch	(8x10^{-6},.5;4x10^{-6})=(8x10^{-6},.4;0)
5.	Density	(9,.5;7)=(9,.3;3)
6.	Cost	(10000,.5;9000)=(10000,.25;1000)

Utility Functions

Operating Temperature

b = -664.7
h = -1.948
k = 0.4382

Strength

b = -9.995
h = 0.5730
k = 0.10915

Toughness

b = -6.5805
h = -0.4473
k = 0.3638

CTE Mismatch

b = 8.3124
h = 0.3546
k = 0.3048

Density

b = 9.441
h = 0.2873
k = 0.3505

Cost

b = 10143
h = -1.193
k = 0.2405

APPENDIX G:

SUBJECTIVE PROBABILITY ASSESSMENT SURVEY

Thank you for participating in the second phase of this study of materials selection for exhaust duct applications. As I have already described to you on the phone, this portion of the study will explore your opinion of two new material alternatives with the potential to be used in exhaust duct applications. These are SiC/SiC composites produced by (1) the slurry infiltration technique and (2) the chemical vapor infiltration technique. The first part of this questionnaire examined the trade-offs you make between various performance attributes, and thus established a materials blind basis for comparing alternatives with known levels of attributes. Unfortunately, for new materials still in the developmental stage, attribute levels are not always easily obtained. Test results for laboratory specimens of these materials help to identify attribute levels, but do not always represent the levels experienced in a given application. Furthermore, manufacturing of components on a production scale rather than an experimental basis may lead to different property levels. Also, biased reporting on the part of the material supplier, who is often the only source of test results, could lead to inaccurate levels of attributes. Additionally, while the materials blind study gave us an unbiased basis for comparing alternatives, materials selection is not usually done in this manner.

Considering all of the information given here, and of course your personal experiences, I would like to explore your opinions of the two materials alternatives and the attribute levels associated with each. Undoubtedly, you may have complete faith in the reported levels for some attributes and less confidence in others. For each alternative, there is a brief description of the material and process by which it was made, as well as a list of the values for each attribute (excluding cost) as reported by its supplier. There are then three questions concerning each attribute. The first concerns your confidence in the reported values. A response of 100% would indicate that you are completely certain of the material possessing this level of the attribute, while an answer of 0% would indicate that you feel there is no possibility of this material possessing the reported level. The other two questions ask you to identify attribute levels that correspond to specific confidence levels. For example, what level of attribute A do you feel there would be a 50% chance of this material minimally possessing? What level for a 90% chance?

SiC/SiC Composite via the Slurry Infiltration Technique

The slurry infiltration technique involves prepregging plies of fiber reinforcement with a ceramic based slurry, followed by a densification step. Typically, a two dimensional fiber cloth is impregnated with a slurry which consists of ceramic powders and a binder material. The impregnated fibers are layed up on a mold to obtain the desired part geometry. Densification of the ceramic matrix and binder removal are achieved by either autoclaving or mechanical loading at elevated temperatures. The result is a near net shape ceramic matrix composite component.

Table 1: Attribute Values for a Slurry Infiltrated SiC/SiC Composite

ATTRIBUTE	VALUE
Operating Temperature	1100°C
Strength	14 ksi
Toughness	30 MPa$\sqrt{m}$
CTE Mismatch	7 x 10-6 in/in/°F
Density	2.5 g/cc

For each attribute please indicate the value you expect it to possess with various confidence levels; 90%, 50% and 10% confidence.

Operating Temperature

1. Value for the operating temperature for which P(actual operating temperature $\geq$ value) = 90% value =

2. Value for the operating temperature for which P(actual operating temperature $\geq$ value) = 50% value =

3. Value for the operating temperature for which P(actual operating temperature $\geq$ value) = 10% value =

Strength

1. Value for the strength for which
   P(actual strength ≥ value) = 90%
   value =

2. Value for the strength for which
   P(actual strength ≥ value) = 50%
   value =

3. Value for the strength for which
   P(actual strength ≥ value) = 10%
   value =

Toughness

1. Value for the toughness for which
   P(actual toughness ≥ value) = 90%
   value =

2. Value for the toughness for which
   P(actual toughness ≥ value) = 50%
   value =

3. Value for the toughness for which
   P(actual toughness ≥ value) = 10%
   value =

SiC/SiC Composite via the Chemical Vapor Infiltration Technique

The chemical vapor infiltration technique involves flowing reactive gases through a fiber preform already in the shape of the final part. The preform is made by laying up two dimensional fiber cloths on a mold. It is then successively infiltrated and machined until a dense part is formed.

Table 2: Attribute Values for a Chemical Vapor Infiltrated SiC/SiC Composite

ATTRIBUTE	VALUE
Operating Temperature	1400°C
Strength	22 ksi
Toughness	30 MPa$\sqrt{m}$
CTE Mismatch	7 x 10^{-6} in/in/°F
Density	2.5 g/cc

For each attribute please indicate the value you expect it to possess with various confidence levels; 90%, 50% and 10% confidence.

Operating Temperature

1. Value for the operating temperature for which
   P(actual operating temperature ≥ value) = 90% value =

2. Value for the operating temperature for which
   P(actual operating temperature ≥ value) = 50% value =

3. Value for the operating temperature for which
   P(actual operating temperature ≥ value) = 10% value =

Strength

1. Value for the strength for which
   P(actual strength ≥ value) = 90% value =

2. Value for the strength for which
   P(actual strength ≥ value) = 50% value =

3. Value for the strength for which
   P(actual strength ≥ value) = 10% value =

Toughness

1. Value for the toughness for which
   P(actual toughness ≥ value) = 90% value =

2. Value for the toughness for which
   P(actual toughness ≥ value) = 50% value =

3. Value for the toughness for which
   P(actual toughness ≥ value) = 10% value =

APPENDIX H:

Subjective Probability Distribution Coefficients

Subject #1

Slurry Infiltration

Operating Temperature	Strength
a = 1100	a = 16
b = 78.125	b = 7.1191
c = 1100	c = 21.474
d = 78.125	d = 2.623

Chemical Vapor Infiltration

Operating Temperature	Strength
a = 1345	a = 21
b = 172.04	b = 7.1191
c = 1413.0	c = 26.474
d = 40.588	d = 2.623

Subjects #2 & #3

Slurry Infiltration

Operating Temperature	Strength	Toughness
a = 1250	a = 25	a = 24
b = 80.645	b = 13.045	b = 10.679
c = 1250	c = 31.841	c = 31.263
d = 80.645	d = 4.8036	d = 2.2418

Chemical Vapor Infiltration

Operating Temperature	Strength	Toughness
a = 1345	a = 30	a = 24
b = 172.04	b = 9.1853	b = 10.679
c = 1413.0	c = 32.990	c = 31.263
d = 40.588	d = 4.545	d = 2.2418

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