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THE ADVANCED DEVELOPMENT OF X-RAY COMPUTED TOMOGRAPHY APPLICATIONS

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The application of X-ray computed tomography (CT) for aircraft and aerospace structures and ancillary equipment has been investigated in the Advanced Development of X-Ray Computed Tomography Applications demonstration (CTAD) program sponsored by the NDE Branch of the Materials Directorate at the Air Force Wright Laboratory (WL). X-ray CT offers a new inspection capability for aircraft hardware that provides quantitative information on material density/constituents and dimensions. This capability has economic value as an engineering tool for improving the evaluation and control of materials and processes used in aircraft/aerospace structures.

The CTAD effort has investigated a wide variety of application areas for CT. These include electronics, closed systems, castings, composites, and advanced materials and processes. Applications of CT in these areas include: configuration control, anomaly detection, dimensional measurements and material uniformity. By using the actual dimensional characteristics of features and anomalies in a component, and the material characteristics, such as density and elemental composition, that are derivable from the CT data, engineers can perform a variety of analyses to arrive at quantitative measurements that are of economical value to improving the overall product cycle from development to deployment. Until specifications requiring CT are implemented, CT will be employed primarily as a supplement to other NDE methodologies for engineering evaluations such as product development/material characterization measurements, failure analysis and engineering problem solving, noninvasive micrography and geometry acquisition. Component acceptance based on such an engineering analysis rather than qualitative inspection standards has considerable potential for reducing scrap rates and increasing component reliability.

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Computed Tomography (CT), X-Ray, Product Development, Geometry Acquisition, Failure Analysis, Electronics, Closed Systems, Castings, Composites, Advanced Materials, Engines, Noninvasive Micrography

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TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF FIGURES

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EXECUTIVE SUMMARY

The application of computed tomography (CT) for aircraft and aerospace structures and ancillary equipment has been investigated in the Advanced Development of X-Ray Computed Tomography Applications demonstration (CTAD) program sponsored by the NDE Branch of the Materials Directorate at the Air Force Wright Laboratory (WL). X-ray computed tomography (CT) is a volumetric feature evaluation tool that offers a new evaluation capability for aircraft hardware that provides quantitative information on material density/constituents and dimensions. This capability has economic value for improving the evaluation and control of materials and processes used in aircraft/aerospace structures. The CTAD effort has identified a wide variety of CT application in the areas of electronics, closed systems, castings, organic composites and, advanced materials and processes. Applications of CT in these areas include configuration control, anomaly detection, geometry acquisition, failure analysis, noninvasive micrography, product development support and engineering fitness for service. Although this program has evaluated numerous test articles in a wide range of areas, this is not an exhaustive study of all possible applications of CT to aircraft and aerospace. Within the time and funding constraints of the program an accurate assessment of the general applicability of X-ray CT has been made.

In general, the benefit of X-ray CT over alternative nondestructive evaluation methodologies is the ability to map the relative X-ray linear attenuation coefficient of small volume elements throughout a component permitting the extraction of dimensional and material characteristics of features and anomalies. With these characteristics, derived from the CT data, engineers can perform a variety of analyses to arrive at quantitative measurements of parameters that are of economical value to improving the overall product cycle from prototype development to deployment. CT data acquisition requires sophisticated hardware and software systems that can be manufactured in a range of configuration and sizes to handle small (< 10 mm diameter) to large (> 1 m diameter) objects with a sensitivity to detail that scales to a first approximation on the order of 1 part in 1000. For objects that fit within the constraints of size and shape for proper CT examination, the CT data offer unparalleled quantification of volumetric features for both detection and measurement. As complexity of design increases, the value of CT measurement capability increases.

Present CT technology is valuable to users of aircraft/aerospace structures and ancillary equipment mostly as an engineering tool to support product cycle activities. Figure I is a summary conclusion graphic describing the applicability of CT to these various activities. Among other conclusions illustrated, CT is an enabling technology which supports concurrent engineering processes to speed products to market. CT is an important measurement tool that can provide a cost benefit to these processes. CT permits geometry acquisition, providing a direct cost saving over traditional approaches to translating existing components into digital models in computer aided design/engineering (CAD/E) workstations. CT evaluation of materials also is useful in performance prediction. This is where engineering and nondestructive evaluation need to meet in order to create the most cost-effective products. CT measurements can be performed on test articles to validate prototypes and models prior to testing, during certain types of tests, and post testing, including noninvasive micrographic evaluations. CT can be an important tool in the manufacturing and process development stages by providing feature and anomaly location for configuration control, and the direct measure of dimensions. The value of CT evaluation is high for assuring a development process has been brought into control. For routine production quality control the application of CT depends on the relation between the object value, CT scanning cost, and the cost of alternatives. The more complex and costly an assembly, the more likely that CT can be a cost effective tool. Ultimately CT has the capability to allow the acceptance of a product based on quantitative measurements and engineering criteria. Such an engineering analysis rather than qualitative inspection standards has considerable potential for reducing scrap and increasing component reliability. Maintenance/repair and failure analysis activities benefit from CT measurements by providing information for making decisions on irreversible steps and/or eliminating disassembly or destructive sectioning to obtain critical data. The long range value of CT technology is that it closes the loop between the engineering and the manufacturing operations by providing quantitative data that can be accessed by engineers, at their workstations. As the realization of the value of this methodology grows, the use of CT will increase for military and commercial product cycle activities.

CT Provides Quantitative Measures

- **Density/Constituents**
- **Dimensions**

Most Beneficial Application of CT Measurements are:

Engineering Applications	Manufacturing Applications
• Prototype Evaluation	• Process Development
• Geometry Acquisition	• Feature/Anomaly Location
• Failure Analysis	• Configuration Control
• Performance Prediction	• Acceptance by Engineering Criteria

Figure I. Summary graphic of CT applicability to the product cycle activities in the aircraft industry.

X-ray computed tomography is limited by the requirement that test articles fit within the field of view of the CT system with 360 degree access. High aspect ratio objects, such as wing skins, are not suited to CT examination due to their large size and flat structure. As a consequence, CT is applied to aircraft substructural test articles or components that meet CT system access requirements. The high quality image data of CT requires more sophisticated (and therefore more costly) data acquisition relative to traditional nondestructive evaluation/inspection (NDE/I) methodologies, and the cost of CT examination tends to scale with the size of the test article. CT has, therefore been used for routine inspection for only very high value objects with inspection requirements that only CT can adequately meet. For components that are currently manufactured under existing specifications, a more expensive evaluation technique would not normally be considered, even if it provided superior inspections. Existing specifications determine the evaluation technology that will be used. Under these conditions, CT will find limited application as a routine quality inspection tool until 1) costs are reduced below existing inspection equipment costs (and specifications are then changed because it is cost effective), or 2) new aircraft components are designed that require CT for a particular design or materials requirements that no lower cost inspection technique can meet. CT costs are decreasing with technology developments and will continue to do so. As aircraft component designs are generated with the knowledge of CT evaluation capability and, lower cost, highly automated CT systems become available the technology will increase in utilization throughout the product cycle.

Because of the cost and physical size constraints of CT systems, CT evaluation is most cost effectively employed as an enabling technology for product and process evaluation, supplementing lower cost NDE/I technologies in various stages of the product cycle. The primary ways that CT serves as an economically viable enabling technology are 1) product development/material characterization measurements, 2) failure analysis and engineering problem solving, 3) noninvasive micrography and 4) geometry acquisition for dimensional measurements and input to CAD/E workstations. Figure II shows a chart of various application areas and the product cycle activity, with examples of CT applications where economic savings have been demonstrated or potential has been identified. The chart is by no means exhaustive, rather it contains examples studied in the CTAD program that provide a reference for engineers, technicians and inspectors to extrapolate to their parts for economic viable CT applications. The detailed information on various examples are reported in the CTAD program interim reports.

The final demonstration of the output of the CTAD program has been the "Advanced Development of X-Ray Computed Tomography Workshop" program that has been presented to government and industry. This program was presented in an open meeting in Salt Lake City, Utah in May 1992 and to each of the five Air Force Logistics Centers. Additionally, the demonstration material has been assembled in the "Interactive Multimedia Presentation of Applied Computed Tomography" (IMPACT) software package that operates on Macintosh workstations.

Because of the ability of CT to support engineering programs, enabling faster product development and assisting engineering evaluation, it is recommended that the Air Force include CT technology capability in the scoring criteria for developmental programs. Also, where appropriate, the Air Force should specify the use of CT for component evaluation. Finally, the Air Force should focus further research activity towards lower cost, higher throughput CT by developments in X-ray source technology, algorithms, volume imaging and related advanced X-ray imaging techniques.

Product Life Cycle Activities	Application Areas				
	Electronics	Complex Systems	Castings	Organic Matrix Composites	Adv. Materials & Processes
Design/Material Development	Optical Devices		Geometry Acquistion Material Properties	Consolidation Noninvasive Micrography	Coatings Ceramics Noninvasive Micrography
Engineering Test/Accept	Electrical Components	Electromechanical Devices	Performance Modeling	Noninvasive Micrography Impact Testing	Bonding/Welding
Manufacturing Development	Potting/Sealing		Internal Dimensional Measurement	Thick Composites Complex Structures Honeycomb Structures	SPF Fasteners Injection Molding
Production/Process Control			Cast Component Evaluation	Automated Manufacturing	Extruded Ceramics
QC Inspection	PWA (Laminography)	Batteries	Engineering Acceptance	Engineering Acceptance	Engineering Acceptance
Maintenance/Repair		Engines			
Failure Analysis	Electrical Components	Electomechanical Devices		Honeycomb Structures Noninvasive Micrography	

Figure II. Examples for economic savings for CT applications.

1.0 INTRODUCTION

The goal of the Advanced Development of X-Ray Computed Tomography Applications Demonstration program (CTAD) was to identify applications for which computed tomography (CT) could be used cost-effectively in the evaluation of aircraft/aerospace components. This final report summarizes the investigation. The program was task assigned, with each task assignment allowing specific applications or application areas to be investigated individually. The results of each task assignment were distributed to government and industry through interim reports [1-19].

1.1 X-ray CT

X-ray CT is a powerful nondestructive evaluation technique that was conceived in the early 1960's and has been developing rapidly ever since. CT collects X-ray transmission measurements from many angles around the component under examination to digitally reconstruct a map of the relative linear X-ray attenuation coefficient of small interior volume elements of the component and view them as cross sectional images. The clear images of interior planes are achieved without the confusion of superimposed features often found with conventional film radiography. CT can provide quantitative information about the density/constituents and dimensions of features imaged. X-ray computed tomography and techniques related to CT are discussed in Appendix A. A detailed description of the technical approach to using CT is found in Reference 19. Figure 1.1-1 lists the advantages and limitations of CT technology.

X-Ray Computed Tomography	
Advantages	**Limitations**
• Quantitative volumetric feature detection and configuration control • Digital data/3-dimensional • Sensitive to small dimensional changes (down to 0.01%) • Sensitive to small density changes (down to 0.1%)	• High capital cost • Requires 360° access • Reconstruction artifacts

Figure 1.1-1 Advantage and limitations of X-ray CT.

X-ray CT provides quantitative volumetric feature detection. The data is digital with known 3-dimensional coordinates relative to a common origin. Sensitivity to both dimensional and density characteristics can be quite high. CT requires more precise equipment and data processing that traditional nondestructive evaluation methods and so has a generally higher capital cost. The technology requires 360 degree access to the parts and, therefore, the objects must fit within the field of view of the CT scanning system. High aspect ratio (> 15:1) are not well suited to CT examination. The data acquisition and processing do have associated image artifacts that may influence the measurements under certain conditions.

Although CT has been predominantly applied to medicine, industrial applications have been growing over the past decade. Medical systems are designed for high throughput and low dosages (less than 150 keV), specifically for humans and human-sized objects. These systems can be applied to industrial objects that have a low atomic number (e.g., polymer matrix composites), and less than one-half meter (20 inches) diameter. Industrial CT systems are designed and built in a wide range of sizes, for the inspection of small jet engine turbine blades using midenergy X-ray sources (hundreds of keV), to large ICBM missiles requiring high X-ray energies (MeV level). Industrial CT systems generally have much less throughput than medical systems. The CTAD program considers a wide range of CT systems, both medical and industrial for their economic value to the evaluation of aircraft/aerospace components.

The sensitivity to fine detail of CT systems is fundamentally determined by the beam width of the X-ray optics design, and is driven by the selection of source and detector aperture sizes and the source, object and detector distances. The beam width, size of the object, and CT image reconstruction matrix must all be considered in a system design. At the present time the typical reconstruction matrix size for CT is 1024 x 1024. To a first approximation this would make the resolution limit roughly 1 part in 1000, and the system would be designed to match the X-ray optics to 1/1000th of the size of the part. For example, a system designed to handle a 0.5 m size part might allow for 0.5-mm size beam width, and a system designed for a 10 mm size part might have a 0.010-mm beam width. It is of course possible, and routinely performed, to reconstruct the 1024 x 1024 matrix over subregions of a component so that a higher resolution beam width finer than 1 part in 1000 of the object can be used effectively. However, the scan must still cover the full size of the part. As the part size is increased, the source to detector distance increases, and the X-ray intensity at the detector falls off quadratically. Thus, it is impractical to use a very small beam width on large parts because of the very long scan time that will result. Practical resolutions for CT systems that handle relatively large components (> 300 mm diameter) are in the range of 1 to 2 lp/mm. For components less than 300 mm diameter 2 to 4 lp/mm can be obtained. For higher resolution, greater than 4 lp/mm (feature sensitivity on the order of 0.125 mm), CT systems are being designed that usually can handle parts of a few centimeters in size.

Figure 1.1-2 shows how the size and detail sensitivity of CT systems are related by the design. Each type of system (A through D) represents a range of capability that can be found commercially, but no one CT system can provide both large object inspection and very fine resolution. Figure 1.1-3 shows how costs of CT systems are also affected by the size requirements. In general, CT systems for small objects will have high detail sensitivity and the lowest cost. As object size increases the CT system costs increase. Examination times and operational costs will also generally increase with size.

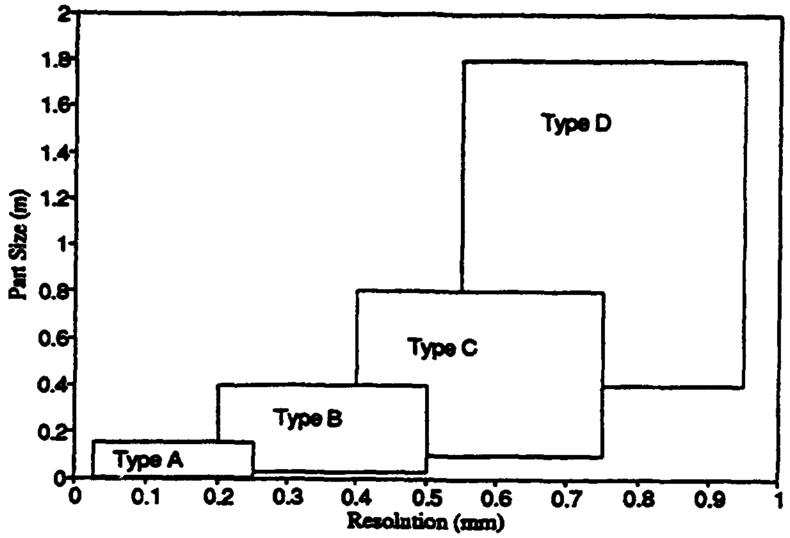

Figure 1.1-2 CT system size versus sensitivity to detail.

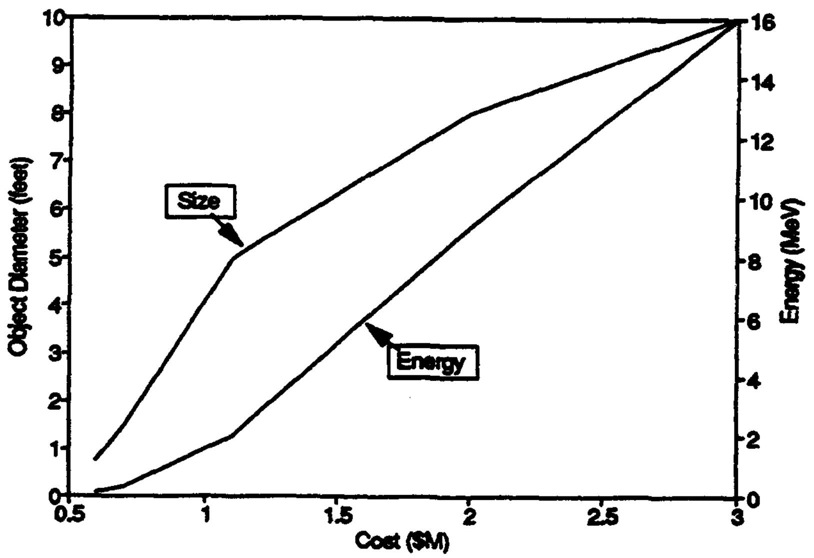

Figure 1.1-3 CT system size versus cost [5].

1.2 Scope and Objective

The CTAD program effort first identified typical aircraft structural components and ancillary equipment with defects and anomalies suited to computed tomography (CT) evaluation. Then, the feasibility and potential economic benefits of CT for the component were evaluated. Specific testing of components was performed in separate task assignments approved by the Air Force. This report discusses the approach, developments and results of the CTAD program effort on CT applications. The economic factors that influence the potential application of CT are addressed. This report serves as an overview for the detailed CT examinations on test objects reported in Task Assignment Interim Reports [1-19].

The CTAD program flow chart is shown in Figure 1.2-1. Application Selection, CT Feasibility Assessment and Preliminary Test Plan preparation were performed in the Core Effort of the program, while specific testing on articles was performed in the Preliminary Test, Final Tests and Demonstration phases of the Task Assignment Effort.

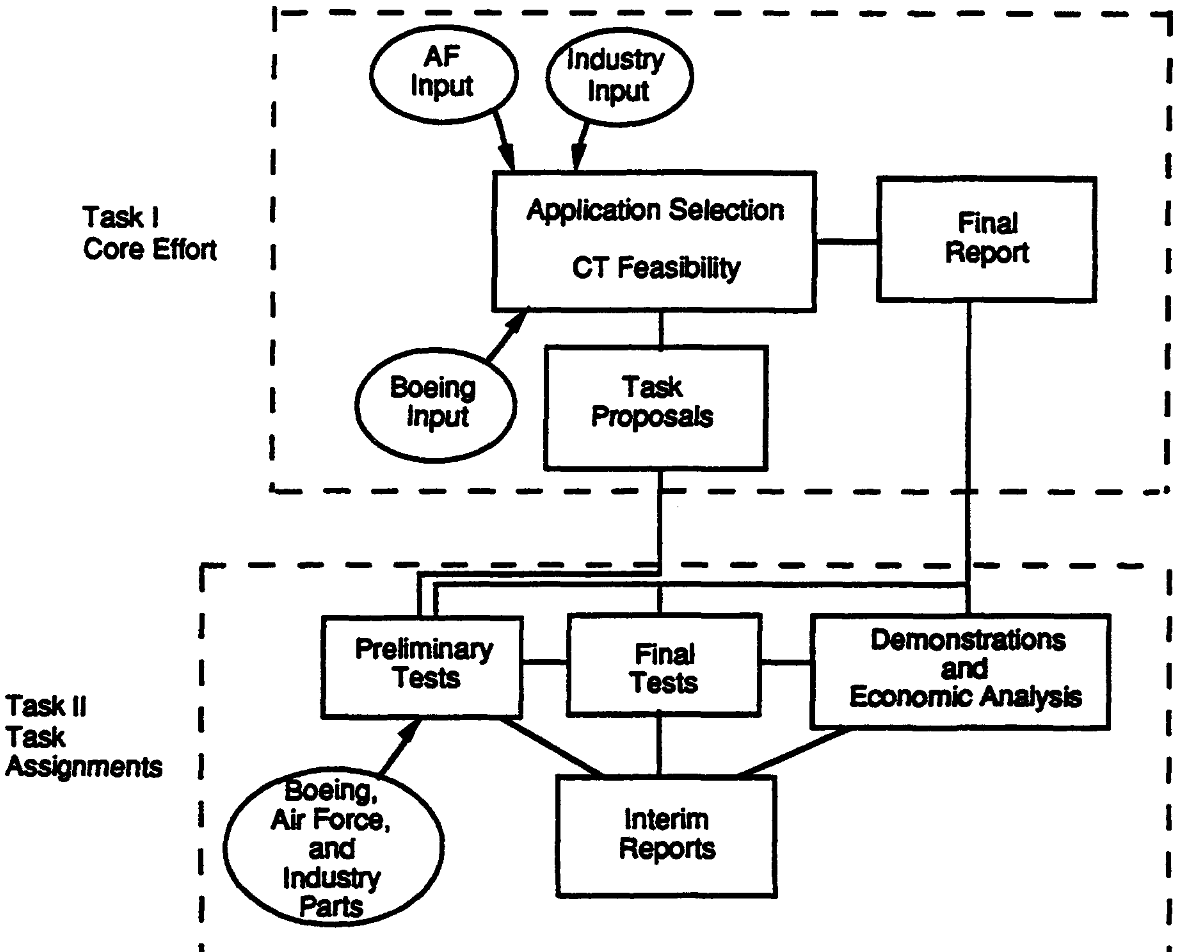

Figure 1.2-1 CTAD program flow diagram.

Figure 1.2-2 shows schematically the interest in and objectives of the Air Force for CT of aircraft components. The Air Force successfully pioneered many of the applications of computed tomography for the rocket community, where CT provides a technically essential and economically viable evaluation technology. Rocket motors and nozzles are high value cylindrical shaped hardware, often with multiple materials having significant radial extent and internal configuration variability. CT is ideal for identifying the material consistency, shape and interfaces which are difficult if not impossible to measure by other means. Aircraft structures, however, are significantly different in nature from rockets. The most critical structures tend to be thin and very large in area. The application of CT to aircraft is, therefore, not straightforward, requiring considerable exploratory effort. The technical capability of CT is unparalleled for material evaluation and, therefore, the potential economic viability of CT as a quantitative evaluation tool for aircraft deserves to be evaluated carefully.

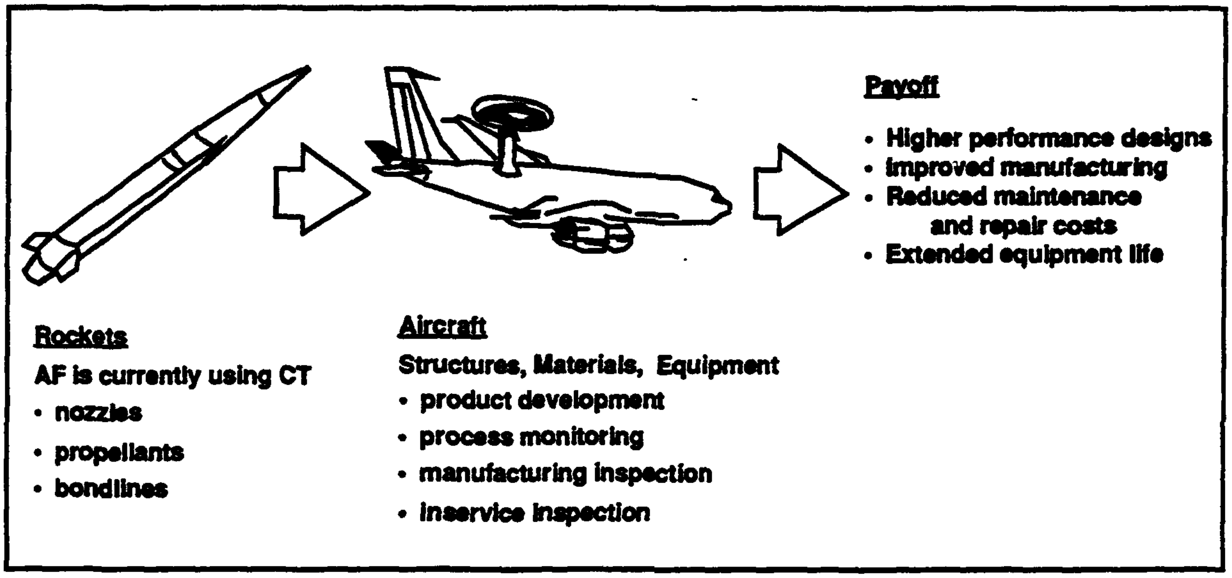

Figure 1.2-2 Air Force interest in CT for aircraft structures and ancillary equipment.

1.3 CT of Aircraft Systems

The application of a new evaluation technique into a mature industry, such as aircraft manufacture and maintenance, is not straightforward. The response of technical contacts who manufacture and service aircraft concerning the applicability of CT for inservice evaluation was a recognition of this potentially powerful tool. This was tempered, however, with concerns about the limitations on component size, geometry, and independence from the aircraft, and the cost and inspection times of current CT equipment, which did not make the technology appealing in this industry. The planar nature of many aircraft parts, (wings, flaps, panels, etc.) are not the preferred geometry for CT, limiting the selection of potential test items to subcomponents in many cases. The necessity to remove parts from the aircraft for CT inspection (at least with today's technology) is generally not cost effective or advantageous over current inservice practice. Although various parts (actuators, gearboxes, landing gears, brakes, etc) are removed for maintenance, they have a designated frequency for breakdown and rebuild specified by manuals that would not obviously be assisted by improved inspection capability. In the case of Air Force Air Logistic Centers and commercial aircraft maintenance centers inspections are dictated by Tech Orders and specifications. CT cannot simply be inserted into these existing criteria.

These issues do not diminish the general overall need of the aircraft industry for better inspection, of which CT is an important potential contributor, but emphasize the need for a different introduction of the technique. As a result, the direction of the CTAD effort has tended towards engineering applications in development and manufacturing. The reason is indicated in Figure 1.3-1 which shows the chain from engineering design requirements and nondestructive inspection (NDI) specifications to manufacturing, quality inspection, and inservice inspection. CT is best introduced in the aircraft industry in the early stages, as opposed to the end (inservice inspection and maintenance). This also draws on the strength of CT as a quantitative analysis instrument, rather than strictly a qualitative imaging device. Figure 1.3-1 also points out a general problem detected in the industry: that there is a lack of communication (shown by the dotted line) between the engineering groups and inspection standards groups with the result that inspection acceptance criteria may not necessarily relate to true engineering criteria. With neither a knowledge and experience base in CT nor CT standards, engineers have been left to design to inspection criteria based on established NDI methods. CT technology offers new opportunities for the future but requires an educational process.

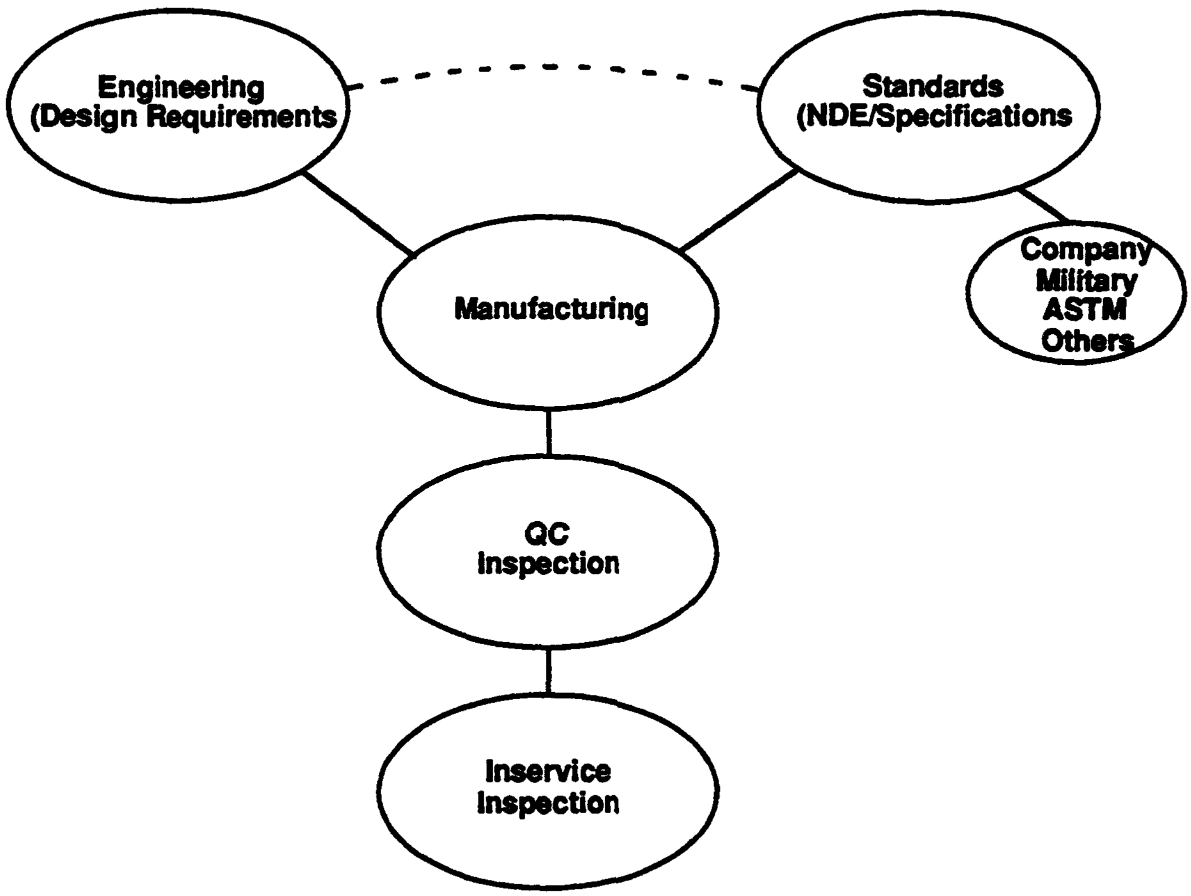

Figure 1.3-1 Flow of inspection requirement in aircraft lifecycle.

The quantitative nature of CT is recognized by engineers on new systems and components as being an important asset. Engineering and manufacturing groups are optimistic about CT, when quantitative aspects are introduced. The application of CT at the engineering level may help to bridge this gap between engineering and standards and lead to the application of CT throughout the aircraft lifecycle.

The education of engineers and responsible individuals to the capability of CT is essential to implementing this new technology and realizing the advantages that CT measurements can provide over existing quality control and evaluation methodologies. It has proven critical to present as many examples of CT scans as possible, in order to assist engineers identifying applications and extrapolating to their problems and concerns. Observing CT results from parts similar to ones own area of interest has been a key to expanding the use of CT. As results from the task assignment studies are published and read, increasing interest in utilizing CT is generated. There is a gestation period followed by applications surfacing as various aircraft/aerospace organizations recognize the use of CT to support their evaluation problems. By recognizing the capability that exists with CT measurements the aircraft engineering community can expand their design options and can refine the materials, processes and requirements of new or replacement systems. With the availability of CT, improvements in aircraft structures and equipment performance can be achieved more economically and quickly than with traditional NDE technology support.

1.4 Approach

The approach taken in this program for the identification of CT applications for aircraft was to break out separate task areas based on material or component characteristics. Figure 1.4-1 shows how different areas may be seen in an aircraft. Figure 1.4-2 shows the major category areas that were studied in various task assignments. The primary application areas were electronics, closed/complex systems, castings, organic composites and, advanced materials and processes. In addition, task assignments were performed that specifically addressed failure analysis of parts and materials. A task assignment was also directed at standards for CT.

Figure 1.4-3 shows a program organizational chart with the various task assignments. The chart also shows that the articles used for CT examination came from a variety of sources and that CT scanning was performed at a wide variety of facilities. A component numbering scheme for test samples was developed to be used with the task assignments and is detailed in Appendix B. Sections 2 through 7 of this report discusss the background in the selection of the areas and the types of articles investigated with CT. This includes the information that led to the selection as an area to investigate and the issues and direction that shaped the investigation. The task reports prepared for each area provide details and CT scanning examples. Section 9 of this report discusses the economic benefits of CT.

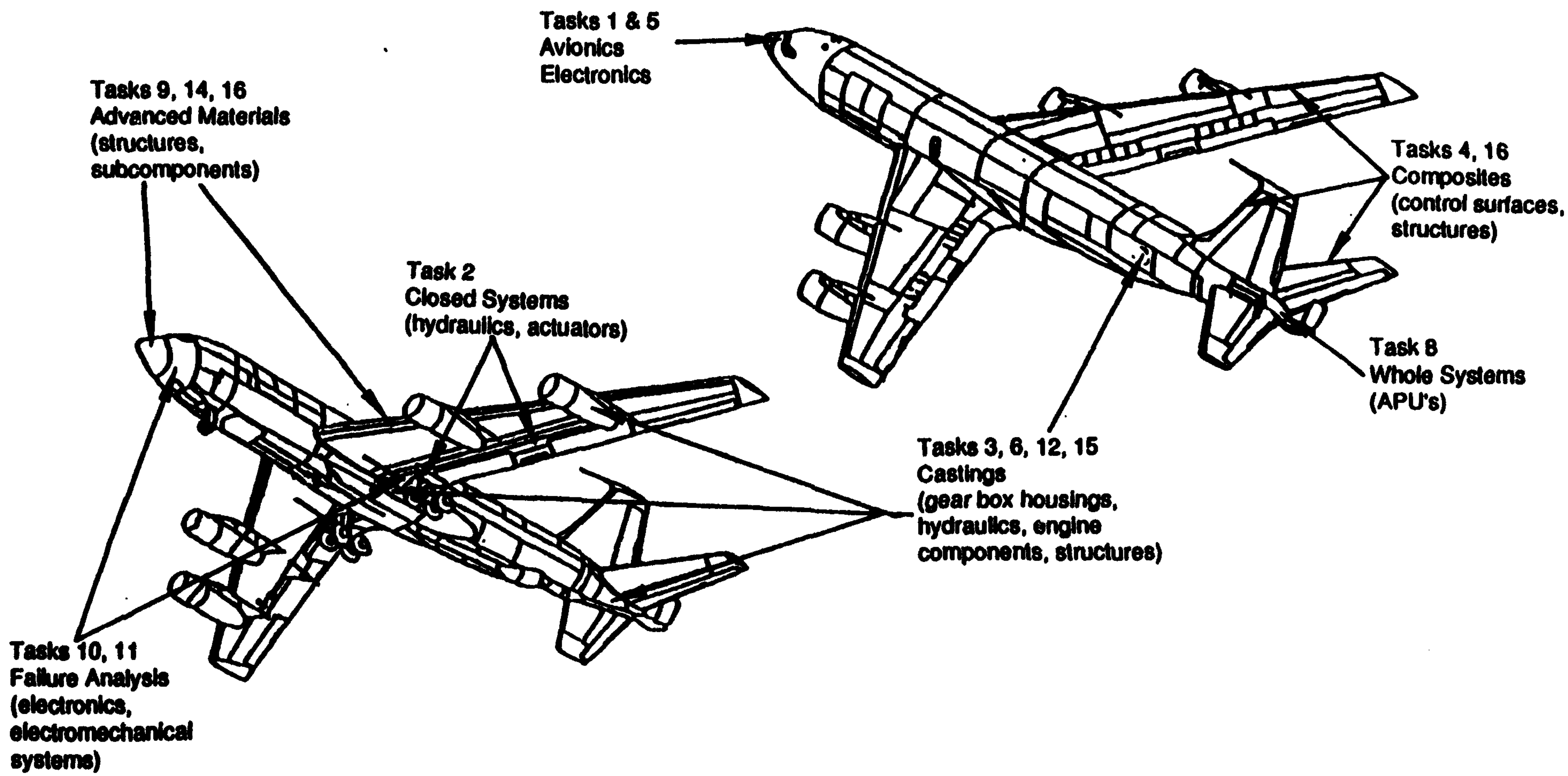

Figure 1.4-1 - Examples of Task Assignment Areas on an Aircraft

Task Assignment	Items/Interest
Tasks 1, 5 & 10 **Electronics**	PC boards, elements on boards, solder joints, electrical component (relays, transformers, connectors, etc.), fiber optics
Tasks 2 & 8 **Closed/Complex Systems**	Batteries, power units, electro-mechanical systems, hydraulic components, gears, acies, jet engines, center of gravity measurement
Tasks 3, 6, 12, & 15 **Castings**	Casting defects (porosity, shrinkage, cracking, etc.), dimensional characteristics, geometry acquisition, finite element analysis
Tasks 4, 10, & 16 **Organic Composites**	Graphite/epoxy, honeycombb, pultrusion, injection molding, stiffeners, sine wave spars, i=noninvasive micrography
Tasks 9, 10, 14, & 16 **Advanced Materials & Processes**	New materials and processes, ceramic matrix, metal matrix, adhesives, welding, bonding, noninvasive micrography
Tasks 11 & 13 **Failure Analysis**	Electromechanical devices, electronic packages, composite damage
Task 7 **Standards**	Resolution, contrast, material calibration, dimensions, test phantoms, MTF, CDD

Figure 1.4-2 Major categories of task assignment activity.

CTAD Program Organization

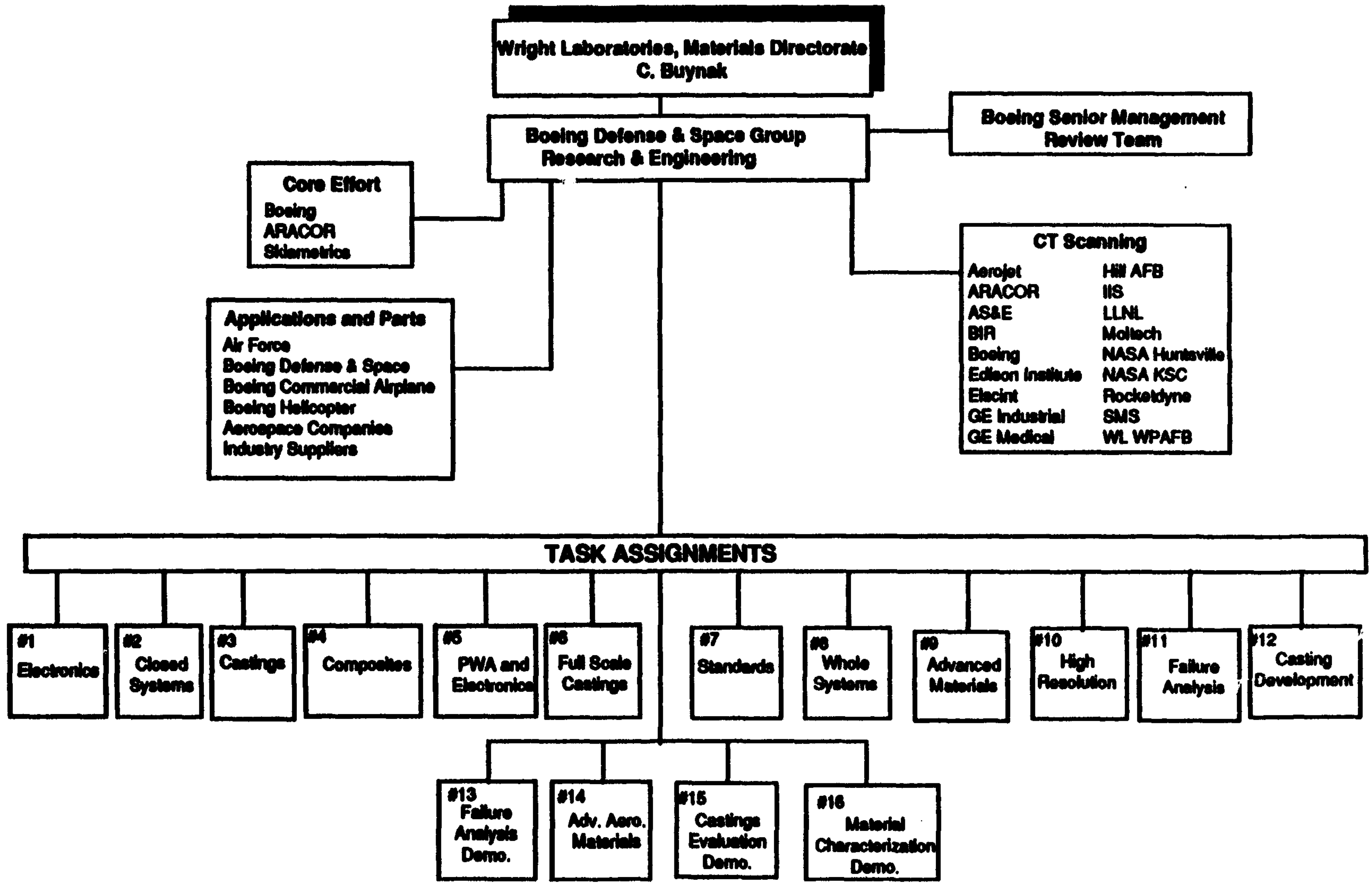

Figure 1.4-3 - CTAD program organizational chart

2.0 ELECTRONICS APPLICATION AREAS

2.1 Background

Electronics represents a very broad designation of components. The two major categories used in this program were electrical components and printed wiring assemblies (PWA). Electrical components are devices that are used in electrical systems such as transformers, connectors, relays, etc. These components can have a variety of inspection needs depending on the material, assembly and application of the components. PWA's consist of printed circuit boards with mounted electronic packages. Solder bond integrity in PWA's is critical to the successful, economic manufacture of reliable electronic assemblies.

2.2 CT Application Assessment

2.2.1 Electrical Component CT Assessment

Electrical components, such as transformers, relays, and connectors are assemblies that have requirements levied against material characteristics, proper fit, clearances and defect level. The inspection of these components to verify internal condition after assembly, is often quite difficult. Quality is most often dependent on manufacturing consistency. Verification of quality is typically based on performance testing and periodic destructive analysis.

Computed tomography offers the ability to look inside many electrical components and evaluate the assembly configuration or identify defects. The effect of CT is to section the part nondestructively. While 100 percent CT evaluation could improve overall reliability of the components, the costs are high relative to the individual item cost. For components that go into critical high value missions, there may be an incentive to perform 100 percent evaluations. However, in general the economic assessment of CT for electrical components is that CT is best suited to product development studies and failure analysis investigations.

2.1.2 PWA CT Assessment

The quality of solder bonds and the cost of performing quality assurance inspections in PWA's are a critical concern of electronic assembly manufacturers. Because of the large growth in the use of electronics and the competitive need to reduce the size of the components, there is a demand for high speed, high reliability inspection of multiplanar, high density boards. Suitable inspection techniques for the evaluation of PWA solder bond quality has been a major industry challenge, particularly for high density, double sided assemblies. Additionally, the use of surface mount technology (SMT) has increased the need for reliable evaluation of the solder bonds because they are not only an electrical connection but also a mechanical bond holding the components to the board. Current quality assurance inspection is very often visual with an increasing emphasis toward X-ray imaging techniques. Radiography and radioscopy have been used; however, on complex double sided assemblies, these methods cannot provide a rapid, automated processing because of the confusion created in the image of the overlapping components and bonds. Computed tomography offers the potential to evaluate PWA's without superposition of information, but the large planar nature of the assemblies makes CT impractical in many cases. Laminography is of interest because it can reduce or eliminate superposition interference in imaging details of hidden solder bond features on double sided assemblies. Laminography (Appendix A, Section 4) is particularly effective for solder bonds because the solder bonds are high density features which are spaced about on a surface. As they are moved in an unfocussed plane, their high attenuation effect on the image is averaged with neighboring low attenuation features or air and so their overall influence is decreased. The high density solder joints at the focussed plane are imaged with excellent resolution and with a reduced interference effect from the defocussed joints above or below by the laminographic process.

Digital laminography can be performed on an industrial CT system by taking a series of digital radiographs (DR) with the part rotated by prescribed angles between each DR. The DR data set can then be analyzed to focus on any desired depth plane in the part. This is not particularly effective for solder bonds because of the scanning and reconstruction time required and the resolution limitations of CT systems required for fine detail. However, it can be effective for analysis of the internal circuit traces on multiple layer circuit boards. For solder bonds a much more efficient laminographic approach is to use a scanning electron beam and fluorescent screen detector to rapidly image PWA solder bonds. This technology is discussed in the Task Assignment 5 report [6].

2.3 Lessons Learned

Electrical components and printed wiring assemblies were evaluated for the applicability of computed tomography in Task Assignments 1 and 5 [1,6]. Task assignments 10 and 11 also included some electrical components [11,12]. Figure 2.2-1 summarizes the major conclusions from the reports.

CT for Electronics	
Area	**Conclusions**
Electrical Components	• CT is cost effective in product qualification. • CT reduces costs in failure analysis of components (solves internal evaluation that cannot be resolved by other means). • Combination radioscopic (RTR) and CT capability is optimal approach for most electronic components.
Printed Wiring Assemblies	• Scanned beam laminography is cost effective for double-sided printed wiring assembly bond quality.

Figure 2.2-1 Electronics conclusions.

Users of connectors, transformers, relays, and other electrical components that have volumetric features were found to benefit from tomographic inspection for both failure analysis, as an alternative to destructive sectioning, and for product development. CT images were useful for determining internal geometric features of a complex assembly. CT has a significant benefit over conventional failure analysis tests because it does not destroy the evidence of failure. In the case of an alternative to destructive sectioning, CT can save the "sectioned" part, which results in a significant cost saving for high cost electrical components. It was also found that radioscopy could be used to determine specific features of interest in many electrical components, using the human observer to evaluate the depth of the features by manipulation of the radioscopic display. The selection of radioscopy or CT for analysis depends on the component design and the nature of the desired results from the examination. Quantitative dimensional and material composition measurements can be readily obtained from the CT data, whereas radioscopy is qualitative.

Conventional CT was determined to be impractical for printed wiring assemblies; however, the program did evaluate alternatives to present visual inspection. It was found that automated X-ray inspection systems, for printed wiring assembly solder bonds, have short term (0.5 to 1 year) payback over visual inspection. The automated inspection algorithms were not evaluated but it is believed that they will provide greater confidence in evaluation consistency than is provided by human observation and will be able to produce objective data. For single-sided PWA's radioscopic systems can be used. However, for double-sided PWA's where components are mounted such that a radioscopic image shows overlapping solder bonds from each side, laminography [6] is more appropriate. Scanned beam laminography offers a method for rapid solder bond inspection of double-sided assemblies. It is possible to utilize the laminographic imaging to build a 3D model of the solder joint. Volume and shape of the bond is one of the most important features for predicting solder joint performance. The data from automated inspection systems can be input to statistical process control (SPC) systems. SPC is critical to modern, high throughput manufacturing, and is an important element in MIL-STD-2000 for electronic manufacturing. Laminography using an industrial CT system was also shown to provide useful data for reverse trace analysis. Individual copper trace planes in multilayer boards could be resolved for boards with 0.40 mm (0.016 inch) spacing between layers. This capability could be improved in both speed and resolution by the use of optimized detector arrays and be very useful for studying unknown or suspect board designs in already constructed assemblies.

3.0 CLOSED/COMPLEX SYSTEMS APPLICATION AREAS

3.1 Background

Aircraft/aerospace systems contain a number of relatively closed or sealed mechanical assemblies and electromechanical devices. Many of these units are quite complex internally, consisting of numerous subsystem, components and materials. Examples of small closed systems include actuators, small hydraulic systems, gearbox drives, thermal batteries, power units, electronics, safe and arm devices, etc. Larger systems would include auxiliary power units, engines and large hydraulic systems. Because of the opaque nature and often numerous internal elements of these systems final assembly verification is only possible with penetrating radiation inspection methods. While radiography can be applied in some instances, the confusion of features due to superposition of information in radiographic images is not always acceptable. Assembly process control and functional testing are then the only methods available to assure the product quality. In highly critical systems this may not be sufficient.

3.2 CT Application Assessment

3.2.1 Closed Systems CT Assessment

Closed systems, such as thermal batteries, mechanical assemblies and electromechanical devices, represent a classification of aircraft/aerospace components that are suited to CT inspection technology because of their generally compact size, the opaque nature of their enclosures and the numerous internal elements that are assembled to make a precise unit. The elements within each closed system require inspection for a variety of reasons. Inspection of a closed system component during prototype development would allow verification of engineering design and component functionality, and evaluation of potential failure mechanisms prior to full-scale production. In-line, or off-line production inspection would provide verification of manufacturing quality control. Adequate nondestructive inspection of failed closed system components would provide valuable insight into the failure mechanism.

Presently little or no post-assembly nondestructive evaluation is performed on closed systems because of the inability to resolve internal details. Functional testing, and occasionally film radiography for some types of units, are the usual testing procedures.

3.2.2 Complex Systems CT Assessment

Engines are a complex assembly of subcomponents that have significant material and structure variations. As such, the results of the engines measurements allow the extrapolation of CT benefits to many other systems that are similar in complexity. Small jet engines used in cruise missile or aircraft drones are of a size that they can be conveniently scanned by existing CT systems.

The maintenance of small jet engines requires a periodic complete overhaul to evaluate the internal conditions. The specific overhaul operations are: remove auxiliary components, disassemble main engine, disbond parts, clean or strip parts, machine parts as necessary, perform visual and physical inspection, perform measurements, perform nondestructive inspection, balance individual parts, balance assemblies, perform finish machining, replace aged or unacceptable parts, bond parts together, seal assemblies, finish mechanical assembly, and power test. These activities require the expenditure of material resources (including some hazardous materials and chemicals) and increase the risk of component damage during handling. There are age sensitive components such as seals and grease packed bearings which must be replaced at well defined intervals and require disassembly, but the majority of the actions at intermediate times are basically inspection issues.

Because CT provides quantitative measurement of X-ray linear attenuation coefficient and position in small volumetric units throughout a cross section of a component, the data can be used to estimate the center-of-gravity (CG) of a component or a combination of components. Vibration must be kept to a minimum in jet engine assemblies, requiring extensive testing of subcomponents and the full assembly, with disassembly and rebalancing operations being iteratively performed until the individual components of the system are in proper tolerance. The practical accuracy of the CG prediction, based on CT data, will depend on a number of parameters such as the CT system resolution, contrast sensitivity, mechanical accuracy, the complexity and density variation in an object, influence of adjacent features on the measurement of the feature of interest and partial voluming of features in the CT slice.

3.3 Lessons Learned

Generally, CT provides informative data on the internal configuration of closed systems beyond that provided by conventional film radiography. A particular usefulness of CT in closed systems is in engineering evaluation of the assembly during prototyping or failure analysis. CT provides highly detailed information on a thin slice through a complex system. With the use of multiple CT slices to form a volume data set, details can be evaluated along any arbitrary plane through the volume. This is sometimes referred to as synthetic tomographic reconstruction or multiplanar reconstruction. Figure 3.3-1 summarizes the conclusions of the Task Assignment 2 and 8 studies [2, 9].

CT of Closed/Complex Systems
• CT measures internal clearance dimensions on closed systems (Risk reduction on high-value parts or mission)
• CT is not cost effective in routine mechanical system manufacture/assembly evaluation
• CT can reduce the cost of failure analysis and engineering evaluations on mechanical systems
• Digital radiography is superior to film for dynamic range in complex system imaging
• CT can verify correct assembly/detect anomalies of reasonable size (> 0.25 mm) in large complex systems
• Increasing the X-ray energy improves image quality in large complex system CT

Figure 3.3-1 Closed/complex system conclusions.

3.3.1 Thermal Batteries

Thermal batteries are a particular closed system that exemplifies the benefits and difficulties in implementing CT. Medium resolution (0.5 to 2 lp/mm) CT and DR are nearly equivalent to radiography in terms of cell layer structure sensitivity, but without the parallax problem of the film technique. High-resolution (2 to 4 lp/mm) CT systems can provide a digital radiograph (DR) that competes very well with film for resolution, but exhibits superior dynamic range. Longitudinal CT slices are better than radiography and DR for quick-look cell structure information. In this study, axial CT slices provided more information than was currently desired by the manufacturer for standard quality control inspections. In fact, defects such as cracked material layers in cells and insulation were found that were unknown to the manufacturer. Axial slices are effective when conducting detailed study of layers within cells and specific dimensional information, such as squib and heat paper configuration. Many axial slices (4-6 per cell) are required to map the battery entirely. CT and DR offer some significant image processing advantages for automated inspection, as shown by the ability to count cells and detect defective cells.

Without specifications requiring the superior CT evaluations, thermal batteries will continue to be inspected with film only, unless DR and CT cost can be reduced below film radiography costs. Multiple battery (batch) inspection is possible with CT to improve the economics. Nevertheless, the present CT equipment cost remains too high for routine application.

Failed batteries, identified during lot acceptance testing, can be inspected with CT to assist in analysis. Currently, the only alternative to film radiography in failure analysis is dissection, which is highly detrimental to the analysis. Economic incentives exist for understanding the failure mechanisms of thermal batteries since they are used predominantly in systems (missiles, rockets, pilot ejection seats, etc.) where failure of the battery could have a serious mission impact.

3.3.2 Other Closed Systems

CT inspection of various mechanical and electromechanical closed systems, have resulted in images suitable for engineering evaluation of the assembly quality. Engineering analysis data and failure analysis studies are the most obvious applications. It would be impractical and economically unsound to purchase a CT for a single aircraft electromechanical system production inspection. The number of units are insufficient. The use of commercial or medical CT facility services, however, for developmental inspection is practical. For example, CT has been requested for evaluation of a lot sample of certain devices for effectiveness of contamination control corrective action.

Gear drive assemblies and hydraulic unit inspections were found to be of interest, particularly from the image quality obtained using high-energy (2 MV) CT systems. In the case of a gear box, the ball bearing, bearing race, shims, and gear angles were adequately imaged. The CT results were highly informative; however, there is no pressing need to move to CT as a routine inspection. The penetration ability of high-energy (2 MV) CT on an hydraulic actuator was sufficient to image the entire 30 cm (12 in) length. A single CT slice in the longitudinal direction, if used during post-manufacturing inspection, would provide valuable assembly information such as O-ring position, mechanical arrangements, and clearances. This would be useful to organizations requiring routine analysis of such parts. There is nothing in the manufacture or repair of the units, however, that indicate a need for production engineering or inservice inspection in large quantities.

3.3.3 Complex Systems

Computed tomography for the evaluation of complex systems, such as engines, could be used for assembly verification and foreign object detection, and as part of an engine maintenance program, reducing the disassembly activity. The F107 CME was CT scanned on four different CT systems, at X-ray energies of 420 kV, 2 MV, 2.5 MV, and 9 MV. The purpose of scanning on the different energy systems was to evaluate the minimum energy required to provide adequate detail information. CT scans were taken across the main axis of the engine to reveal details of compressor stages, stators, burner/combustor, and seals. The 2 MV and higher energy systems also had sufficient penetration capability to allow longitudinal CT scans of the engine while in the shipping container. The ability to be sensitive to internal details generally increases with the CT system energies used from 400 kV to 2 MV to 9 MV. For long metal paths the highest energy available is preferred; however, many of the 2 MV images can show good sensitivity to internal details, and even 400 kV can be usefully employed in some regions of an engine.

Experiments from a test phantom show that it is technically feasible to use CT data for measurement of the CG. The method as demonstrated with a ring test phantom is sensitive to within 0.15 g-cm at 3 cm radius in aluminum. The absolute position measurement with CT may be subject to an offset that will require correction if a single CT measurement is used. The preferred technique is to use 360° scans and a comparison of the CG shift between multiple positions. The influence of adjacent structure has been shown to greatly affect the CG calculations. Compensating for static adjacent structure may be possible by performing the CT measurement of CG using multiple rotational positions. The presence of the static structure would be expected to reduce CG measurement accuracy in proportion to the relative mass that is present. It should be noted that this technique is not limited to circular or high degree of symmetry parts but is applicable to parts with complex geometry.

CT examination of engines should utilize as high an X-ray energy source as can be practically obtained. In addition, due to the complexity and detail of the parts examined under this task assignment, it is recommended that 360° tomographic scan and reconstruction, region of interest or larger format image matrix reconstruction, and a high signal to noise are highly advisable. The use of 360° tomographic scanning is essential for measurements such as CG, and advised for detail evaluation across a complex system. The reconstruction pixel size should be on the order of one-half the inherent resolution of the CT system. Thus, as the system size increases, the reconstructions should be performed over subset regions of interest, or a larger format (such as 2048 x 2048) would be required to obtain full resolution of the detail.

4.0 CASTING APPLICATION AREAS

4.1 Background

Castings are used extensively in the aircraft/aerospace industry and include aluminum, magnesium, titanium, steel, and nickel alloys. Castings can be produced in complicated shapes that are impossible with machining techniques. Castings offer a simple, low-cost solution for manufacturing complex, and often critical, aircraft parts. However, detection of casting defects, such as porosity, microshrinkage, cracks, improper dimensions and misassembly, too frequently result in high scrap rates and excessive costs.

Most castings contain imperfections to some degree; some are serious. Surface flaws are detected using visual and dye penetrant inspection. However, penetrant inspection for the detection of surface anomalies leads to excessive rejection rates while being limited in the ability to characterize defect depth. Subsurface flaws are detected with radiographic inspection. The X-ray inspection of aircraft castings has been a costly and time-consuming process due to the high cost of X-ray film and the need for multiple radiographic exposures to cover the widely varying material thickness and complex geometries of many castings. The interpretation of flaw severity by film radiography is subjective and may vary widely between independent radiographers. Additionally, the thickness of the part influences the detectability of flaws. A radiograph of a thicker part with the same flaw condition as a thinner part will produce a lower contrast image. Interpretation of radiographs is often compromised by surface features or irregularities which may give the false appearance of nonexistent internal flaws. The depth and distribution of flaws cannot be known from a single radiograph due to the lack of three-dimensional information. Also, film radiography may provide little or no useful information in critical inspection areas because of the difficulty of film placement and X-ray beam orientation on specimens of unusual geometry, i.e., complex shape, thickness, or curvature. Added to this is the difficulty of suitable radiographic inspection criteria because the defect indications do not necessarily relate well to engineering criteria. This is due to the difficulty of viewing, locating, and accurately sizing the porous defect on a 2D film. Because RT cannot precisely define flaw size and location throughout a complex part, the acceptance criteria must be extremely conservative, often resulting in the rejection of useful product.

4.2 CT Application Assessment

If casting defects could be quantitatively evaluated, then engineering principles could be applied to allow wider application of castings. If these defect and performance issues could be resolved, it has been estimated that shifting from forgings to castings, for example, could reduce part costs by factors of 2 to 8 (depending on part complexity) in aircraft applications. Even greater cost savings are possible if castings are used to replace assemblies, reducing part count, assembly labor and weight.

CT offers a better inspection modality than radiography with its ability to handle complex geometries, and perform dimensional measurements. The CT data are digital and can be transferred to engineering workstations for evaluation of the as-built part geometry. Digital data acquisition would also reduce radiographic film usage, which appeals to many companies because of the high cost of environmental compliance associated with the use of film processing chemicals.

The defect sensitivity of a CT image is a function of both CT system parameters and the size of the casting. The X-ray energy, CT slice thickness, and casting wall thickness will affect the detectability of small voids. Based on casting dimensions and defect sensitivity desired, CT system parameters can be selected for the most effective casting inspection.

4.3 Lessons Learned

Computed tomography provides information for improved casting and casting processes evaluation that can be economically viable. Figure 4.3-1 summarizes conclusions from the studies of CT for castings performed in the Task Assignments 3, 6, 12 and 15 studies [3,7,8,13,16]. CT provides flaw characterization capability in critical regions that are not available with conventional casting NDE methods. This capability allows the evaluation of regions which tend to have defects in the developmental stages of a casting process, and can assure material quality in the same region during production. It also allows a quick and inexpensive means of evaluating the material quality in critically stressed regions, which often cannot get thorough coverage with radiography. By using CT on "just cast" parts, valuable information is provided which can reduce costs through early screening or repair planning. The "dead end" costs associated with completing the manufacturing steps on castings that will ultimately be rejected by radiography can be reduced or eliminated. A more significant payback, however, is in the ability of CT to demonstrate that an anomaly such as a void is noncritical, and to provide exact locations for repair when required, therefore saving an otherwise scrap part. This is particularly advantageous on high value parts where CT costs are small fraction of the casting value.

CT evaluation provides internal dimensional measurements in castings that are as good or better than destructive sectioning. Dimensional measurements to better than 0.050 mm (0.002 inch) are fairly easy to achieve with the CT system configurations tested. Using appropriate techniques, measurements that have previously been considered to be beyond the inherent resolution of the CT system can be made. Dimensional measurements should provide accuracies on relatively large parts that are in the range of 1 part in 10,000. The relative cost of the CT dimensional measurement depends on the number and difficulty of the measurement, but appears to be very competitive with destructive sectioning, particularly if many measurements are desired. If the casting is within dimensional tolerance, the use of CT saves the cost of the component. For foundries with very high cost components such as jet engine castings, the direct cost benefits of CT in saving the casting from destructive sectioning can justify the cost of CT evaluation.

The quantitative nature of CT allows an engineering evaluation of castings based upon a correlation with performance. This study has shown that CT can provide a measure of porosity and voiding which correlates with the level at which casting strength begins to degrade and to shift out of the distribution of normal mechanical properties for tensile specimens. This can greatly reduce the current number of "good" castings which are rejected based upon the qualitative assessments from presently employed NDE techniques. The high scrap rates associated with subjective inspection methods for castings can be reduced through the implementation of CT. CT provides the link in the inspection methodologies to engineering evaluation that can allow the engineer to design and utilize castings with greater confidence. CT sensitivity to anomaly sizes has been measured by the use of image quality indicators. CT imaging may be as sensitive to volumetric defects as radiographic inspection, with respect to MIL-STD-453 requirements.

CT of Castings
• CT provides a more reliable measure of the quality of complex castings than radiography: CT is particularly beneficial for detail sensitivity needed in critical regions. • CT can be cost effective for foundry use: CT benefits new product development, dimensional measurement, and critical region inspection. • CT provides noninvasive dimensional measurements: Accuracy to better than 0.05 mm (0.002 inch) for CT systems with inherent resolutions of 1 lp/mm and higher can be achieved. • CT can be effectively used to acquire casting geometry in digital definition to be input to CAD/E workstations (reverse engineering). • CT data enables engineering assessment: Scrap can be reduced through quantitative evaluation of the effects of anomalies. Finite element analysis of the effect of casting defects can be performed from CT data. CT data can correlate to material properties.

Figure 4.3-1 Casting conclusions.

The three-dimensional location capability of CT allows CT data to be converted to CAD/E workstation files. CT can be effectively used to acquire casting geometry in digital definition (reverse engineering) and reconstruct components for visualization as part of the engineering analysis. This geometry acquisition capability can also allow drawings to be made of components in their as-built condition or of components for which drawings do not exist. If the location and definition of flaws, obtained from CT evaluation of castings, is included in the CAD/E data, the information can be input to finite element engineering models to analyze the performance as a function of the casting condition.

Although presently available capability and inspection specifications currently prevent realization of potential cost benefits from using CT for general inspection of aerospace/aircraft castings, there are categories of casting manufacture for which CT is optimally suited. CT is an excellent enabling technology for castings. It can be used today for new product development and for specific areas of production inspection to reduce scrap. The analysis of the CT testing revealed that there is currently a technical and economic benefit to using CT in new product development, early screening, complex geometries, and critical region inspection. The foundry in which CT will be economically viable will have one or more of the following characteristics: sufficiently large production, a requirement for internal dimensional measurement capabilities, high production of complex castings, or material review board authority.

In the near future, CT system speed and image resolution should continue to increase, and costs will continue to decrease, making CT more and more cost effective for casting evaluation. High throughput CT, such as cone beam CT, will become very cost effective for casting inspection, provided required sensitivity to critical defect size is achieved. As CT system and operating costs decrease, CT will compete with radiography in most areas of casting inspection. Digital radiography and CT can be implemented in combination to allow a rapid DR evaluation followed by selective CT scanning at critical locations.

Although CT is technically applicable to many foundry needs, for it to become universally economic, CT results must be acceptable (and perhaps even required) by specification and called out on casting drawings. Low cost CT data acquisition that is competitive with the cost of film radiography will need to be available as well. It will also be necessary to modify existing inspection specifications for castings to allow for CT examination to be used in the accept/reject mode of current aircraft/aerospace practice. This change will involve considerable effort and education. However, the opportunity exists to make a significant economic and technical impact in some areas by changing from contemporary qualitative, subjective inspections with radiography to quantitative CT evaluations. This will allow castings to be designed and accepted based on performance criteria. It is recommended that engineers be educated in the application of CT to castings and that they incorporate its use in the casting inspection criteria using critical defect size and location analysis as a fundamental approach to casting design.

5.0 ORGANIC COMPOSITES APPLICATION AREAS

5.1 Background

Due to demanding requirements imposed on current and future high-performance aerospace structures, organic composite materials are being developed for and used on a variety of aircraft/aerospace applications. High strength-to-weight ratios and the ability to tailor the material to meet specific criteria (e.g., stiffness in only one direction) make composites highly attractive for these applications. However, the nonhomogeneous nature of composites (typically a mixture of fibers and a matrix) and the problems which arise in their manufacture and handling, result in defects unique to these materials; some which can be hidden or uncharacterized. These defects include delaminations, porosity, nonuniformities, wrinkles, improper layups or fiber volume fractions, honeycomb damage (in sandwich composites), disbonds, unacceptable resin content, nonuniformities, cracks and damage due to impact. In addition, many composite parts are complex, for example: channel shapes with tight radii, parts with filler materials; multilayered honeycomb structures, injection molded parts, 3-D braided preforms, and composites with embedded sensors or actuators (smart skins).

It is widely recognized that composites will require improved nondestructive inspection techniques over conventional methodologies (ultrasonics, radiography and visual) to fully characterize and understand their properties and defects. Many composites have not been inspected very well in the past because no adequate inspection method or acceptance criteria have been available. It is also important to note that the complexity and level of maturity of composite materials and applications, as well as the diversity of defects and their causes, makes composites a broad area to investigate.

5.2 CT Application Assessment

CT offers considerable potential to reveal three-dimensional quantitative information useful to composite design, manufacturing and inservice inspection and to serve as a tool for process control of composite manufacturing processes. The nonhomogeneous nature of composites and the defects which inevitably arise due to current manufacturing and handling methods place high priority on inspection and quality verification. The mapping of composite structure consolidation and consistency with CT is certainly advantageous to material processing.

Figure 5.2-1 lists some of the organic composite types that could benefit from CT. Processes which may also benefit from CT for process control and inspection include filament winding and injection molding. Injection molding, for example, is a process whose manufacturing costs are more than 10 times lower than conventional processes on any given part. As embedding technology develops for "smart" composite structures, the need for configuration verification in complex parts will become increasingly important. Large, composite structural components present interesting challenges for conventional inspection techniques. And, CT may play a significant role as the complexity increases. Parts consisting of multiple materials such as helicopter rotor blades, large honeycomb structures with internal septa, or multiple layered thick structures should benefit from the application of CT. A challenge for CT are large, relatively flat control surfaces of aircraft. The applicability of CT on these flat, large aspect ratio parts, does not appear to be very good without significant advances in CT systems technology.

Item	Problems
General Composites	Delaminations, voids, fiber/resin ratio
Graphite Epoxy Structures V's, T's, I's, etc. sine wave spars	consolidation at bends/ joints, ply drop-offs
3D Braids	voids
Honeycomb	face sheet bond quality
Large Honeycomb	internal septa condition, honeycomb bond
Filament winding	voids, delaminations
Injection Molding	voids, flow pattern
Embedded Sensors	sensor location

Figure 5.2-1 Organic composites.

The applicability of CT for composite bonds is a major consideration because CT is a volume measurement technology. CT detects disbonds that have "opened" a sufficient amount to create a volume defect, but could not be expected to detect weak bonds or closed disbonds. Bonds which use filler materials can be evaluated with CT for the presence of the filler. Internal bonds in complex structures can be measured with CT, where no other technique can be applied.

5.3 Lessons Learned

The CTAD program tested CT a wide range of composites in Task Assignments 4 and 16 [4,17] and also as part of Task Assignments 10 and 11 [11,12]. Pultrusions, honeycomb structures, basic laminates, filament windings, and braids were considered. The technique is effective for evaluating density variations, voids, delaminations, and dimensions and could even detect wrinkles. A variety of industrial and medical CT systems were tested with a range of resolution capability, signal to noise and scan speeds. Figure 5.3-1 summarizes the conclusions.

The results reported in the task assignment demonstrated that CT has the potential to meet or address several composite problems and needs. However, it has not yet been shown what economic value the technology will have for routine inspection because acceptance of composite components in aerospace has traditionally been nearly completely restricted by specification to tap tests and ultrasonics. CT (and other radiographic techniques) are therefore used only as additional information. In general CT is an excellent enabling technology for composite product development and has been shown to be particularly cost effective for thick composite structures. To date, these types of structures have been limited in use on aircraft.

The use of CT to monitor composite consolidation was found useful to process selection and control. Evaluating defect types and location was found important to improving overall product quality. CT was also found to have potential for on-line monitoring of some composite manufacturing, but without specific requirements and product demand, this was not implemented. Complex composite structures, such as large honeycomb with internal septa, do benefit from CT evaluation as the only method to confirm the internal bondline condition. CT is also applicable to composite damage measurement for small subsamples from failed structures. This is referred to as noninvasive micrography and is discussed in Section 6.3-3.

It was found that CT systems with resolution in the range of 1 lp/mm and signal to noise of greater than 50 to 1 provided excellent results on composites. CT images of composite materials are low contrast, in which detail sensitivity benefits more strongly from higher signal to noise than from greater resolution. With the relatively low density of composites (< 2 g/cm^3 (0.072 lb/in^3)), medical CT proved very effective both technically and economically. When the composite walls are thin (< 3 mm (0.12 in.)), then higher resolution (> 2 lp/mm) systems produce better image data.

CT of Organic Composites

- CT enables efficiencies in new product development

    Cost savings provided by reduction of cycle time and number of cycles

    Increases design options

    Best on thick composites

- CT monitors composite consolidation and quantifies anomalies and defects

- CT can provide on-line process evaluation, feedback and control

- CT is cost effective for noninvasive micrography

    Required resolutions of 0.1 mm or better are available

- CT is an alternative to destructive tests for interface evaluation

    Use in failure analysis

Figure 5.3-1 Organic composites conclusions.

6.0 ADVANCED MATERIALS AND PROCESSES APPLICATION AREAS

6.1 Background

Materials are often called "advanced" if they exhibit properties, such as high temperature strength or high stiffness per unit weight, that are significantly better than those of more conventional structural materials, such as steel or aluminum. Advanced materials include structural ceramics (also ceramic matrix composites (CMCs)), polymer matrix composites (PMCs), metal matrix composites (MMCs), and new high temperature/high strength alloys.

The key to advanced materials is that they are "tailored" to have the properties required for a given application. However, due to the nonhomogeneous nature of advanced materials (which are often a mixture of fibers or particulates and a matrix), problems arise in their manufacture and handling which result in defects unique to these materials, some of which can be hidden or uncharacterized. These defects include delaminations, porosity, nonuniformities, fiber misalignment, improper layups or fiber volume fractions, honeycomb damage (in sandwich composites), facesheet/webbing disbonds, matrix cracks, and damage due to impact. In addition, many advanced material parts are complex, and therefore are difficult to inspect. Advanced materials may include channel shapes with tight radii, multilayered honeycomb structures, injection molded powder metal parts, and diffusion bonded alloys.

Materials fabrication techniques are currently being developed and utilized which offer lower production costs than traditional methods. The materials are often made up of metals, alloys, or plastics. The parts manufactured by these methods can contain defects which are unique to the process and material. Aircraft and aerospace structures are dependent on the joining of materials for their assembly and strength in service. New methods and techniques of assembly involve bonding and fastening processes that are performed in cleaver new ways, always seeking the lowest cost, highest reliability. These assembly techniques benefit from nondestructive evaluations that provide quantifiable data for establishing performance level.

6.2 CT Application Assessment

Conventional qualitative methodologies (ultrasonics, radiography and visual) are often inadequate to fully characterize and understand properties and defects of advanced materials and processes. CT offers considerable potential to reveal three-dimensional quantitative information useful for design and manufacturing inspection and analysis. CT can precisely define the size and location of voids, inclusions, low density areas, and cracks within the inspected component. Depth information is useful in categorizing and evaluating defects. It is sensitive to density variations, and can quantify gradients and material differences. CT can define the details of internal structure of complex configurations. Because complete spatial information on part configuration and defect location is available from CT, an engineering assessment of the as-built component is possible.

Advanced materials for which CT has been tested in this effort have been subdivided into the major categories of carbon based composites, metal matrix composites and ceramics. High temperature carbon-based composites have been utilized extensively in a variety of aerospace applications, including ablative nose cones, rocket nozzle throat entries, and exit cones for space vehicles. As flight technology heads toward higher speeds, there is an increasing interest in oxygen protection of carbon composites used for high temperature aerodynamic surfaces on aircraft that operate in the earth's atmosphere. Methods for evaluating the coatings and the composite underneath need to be developed. CT has potential to meet this need in some applications. Metal matrix composites (MMCs) are being developed for a variety of high temperature, high performance applications in the aerospace industry. Selection of adequate design margins and lifetimes under expected loading conditions requires proper understanding of possible failure mechanisms. The evaluation of material systems for correlation with mechanical properties represents a substantial portion of the material development effort in terms of time and money. High resolution CT should be very effective as a nondestructive method that provides important understanding of MMC microstructural behavior and material forming processes.

Ceramic or CMC inspection for texture, structure, or flaws requires high spatial resolution NDE techniques. Internal flaws such as cracks, voids, inclusions, and density variations may exist in a ceramic component, but will often be quite small. Because of the brittle nature of ceramics, catastrophic failure under stress can originate from small defects. External flaws may also exist due to machining or handling. Typical NDE methods for ceramics include low-frequency UT, microfocus X-ray, and ultrasonic microscopy. CT's unique capabilities to map density variations and represent internal structure should mean that CT will find applications in ceramic material evaluation. Ceramics undergo various stages of processing before the final product. Unique defects can be introduced at any of these stages, which are often not well understood. By using CT to monitor a ceramic part throughout the manufacturing process, one can better understand the process stages, and how defects are created.

Lower production costs are the primary goal of advanced processes. Processing methods such as pultrusion, superplastic forming, injection molding, and powder metallurgy can be very cost effective, but the parts manufactured by these methods can contain defects which are unique to the process and material. CT provides a method to evaluate internal defects for many of these processes. New fastening and bonding techniques can also benefit from CT evaluation as part of the development program. Recent advances in fastener and bonding design have increased the complexity of the tooling and the interfaces. Evaluation of these structures nondestructively, prior to load testing, can be a significant aid in determining characteristics of the process which affect final performance. CT offers considerable potential to aid this activity.

6.3 Lessons Learned

The results of the CT testing revealed four focal areas in which CT currently provides a technical and/or economic benefit. These areas are 1) new product development, 2) process control, 3) noninvasive micrography, and 4) material performance prediction. Figure 6.2-1 summarizes the conclusions drawn from the Task Assignment 9, 10, 14 and 16 activities [10, 11, 17].

Fundamentally, developers of advanced materials should plan for CT scanning services or leasing agreements when costing the development of new materials or components. If the development programs or manufacturing production are sufficiently large, then purchase of a CT system can be cost effective. This is particularly advocated for material production where CT can be used as a process control tool. The CT sensitivity must, of course, be tuned to the requirements of the advanced material evaluation. Resolution, contrast sensitivity and component size must be traded-off in the selection of the scanning system or technique. High resolution CT systems or scanning services should be considered by companies that perform a great deal of sectioning and micrography for advanced material assessment and qualification. The volume of work will determine whether or not the purchase of a CT system is cost effective.

CT of Advanced Material
• CT enables efficiencies in advanced material development Access to CT may prove essential to compete in new product development CT system lease or purchase is recommended for advanced material product development • CT measurement has been demonstrated to correlate to structural performance Consolidation measurement can be a useful parameter for composites CT testing under test conditions such as temperature, load, environment, etc. shows promise • CT is cost effective for noninvasive micrography Required resolutions of 0.1 mm or better are available • CT is an alternative to destructive tests for interface evaluation Use in failure analysis and material qualification testing Use on specimens with internal stress

Figure 6.2-1 Advanced materials conclusions.

6.3.1 Product Development

New materials or products usually involve an iterative cycle of manufacture and testing to bring the manufacturing process under control. CT provides important information about the product to the manufacturing engineer which can reduce that cycle time. CT serves as an enabling technology for the development of new materials, products, or manufacturing processes. The information CT provides allows engineers to reduce the cycle time in product prototyping and often "leap frog" product development steps. Reduced development time often results in significant initial cost savings and reduced risk of poor designs being manufactured that can result in enormous savings over the lifetime of a program. CT is a tool to be used in the "Concurrent Engineering" process.

6.3.2 Process Control

CT can be used for developing and controlling a manufacturing process as part of a "Total Quality Management" program. The CT measurements of X-ray linear attenuation coefficient (directly related to density and a function of atomic number) and the accurate dimensional information provided are ideal for making important statistical measurements as well as for defect characterization for many advanced material processes. Under certain conditions, the CT measurements can be correlated to mechanical properties to allow nondestructive performance prediction of advanced materials.

6.3.3 Noninvasive Micrography

Noninvasive micrography refers to obtaining detailed micrographic information about the interior of an object without destructive sectioning. The CT images are maps of X-ray linear attenuation coefficient, which are different than optical reflection maps from cut surfaces. The CT images, however, are obtained without the damaging effects that will result when mechanical sectioning is performed. Mechanical sectioning damage can be surface distortions, release of residual stresses, insertion of new defects and destruction of valuable material. The micrographic evaluations by CT are applicable to materials whose characteristics are determined by variations in X-ray linear attenuation coefficients. Composite materials are particularly suited for noninvasive micrography because CT differentiates between fibers, resins, voids and coating materials by their compositional properties rather than their optical properties.

The limitation of detail sensitivity of CT systems capable of handling medium to large components (> 100 mm diameter) to approximately 0.25 mm features requires that subcomponents be examined with high resolution CT for detail measurements. The high resolution CT provides cross-sectional image information useful for the evaluation of small components that rivals, and in some applications, surpasses conventional micrography. Many items are of a size such that they can be evaluated with high resolution CT system field of view, and it is possible to section critical regions from larger structures for high resolution evaluation. In this case, CT is not strictly a nondestructive evaluation because of the subsection requirement. The data are obtained on parts that may have residual stresses without altering the internal configuration as would occur for destructive sectioning. For example, features such as fibers, resins, voids, gaps, cracks, coatings, and density variations can be identified. The ability to use 3D CT data sets allows micrographic information to be obtained from all orientations in a sample, which cannot be obtained by other means.

The major economic incentive to use CT is difficult to quantify directly from manufacturing cost analysis because it is primarily an engineering benefit. The nondestructive data for the material or component provide information that improves decision making and reduces overall risk. The ease and rapid acquisition of information about test samples from CT provides a means for faster, improved decisions which can accelerate a development program schedule significantly, with indirect economic benefit. For advanced materials programs that have large micrographic requirements (over 600 samples) high resolution CT can have a direct cost benefit. High resolution CT can be an effective alternative to destructive sectioning and polishing based on the relative costs of CT and destructive micrography. The actual cost benefits will depend on the specifics of the materials and the requirements of the desired analysis.

Organizations involved in micrographic analysis, particularly of composite materials, should consider the acquisition or contracting of services for high resolution CT. Failure analysis laboratories that require micrographic analysis of components likewise would benefit from CT analysis. CT can be used in conjunction with real-time radiography in many failure analysis investigations.

6.3.4 Material Characterization

High resolution CT is useful for the evaluation of numerous types of material studies where sectioning is used to obtain important data. Coating thickness, interface quality, material consistency and defects are measurements that can be made with great accuracy using CT.

The assessment of damage is an important part of material characterization. One particular area of critical damage assessment is in organic composite laminates. When composite laminates are impacted, the damage is manifested on multiple layers of the laminate. Although ultrasonic imaging is the traditional approach to showing the defect area, the delamination pattern on each layer is partially shadowed by the delamination of the layer above. Three-dimensional CT has been used successfully to image damaged areas in detail. The multiple CT slices are processed to extract the delamination and cracking features. These can then be displayed in a 3D format to assist in the assessment of the material performance.

CT can provide measurements on materials during environmental or load testing with proper equipment. Such measurements can be particularly useful for material testing when the environment extremes exceed the capabilities of conventional test instruments such as strain gauges and/or vision systems.

7.0 FAILURE ANALYSIS APPLICATION AREAS

7.1 Background

Failure analysis of systems are an important part of the product cycle. During development engineering analysis is performed on systems to ensure that they operate over the proper regimes. Engineers must also follow the product throughout its cycle. Whenever failures occur, they must be evaluated and understood.

Components fail when the operational loading produces localized stresses which exceed the strength of one or more of its constituent materials. The failure may be due to a reduction in strength of a constituent material, or the operating loads are raised above a critical value. The degradation of material properties through such phenomena as fatigue cracking, erosion, oxidation, and improper manufacture also can result in failure. Excess temperature, vibration, or pressure loading can also cause failure, either by degrading the material properties, or by subjecting the component to stresses which exceed the inherent strengths. Determination of the initiation site and understanding the actual cause of an unplanned failure is critical to preventing future failures. Failure mode evaluation of destructively tested specimens is also very important for the development of a new material.

Because it may be one of a number of possibilities, the cause of failure in complex systems (such as some composites and other advanced materials) is usually determined through time-consuming and costly evaluation methods such as destructive sectioning, microscopy, and chemical analysis.

7.2 CT Application Assessment

CT can be a supplemental evaluation tool, and in some cases, an alternative tool for failure analysis of materials. It provides the capability of examining the interior of a material system before or in lieu of destructive sectioning, and allows quantitative measurement of dimensional and density information.

Mechanical devices depend on the materials selected, structural design, dimensions used, and proper assembly to achieve the desired application. Both macroscopic and microscopic details are important. CT can be used as an investigation tool capable of supporting failure analysis and evaluation by providing dimensional, density and defect information. This can be accomplished at the macroscopic level on complete assemblies and at the microscopic level on reduced size specimens. Electromechanical systems are complex in nature not only from their physical construction but also from the functional aspects and the environmental extremes that they must withstand. The two criteria for classifying a device as electromechanical are electrical input or output, and mechanical motion. The mechanical motion that occurs will be either translational or rotational, and can be either an input, output or intermediate process. This mechanical motion typically controls a hydraulic/pneumatic source/supply or provides mechanical restraint or motion. It is difficult to interpret malfunctions in these devices from simple external measurements.

Electrical components have a full spectrum of mechanical aspects and properties in addition to their electrical/electronic properties and characteristics. Many of these mechanical aspects can be responsible for a failure, such as bond wires, die attachment, die layout, packaging defects, contaminants and others. Failure analysis of small electronic components using CT was identified as an important application for high resolution CT in Task 1, "Computed Tomography of Electronics," and Task 5, "X-ray Tomographic Inspection of Printed Wiring Assemblies and Electrical Components," [1,6]. Additionally in the Task 10 effort on high resolution CT [9], small (typically <5 mm (0.12 inch)) electronic components were also investigated.

7.3 Lessons Learned

The CTAD failure analysis results were reported in the Task Assignment 11 and 13 reports [12, 15]. Computed tomography cross-sectional image information provided useful three-dimensional spatial details on material conditions that were used to assess internal configurations nondestructively for failure analysis investigations. CT was particularly advantageous on complex systems, composite failure studies and testing under operational or environmental conditions. CT, as a tool available to a failure analysis laboratory, would provide a benefit to approximately 10 to 30 percent of the workload with a considerable economic benefit. Figure 7.3-1 summarizes the conclusion of the failure/engineering analysis task assignments.

CT for Failure Analysis

- Electronics failure analysis laboratories can benefit from CT capability

  Combination radioscopic (RTR)/micro-CT may be best approach

  Electronic components need 0.1 mm or better resolution

- CT enables more reliable failure analysis of electromechanical assemblies than traditional methods

  Electromechanical assemblies need 0.25-mm resolution at 400 kV or above

  Fast response, ready access to CT capability is needed

- Composite failure can be analyzed with CT

  CT systems with better than 0.05-mm resolution are necessary

  3D imaging significantly enhances analysis; mathematical morphology is a convenient, intuitive approach

Figure 7.3-1 Failure analysis conclusions.

The largest area for use of CT in failure analysis studies appears to be in the electronic/electromechanical area. Failure analysis studies in these areas require high resolution CT systems for relatively small (less than 50-mm-diameter) components. A reasonably large laboratory (>$500K/year workload) could justify a microfocus based CT system for such studies. For electrical parts there is a need for 3-D imaging of electronic parts for contamination, wire detachment and connectors. The resolution required is estimated to be in the range of 0.1 mm for most items.

The use of CT in failure analysis of larger electromechanical and mechanical systems does not appear to offer enough incentive to justify the acquisition of a CT system for that sole purpose. CT can, however, be used effectively from a service facility. However, in many cases the ability to obtain the service must be fast and with minimal difficulties in transportation of the parts and information. Also to make CT truly valuable, analysts must become familiar with the results and data manipulation possibilities. Presently CT is relatively new and, therefore, is overlooked in its capability to provide cost-effective information. CT can also be applied with the component undergoing operational conditions (pressure, temperature, mechanical actuation, etc.) provided the appropriate conditions or environment can be generated at the CT facility. Also in failure analysis studies, it is recommended that whenever possible a known component be scanned with the unknown to assist in the interpretation of features and details. For electromechanical and mechanical systems, there appears to be a need for at least 0.25 mm resolution with energies in excess of 400 kV.

CT for composite material failure analysis evaluations has been shown to be a useful tool. In some cases macrographic information from CT on larger composites may be useful. More generally the material failure analysis requires very high resolution (better than 0.05 mm) imaging, which with CT, limits the size of the component that may be examined. For these micrographic evaluations though CT can be very beneficial and less costly than layer by layer dissection and photography.

Scanning speed is a critical parameter for any CT system data acquisition. Rapid scanning is needed for the 3-D studies of articles such as relays or composite damage. The use of multiple slice CT for three-dimensional modeling was useful in the case of composite damage analysis. It can also be useful in other failure analysis evaluations as well. The development of "cone beam" or volume viewing CT systems (see Appendix A, Section A3.2) that have adequate inherent resolution and contrast sensitivity will make an important advance in providing economic implementation of CT imaging. The failure analysis studies indicate that a general purpose CT system would need the speed of medical systems, the high resolution available in small volume industrial systems, and capability to go to high X-ray energies. These are conflicting criteria for the construction of any one CT system. Thus the availability of a variety of systems is desirable. Additionally there is a need for analysis tools that allow expeditious data reduction.

A CT system need not necessarily be purchased, but should be available. A CT service capability, set up to readily assist failure analysis organizations with scanning and interpretation could be worthwhile if a sufficient number of failure analysis laboratories would participate. In very large organizations, the failure analysis needs to extend across many groups and they all need to be aware of the availability and applicability of CT to assist them in performing their functions better. For electronic failure analysis laboratories of sufficient size, a small microfocus based CT system would be a worthwhile acquisition. The system could provide multipurpose high resolution real-time or digital radiographic examinations as well. Such a system would be in the range of expense of scanning electron microscopes, which are common tools of these laboratories.

8.0 STANDARDS

8.1 Background

X-ray CT systems are imaging instruments that measure X-ray linear attenuation coefficients in small volume elements of an object. It is important with any instrument to have quantitative measures of performance. The use of test standards, or phantoms, to evaluate the performance of a computed tomography (CT) system is critical to monitoring the system performance and ensuring the sensitivity to features of interest. Test phantoms for monitoring performance have been used by the CTAD program to establish quantitative measures for the inherent image quality of the CT systems used to perform evaluations. Figure 8.1-1 lists parameters of interest that may be measured from data taken by a phantom that contains features which represent the parameter. A single phantom unit may contain a variety of subsections that will measure various parameters. The parameters themselves are not independent, but often are different manifestations of the fundamental performance characteristics of the system. Figure 8.1-2 lists some key categories for a phantom and potential methods of obtaining the measurements. The use of the modulation transfer function (MTF) and contrast discrimination curves (CDC) calculated from scans of image quality phantoms can be used to successfully characterize system performance. When CT evaluations are to be performed on a specific component type, a phantom that measures the specific characteristics desired in the inspection should be used.

Parameter	Notes
Artifact level	Mechanical misalignment Data acquisition and reconstruction effects
Slice Thickness/Geometry	Vertical coverage Alignment and uniformity of CT plane in object
Spatial Uniformity	Variation of CT measurement across scan plane
Noise	Random variation in attenuation measurements (measured by statistical variation or noise power spectrum)
Low Contrast Sensitivity	Ability to detect small contrast changes (This is mainly limited by noise)
Spatial Resolution	Ability to distinguish two objects as separate (Measurement should be under noise free conditions)
Modulation Transfer Function	Quantitative measurement of high contrast spatial resolution
Effective Energy and Linearity of CT Numbers	Monochromatic photon energy that would give the equivalent result as the polychromatic spectrum used
Accuracy and Precision	Reliability and stability of the CT measurements
Dose	Patient exposure (for medical CT)

Figure 8.1-1 Parameters of interest in CT image quality measurements.

Type	Example Construction/Technique
Resolution	holes squares line pairs pins/wires MTF calculation
Contrast	signal to noise in a uniform material sample small density variation
Material/Density	various solids liquids of different mixture percentages porous material compaction
Slice Thickness	pyramids cones slanted edges spiral slit
Dimensional Accuracy	step block block with precision holes

Figure 8.1-2 Phantom categories and measurement technique.

8.2 Lessons Learned

The CTAD program efforts on standards has resulted in the application of several phantom types to the measurement of CT system operational parameters. Figure 8.2-1 summarizes the Task Assignment 7 conclusions.[18] Phantoms are indicators of the expected performance on object materials and sizes related to those of the phantoms. For the CT examination of components, a phantom containing critical measurement features that match as closely as possible the object is recommended.

The simple line-pair resolution phantom is easy to use. However, the line-pair phantom results should not be considered completely accurate measures of resolution except in so far as they are used self consistently for repeat studies. Variations in the manufacture of a line-pair phantom can be expected to produce a difference in the results. The modulation transfer function (MTF) method of assessing resolution provides insight into the characteristics of the CT system from the shape of the curve. Cut-off frequencies can be taken from the MTF curve to be used as simple performance indicators. The mathematical approach used in the calculation of the MTF will affect the results, particularly as the resolution of the system increases. The effect of asymmetric line spread functions must be considered as well.

Contrast sensitivity is measured with a uniform material phantom. The relatively simple signal-to-noise measurement, based on the division of the mean by the standard deviation in a region of interest in the phantom, is an important measure of performance. Contrast discrimination curves (CDC) can be calculated using measurements of the standard deviation of the mean values as a function of feature size and the MTF, all of which can obtained from data taken on the uniform disk phantom. The CDC provides a useful description of the performance characteristics of a CT system. However, the curves do need to be validated against the detectability of known features in industrial objects. The selection of the false positive and false negative values used in the CDC calculation remains a subjective issue which needs to be better defined with respect to the routine inspection of industrial objects.

CT Standards

- Line gauge, homogeneous disk and material calibration phantoms provide a baseline for monitoring CT system performance
- MTF and CDC calculations provide improved measures of system performance

  Compatibility is compromised on systems with asymmetric point spread functions
- Dimensional measurement phantom results show promise for defining system dimensional accuracy
- CT IQI correlates to radiography penetrameter sensitivity

  (May permit the use of CT by section 5.3 of MIL-STD-453C)

Figure 8.2-1 CT standards conclusions.

A material phantom can be usefully employed as a relative calibration standard. For any specific industrial application area, the plugs should be altered to represent the materials typically encountered in CT examinations. The background material could also be altered. When properly designed, the phantom can be used as a periodic system performance monitor and data can be taken for MTF and CDC calculations as well.

Dimensional measurement accuracy and precision are critical to many CT applications. A special dimensional measurement phantom with precisely located holes can be used to establish the repeatability of a CT system for making measurements over its field of view. The use of holes for finding dimensional position can be extremely accurate because the center of the hole is determined using the numerous data points that make up the edge. The transform between the hole center positions in the test phantom and the hole center positions in the CT image are a measure of the CT system dimensional accuracy. The repeatability of the CT image hole locations for multiple CT scans is a measure of the system precision.

An image quality indicator phantom can be used which simulates, in a CT slice, the size of feature detected in radiographic images of a standard penetrameter required in radiographic examinations. This penetrameter is required by specification (MIL-STD-453C) for radiography to define the sensitivity in the image. By showing the equivalent sensitivity in a CT slice through a part, CT may be used as an alternative inspection technique under the specification. The phantom data is a measure of the sensitivity of the system to a small void.

9.0 ECONOMIC BENEFITS

Computed tomography has been shown to be a superior nondestructive evaluation technology from conventional approaches. The primary advantage of CT is its ability to produce the highly detailed, quantitative images of the inside of a test specimen. The quantitative nature of the data in terms of dimensions and material characteristics is a nondestructive evaluation link back to engineering criteria. The acquisition of quality CT data requires precision motion control hardware, low noise X-ray detection and complex software which combine to create a sophisticated system that is more capital intensive than other traditional NDE systems.

For objects that are currently manufactured under existing specifications, a more expensive evaluation technique would not be considered, even if it provided superior inspections. In most cases, existing specifications will determine the evaluation technology that will be used. Under these conditions, CT will not be employed as a routine quality inspection tool until 1) costs are reduced below existing inspection equipment costs (and specifications are then changed because it is cost effective), or 2) new aircraft components are designed that require CT for some reason due to the design or materials employed that no other technique can monitor. However, CT is employed applied as an enabling technology to the product cycle.

The last point (CT as an enabling technology) is where this program has found CT to be most economically viable at this point in history. Figure 9.0-1 lists the primary ways in which CT serves as an enabling technology for engineering development and manufacturing efforts.

CT Economic Areas

- Product Development/Materials Characterization
  - Castings
  - Composites
  - Advanced Materials
- Failure Analysis and Engineering Problem Solving
- Noninvasive Micrography
- Geometry Acquisition

Figure 9.0-1 CT economic benefits as an enabling technology.

9.1 Product Development/Materials Characterization

The CTAD program has encountered examples of applying CT to product development and material characterization that provides economic benefits. The aircraft casting industry is one area where CT can benefit the development of products as discussed in Section 4. On average, a foundry will expend roughly 5 percent of its effort on new product development, even for different types of foundries such as sandcasting and investment casting. For a foundry that does $100 M/year the company is spending $5M per year for new product development. Saving just a week in development time is worth nearly $100K to the company. A $2M CT system ($1M purchase price plus $1M for operation and maintenance) would pay for itself in this foundry if it could save just over 20 weeks of development time over its useful life. Figure 9.1-1 estimates how long it would take for such a CT system to pay for itself if used for new product development in different sized foundries.

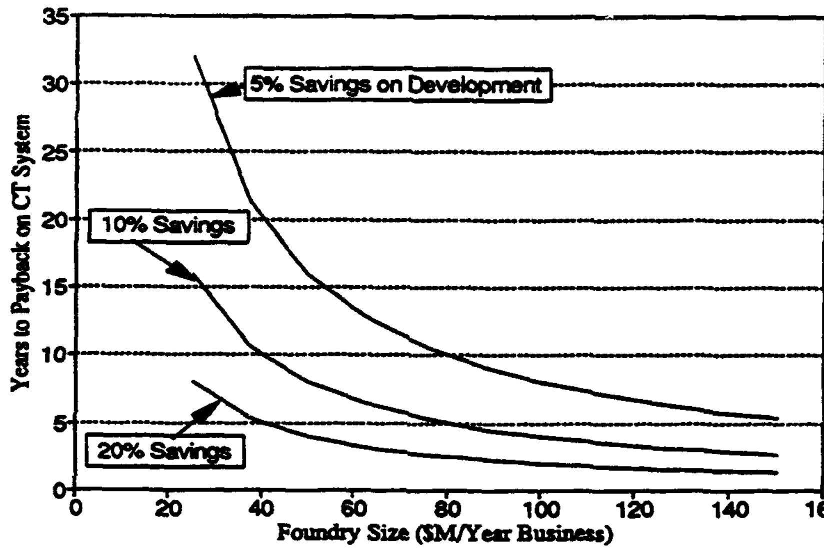

Figure 9.1-1 Estimated time for return on investment on $2M CT system used for new product development in foundries of various size. Values given for 5, 10 and 20 percent savings on development.

In the area of composites similar benefits are anticipated. New product development or materials measurements using CT can be extremely valuable. This has been particularly true in thick composite structures. The economic gains are highly variable depending on the parts. Savings of 50% of the development costs are possible with early application of CT.

Advanced materials developers are using CT to aid the understanding of the materials and processes. Direct economic savings data are not calculated because CT is viewed as essential, in many cases, to the development of the materials themselves. CT costs are imbedded in the product development effort.

9.2 Failure Analysis and Engineering Problem Solving

The economic benefit of using CT in failure analysis and engineering problem solving is difficult to quantify, because if CT is not utilized, the result may be an incorrect evaluation, whose consequences may never be known. However, in an evaluation of a failure analysis laboratories that deal with aerospace equipment, it was estimated that CT would be applicable to approximately 10 to 40 percent of the items examined and would provide a benefit to the engineering evaluation performed. Figure 9.2-1 shows the applicability of CT versus relative size of laboratory (in terms of operating budget/year) for which the management of a laboratory would consider acquiring a CT system. As the applicability increases to the types of products examined, management is more likely to utilize capital equipment dollars for a CT system. In many failure analysis laboratories, small CT systems of relatively low cost could be considered, particularly in conjunction with radioscopy (real-time radiography) equipment. Many cases exist where the use of CT has saved orders of magnitude over the cost of the CT data acquisition in terms of the parts saved or the decisions made.

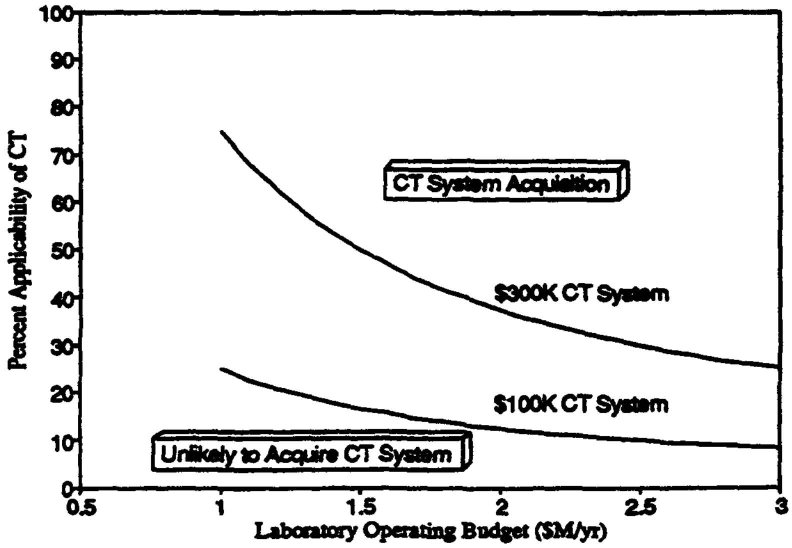

Figure 9.2-1 Laboratory size for CT system acquisition for various percentages of CT applicability to product evaluation.

9.3 Noninvasive Micrography

CT provides a benefit to micrographic evaluations in several ways. Figure 9.3-1 depicts these benefits and Figure 9.3-2 compares optical micrography and CT. Because CT is nondestructive, there is the opportunity to gain not only from easier slicing, but slices can be taken without destroying the component. The additional information available from these evaluations reduces the risk any program faces. Rapid information gain can be used to accelerate schedules because decisions are made earlier, and with greater confidence. The saving of a few weeks time in the efforts of a sizable research and development staff translates into significant dollar savings. These benefits are difficult to quantify economically but are real.

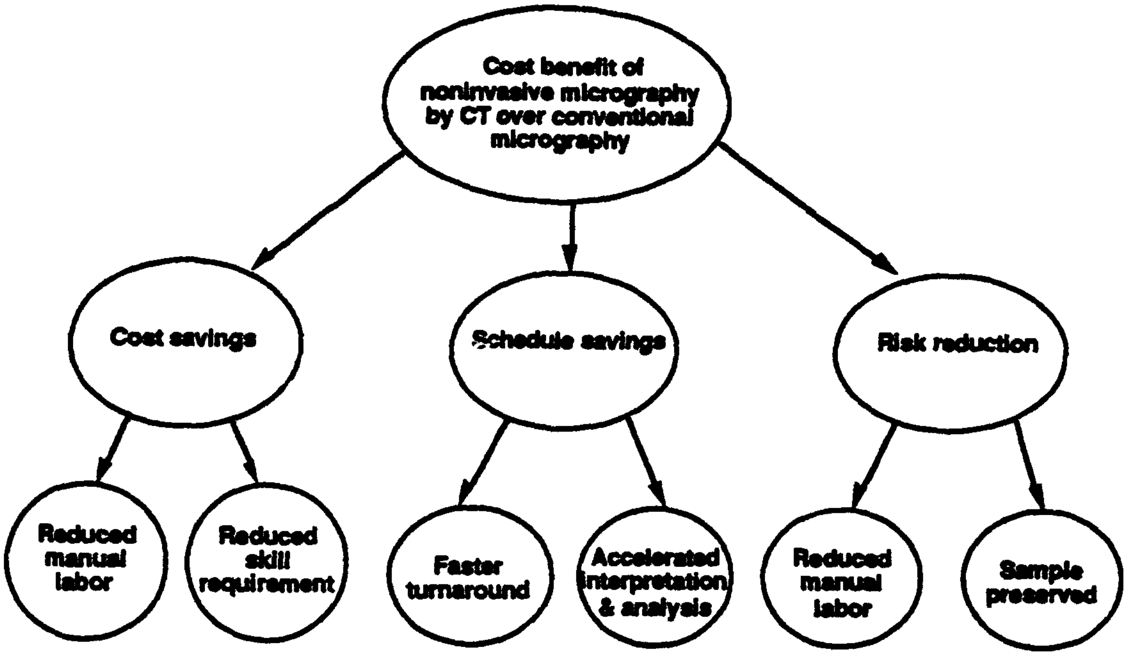

Figure 9.3-1 Cost benefits of CT for noninvasive micrography.

	Optical Micrography	CT
Cutting	Destroys Sample Many influence results	Nondestructive
Multiple Cuts	Difficult	Easy
3D Models	No	Yes
Cross Sectional Size	Unlimited	Less than 25 mm
Resolution	Submicron	25- 50 micron
Cost Capital First Slice	 \$10K - \$50K 2 hrs	 \$200K - \$500K < 1 hr

Figure 9.3-2 Comparison of optical micrography and CT for noninvasive micrography.

CT scanning can be much faster than conventional micrography and therefore offers some economic advantage. There may also be a cost savings in the skill level of the personnel used for CT relative to conventional micrography for many classes of components such as those made from advanced composite materials. For micrography of traditional engineering materials, this would not be true; however, for advanced composite materials CT can potentially eliminate the costs of training and maintaining specialized, skilled personnel for performing micrography. These individuals may be productive at only a 10 to 20 percent level due to the sporadic nature of qualification and failure investigations required for testing. In addition the skill level required to operate a high resolution CT system is approximately 20 to 40 percent lower than for conventional micrography of advanced composites. Absolute cost benefit comparisons may be misleading because CT images and photomicrographs are not identical. CT images must contain the information of interest desired in the micrographic study of the component. Conversely, CT images may provide unique information not available by conventional micrography.

Figure 9.3-3 shows an economic comparison of having a high resolution CT capability and photomicrographic capability assuming operator cost of $50/hour and facility costs of $60K/year for CT and $20K/year for photomicrography. The cross over between CT and micrography occurs at about 650 slices. Of course, it is not realistic to suggest that CT replace micrography entirely. But the economics do suggest that CT is worthwhile and not significantly more expensive than conventional approaches for obtaining information on the internal, micro-structure condition of a component or material.

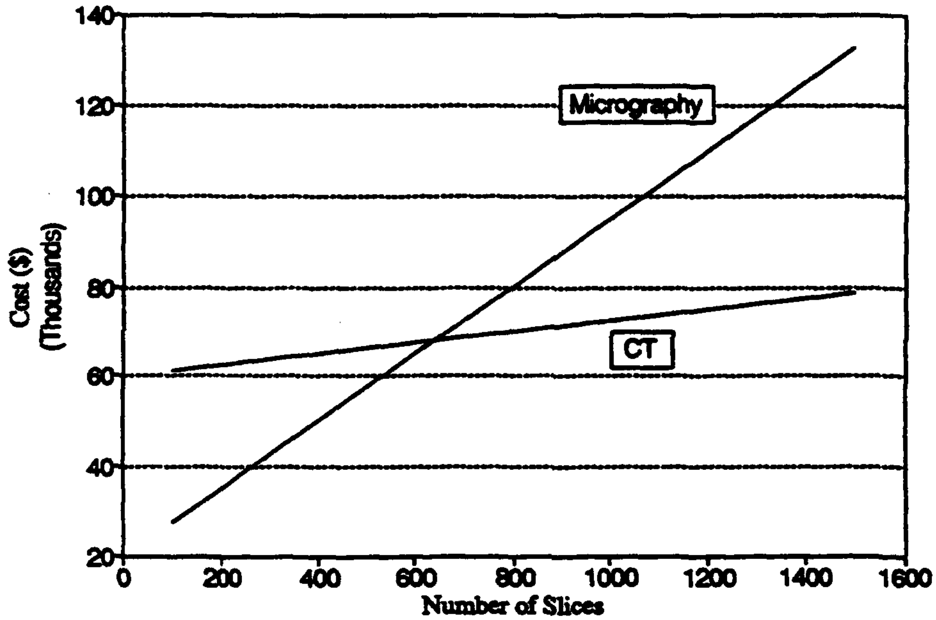

Figure 9.3-3 Comparison of the cost of slicing samples using CT or micrography as a function of the number of samples.

9.4 Geometry Acquisition

CT serves as a very useful tool for acquiring digital data into CAD/E workstations. This data transfer links the nondestructive evaluation data back to the engineering/design activities. The areas in which CT can be of technical and economic value are dimensional measurements (particularly for internal cavities), and digital data acquisition for ergonomic, aerodynamic or aesthetic articles and components that have no digital design drawings. Defining complex shaped components digitally for input into CAD models for engineering design and assessment can be done using CT at a faster rate and at a lower cost than conventional methods, provided the material and size of the part are suited to the capability of available CT systems.

Cost savings using CT have been found to be significant over other approaches for geometry acquisition for complex objects that are suitable for CT examination. CT can generally be done at a lower cost, in less time, and include interior features, relative to optical or physical dimensioning. Compared to physical dimensioning of a part by a designer and hand input of the data into a workstation, CT is more accurate and reduces risk of erroneous inputs. As the geometric complexity increases, the value of CT for geometric acquisition increases substantially. Typically, CT provides a digital overdefinition of the component which then needs to be reduced in the workstation. However, it is much easier to delete data in a workstation than input additional data, which is why the use of CT data generally provides a cost benefit.

Generally it appears that for geometry acquisition, the CT cost is comparable to other approaches for acquiring dimensions (such as physical measurements or coordinate measurement systems) of parts of relatively modest complexity, such as a B-17 tail wheel [14]. The CT data can provide a more accurate base to begin the model than a designer would traditionally have at his/her disposal and provide greater confidence. As the object becomes more complex, the advantages of having CT data increases with a modest increase in cost, while the cost of traditional approaches on more complex structures would grow substantially. Savings of up to 50% are possible on parts that require person-month levels of design effort. In addition to the direct labor cost savings that CT can provide, schedule savings can also be significant. CT geometry acquisition has cut schedules in half with 50% labor savings.

10.0 CONCLUSIONS

X-ray CT has a number of technical benefits as a nondestructive evaluation tool. Economically, at this time, CT is finding increasing application as an engineering tool to provide quantitative information on materials and dimensions for increasing decision confidence and reducing risk. Particular examples include failure analysis studies, geometry acquisition (reverse engineering), prototype or first article evaluations, complex object dimensional measurements/defect location and material review board activity. The growth in utilization of CT depends on the education of engineers to its potential and the benefits that can be derived using the tool. Figure 10.1 lists these primary conclusions.

Conclusions
X-Ray CT provides economic benefit as an engineering tool. • Enables accelerated product development by improving engineering feedback • Reduces program risk and increases confidence in flight hardware Benefits are realized by educating engineers to capability • Case studies are an effective medium

Figure 10-1 Primary conclusions from the CTAD program.

CT provides cost-effective benefits to aircraft/aerospace structures and ancillary equipment as a product "enabling technology" for engineering development and manufacturing. For development, CT is an enabling technology which supports concurrent engineering processes to speed products to market. CT is an important measurement tool that can provide a cost benefit to these processes. CT permits geometry acquisition, providing a direct cost saving over traditional approaches to translating existing components into digital models in computer aided design/engineering (CAD/E) workstations. CT evaluation of materials also is useful in performance prediction. This is where engineering and nondestructive evaluation need to meet in order to create the most cost-effective products. CT measurements can be performed on test articles to validate prototypes and models prior to testing, during certain types of tests, and post testing, including noninvasive micrographic evaluations. CT can be an important tool in the manufacturing and process development stages by providing feature and anomaly location for configuration control, and the direct measure of dimensions. The value of CT evaluation is high for assuring a development process has been brought into control. For routine production quality control the application of CT depends on the relation between the object value, CT scanning cost, and the cost of alternatives. The more complex and costly an assembly, the more likely that CT can be a cost effective tool. Ultimately CT will allow the acceptance of product based on quantitative measurements and engineering criteria. The use of engineering criteria to accept products is presently often performed in material review board (MRB) decisions. CT is already being used to provide data to these MRB decisions today, and in the future may be used routinely for product acceptance.

The insertion of CT into mainstream NDE of aircraft components will require changes to existing product specifications. The most likely developments that will increase the application of CT will be new products whose advanced designs require CT for adequate evaluation. New, complex turbine blades and certain helicopter composite structure designs are examples where CT could become the required NDE method. It may also very likely become the method of choice on advanced structural castings for aircraft, thick composite structures, and matrix materials.

The relatively high cost of CT compared to other NDE methods is a function of the lower throughput that is obtained with presently available technology. The cost of 100 percent coverage of components using CT, as routine nondestructive testing (NDT) equipment for production inspection, continues to be prohibitive except for the highest valued systems. Technology (such a source configurations, computer processing schemes, data acquisition approaches, etc.) is being developed for lower cost and higher throughput that will certainly reduce individual CT slice cost to lower than film radiographic costs. Combining digital or real-time radiography, for 100 percent coverage, with selective CT slicing for critical region inspection or dimensional measurements, CT systems can become competitive with traditional radiography for critical components. Rapid volume inspection approaches promise throughput that will allow CT to compete economically with currently utilized NDT methods in the future.

The CTAD program has provided government and industry with a number of examples of how and where CT can be applied effectively. It has also demonstrated the use of CT data for a variety of quantitative measurements. The task assignment reports [1-19] provide interested individuals with useful information to guide them in the application of CT to solve their problems and accelerate development of new and superior products. Additionally, an Interactive Multimedia Presentation for Applied Computed Tomography (IMPACT) has been produced on compact disk (CD) for use on Macintosh workstations. This CD contains details on the CTAD program results with examples [20]. A significant finding of this study has been the need to educate engineers and other responsible individuals to the potential benefits of CT for product evaluation. Using examples from the task assignments, engineers are able to extrapolate the technical and economic factors surrounding the application of CT to their particular problem. As CT technology advances, the technical benefits will be achievable at reduced costs.

11.0 RECOMMENDATIONS

Based on the results of the CTAD program several general recommendations can be made. If implemented these recommendations will provide immediate benefit to the Air Force as well as direction for future activities. Figure 11-1 lists the recommendations.

Recommendations
• Include CT technology capability in the scoring criteria for developmental and manufacturing procurements. • Require CT in appropriate procurement specifications. • Focus R&D funding in key technology requirement areas such as: High intensity, small effective focal spot X-ray sources Imaging technology with very high voxel throughput Algorithm improvement for greater detail sensitivity Techniques for parts not suited to traditional CT scan geometry

Figure 11-1 Recommendation from the CTAD program.

This Air Force program has demonstrated that CT data provides engineering and manufacturing with information that reduces the overall risk in developing new products and processes. It is therefore recommended that the Air Force include CT capability in the scoring criteria on developmental and manufacturing programs. The availability of CT to developmental programs will benefit the Air Force immediately by reducing program risk. CT evaluations are often particularly beneficial when problems arise which require quick diagnosis to determine the source of difficulty. Such benefits have been realized on B2 and ATF programs during the period of performance of the CTAD program.

Additionally CT should be required in appropriate procurement specifications. The Air Force will need to work with industry to develop specifications for CT operations. There are items where CT can provide a superior inspection, and the reduction of risk could be worth the benefit. Thermal batteries, advanced composite structures (e.g. large honeycomb, thick layered composite structures) and retrofit castings are examples where CT can provide the Air Force with greater confidence in the final product than present NDI requirements.

CT technology needs to continue its advancement for greater economic application. The Air Force should therefore continue to fund key technology areas related to CT. In particular, higher CT throughput is needed. X-ray source technology is a fundamental limitation because available X-ray flux determines the data acquisition time. Greater use of available flux with cone beam or other volume imaging schemes are also possibilities. Sensitivity of CT needs improvement, which will benefit in many cases by better sources, but also can be improved with reconstruction and measurement algorithm development. Finally, for a number of aircraft objects, the traditional CT data acquisition and reconstruction is not appropriate, requiring clever new schemes for part handling, data acquisition and image reconstruction, such as limited angle CT reconstruction, annular reconstructions, scanned beam X-ray sources and others.

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APPENDIX A - X-RAY IMAGING TECHNIQUES

The three techniques of X-ray imaging discussed in this report for use on castings are film radiography, digital radiography, and computed tomography.

A1.0 Film Radiography

Conventional film radiography, as illustrated in Figure A1-1, uses a two-dimensional radiographic film to record the attenuation of the X-ray radiation passing through a three-dimensional object. This results in a shadowgraph containing the superposition of all of the object features in the image and often requires a skilled radiographer to interpret. The sensitivity in the image is determined by the attenuation coefficient for the material at the effective energy of the radiation beam, response of the X-ray film, film resolution, X-ray source spot size, and source-to-object-to-detector geometry. For objects which vary significantly in thickness, the appropriate X-ray exposure will vary and can only be compensated for by multiple exposures at different energies or times, or as is commonly used, multiple film loads of variable sensitivity radiographic films.

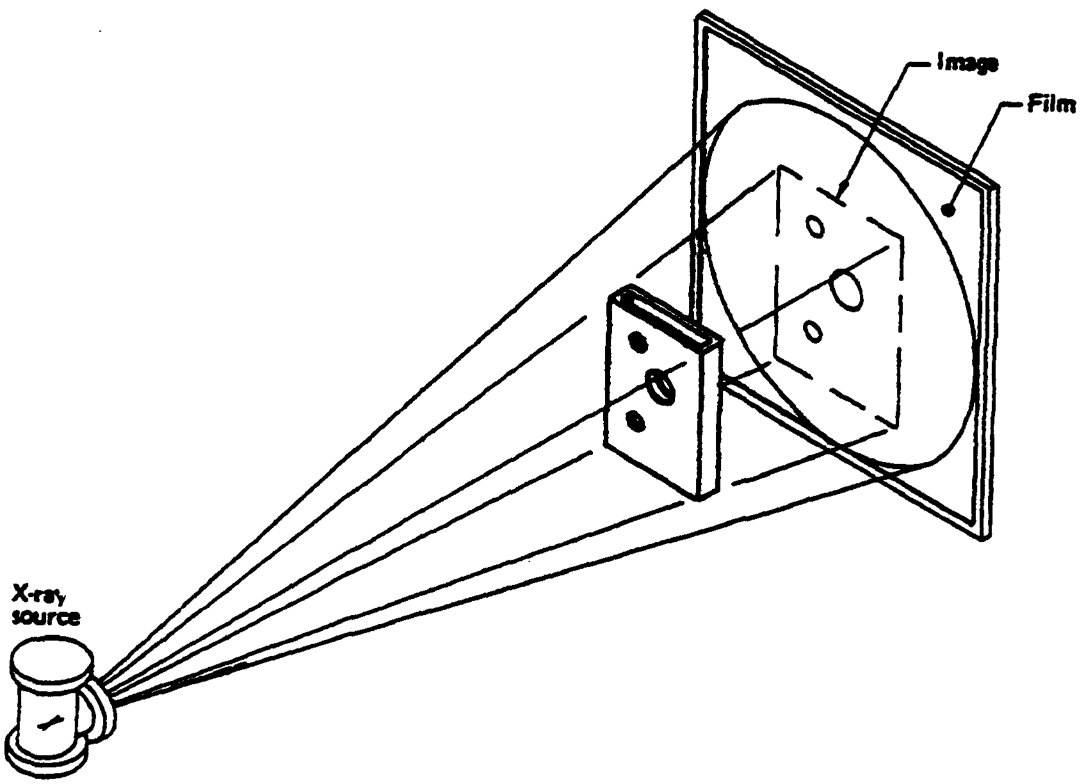

Figure A1-1 Film radiography.

A2.0 Digital Radiography

Digital radiography (DR) is similar to conventional film radiography. The DR is performed on a system where the film is replaced by a linear array of detectors and the X-ray beam is collimated into a fan beam as shown in Figure A2-1. The object is moved perpendicular to the detector array, and the attenuated radiation is digitally sampled by the detectors. The data are "stacked" up in a computer memory and displayed as an image. The sensitivity is determined by the geometric factors, and the resolution, signal to noise and dynamic range of the detector array. Usually DR images have a sufficiently large dynamic range that allows a wide range of the thickness in a single object to be imaged at suitable signal to noise with one scan.

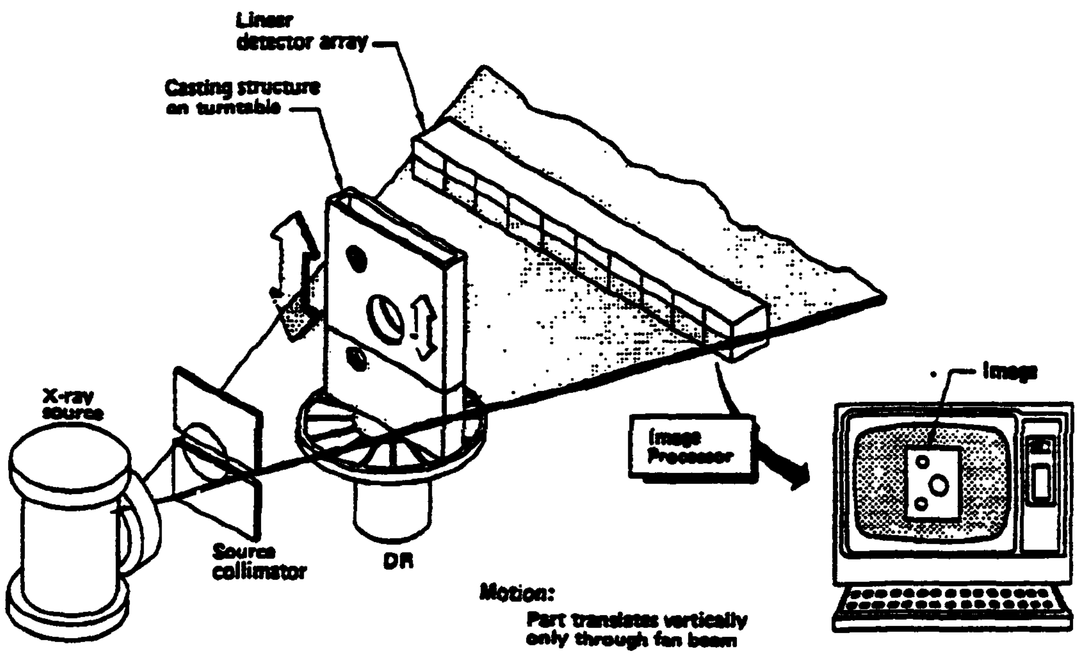

Figure A2-1 Digital radiography.

A3.0 Computed Tomography

Computed tomography (CT) uses X-ray transmission information from numerous angles about an object to computer reconstruct cross-sectional images (i.e., slices) of the interior structure. To generate a CT image, X-ray transmission is measured by an array of detectors. Data are obtained by translating and rotating the object so that many viewing angles about the object are used. A computer mathematically reconstructs the cross-sectional image from the multiple view data collected. A primary benefit of CT is that features are not superimposed in the image, making CT images easier to interpret than radiographic projection images. The image data points are small volumetric measurements directly related to the X-ray attenuation coefficient of the material present in the volume elements defined by the slice thickness and the horizontal resolution capability of the CT system. The values and locations provide quantitative data for dimensional and material density/constituent measurements.

A3.1 Conventional CT

Conventional CT is shown in Figure A3-1. The X-ray beam is collimated to a narrow slit and aligned with a detector array to define a CT slice plane in the component. For 100-percent coverage, multiple, contiguous slices must be taken over the entire component.

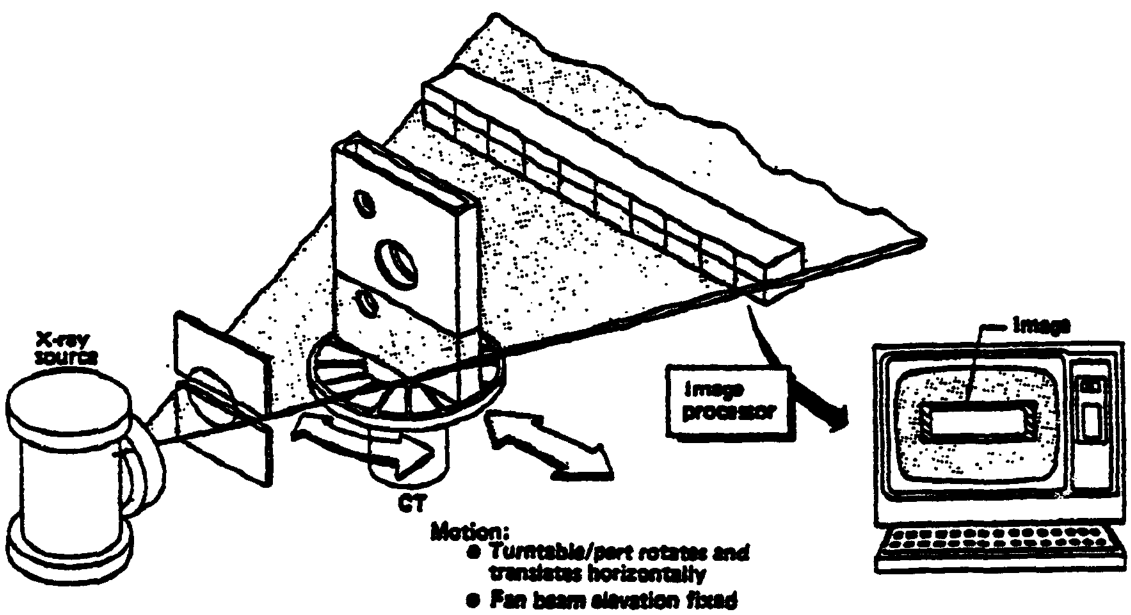

Figure A3-1 Computed tomography.

A3.2 Cone Beam CT

Cone beam CT is fundamentally the same as conventional CT; however, instead of collimating to a thin slice of radiation and using a linear detector array, an entire cone of radiation is used with an area array detector, as shown in Figure A3-2. The data acquisition in each angular view includes information for multiple CT slices along the object axis. The object will be rotated for data acquisition of multiple views. The data handling and reconstruction for cone beam CT is substantially more complicated than conventional CT, and a suitable display mechanism for viewing multiple plane images from the volumetric data set is needed. The advantage of the technique is that an entire volume can be scanned much more rapidly than is possible using conventional CT and taking scans at multiple axial positions. This offers a substantial cost savings for CT examinations of entire volumes.

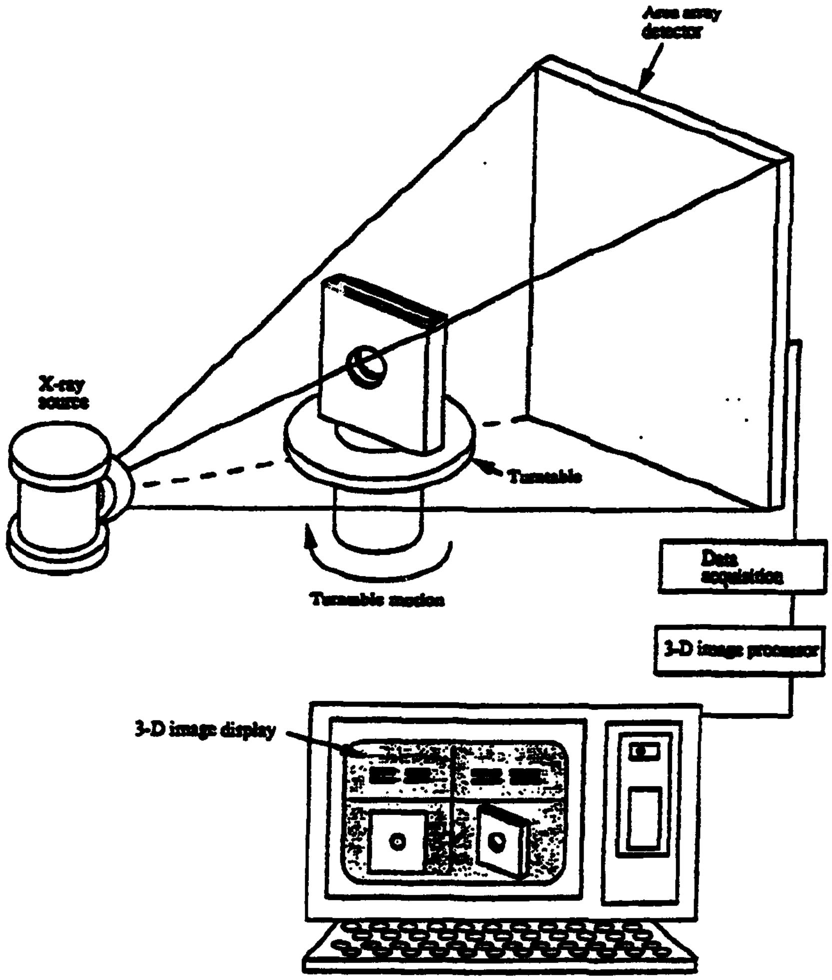

Figure A3-2 Cone beam CT.

A4.0 Laminography

Laminography (body-section tomography, focal plane tomography, etc.) is a term given to techniques which generate a focussed plane of information in an object while defocussing surrounding planes. This is particularly effective for objects which contain structures that overlap from different planes. By defocussing planes above and below a plane of interest, the structures that are not of interest will be blurred, thus reducing their overall contrast effect in the image. The structure at the plane of interest will remain in focus, and the final image will be observed with improved sensitivity to detail. Objects that are homogeneous (i.e., do not contain structure) generally will not benefit from laminographic examination.

Laminographic imaging using X-rays dates back to the early days of radiography when physicians recorded body-section tomograms using a synchronously moving source and detection medium (i.e. film). By forming an X-ray focal plane in a patient, features within planes of interest could be brought into focus while regions not of interest could be "defocussed." Various motions of synchronism were explored including linear and more complicated polytomographic (circular, figure eight, clover leaf, etc.) techniques to achieve maximum resolution capabilities.

A4.1 Computed Laminography

Laminography imaging may be performed from digitized radiographic images by computer reconstruction. Computed laminography is typically performed on industrial CT systems. A series of digital radiographs (DR's) are taken at various angles about the normal to an object. The data acquisition time may vary depending on the resolution required and can range from a few DR's to 12 or more. A laminographic plane is selected, backprojected onto each DR and summed to form the final image. Computed laminography is time consuming if only a single image plane is desired, but can be highly advantageous (i.e., time and cost saving) where several inspections of a single object are required. Since DR's are taken at various angles from around the object, each DR contains superimposed information of features within the object. After backprojection, the laminographic image "focuses" on the desired image plane and "defocusses" other object features. Similarly the technique can be used on nonplanar objects to "focus" on arbitrary curved or object dependent surfaces. Figure A4-1 shows computed laminography.

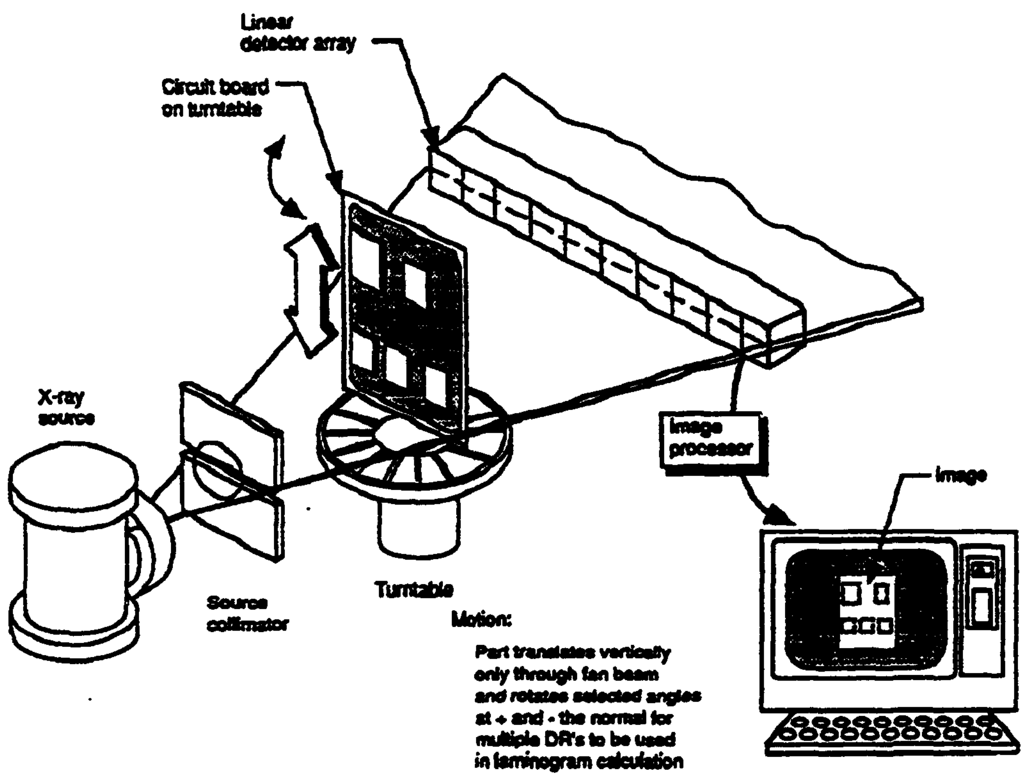

Figure A4-1 Computed laminography.

A4.2 Scanned Beam Laminography

A modernized version of laminographic imaging replaces a mechanically moving source with an electronically scanned source, and film with a scintillating phosphor screen/CCD camera to transfer the images to a video terminal in real time. The scanned source shown in Figure A4-2 creates a focus plane. The object is raised or lowered through the focal plane to image the plane of interest. Features outside of the focal plane are "defocussed" and therefore averaged across the field, thus lowering the contrast contribution in the resulting image.

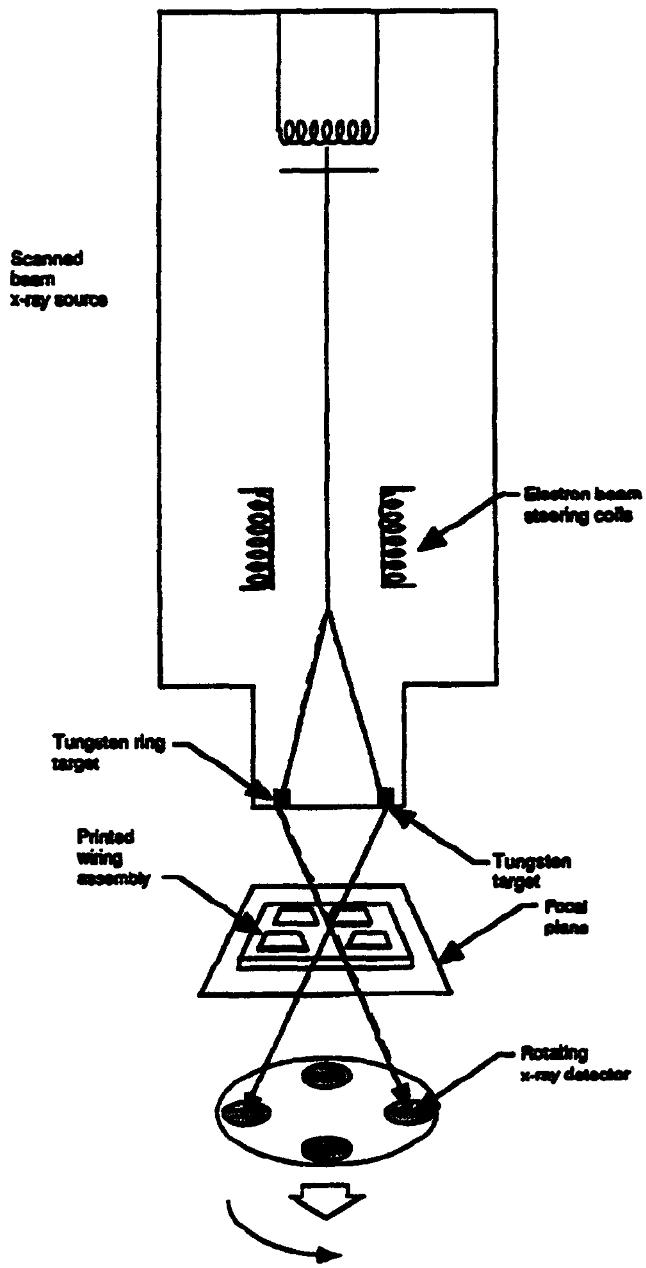

Figure A4-2 Scanned beam laminography.

APPENDIX B - PART IDENTIFICATION INDEX

Application Areas	Identification Prefix	Description
Standards	00 01 xx	Resolution Standards
	00 02 xx	Density Standards
	00 03 xx	Noise Standards
	00 04 xx	Laminography Standards
Electronics	01 01 xx	Printed Wiring Assemblies
	01 02 xx	Switches, Relays,
	01 03 xx	Transformers
	01 04 xx	Electronic Components
	01 05 xx	Connectors
	01 06 xx	Sensor
	01 07 xx	Miscellaneous
Closed Systems	02 01 xx	Thermal Batteries
	02 20 xx	Complex Machines
Castings	03 01 xx	Aluminum Castings
	03 02 xx	Magnesium Castings
	03 03 xx	Titanium Castings
	03 04 xx	Other Castings
Composites	04 01 xx	General Organic Composites
	04 02 xx	Honeycomb/Organic Composites
	04 03 xx	Pultrusions
	04 04 xx	Injection Moldings
	04 05 xx	Smart Skins (Embedded Sensors)
	04 06 xx	Filament Windings
	04 07 xx	Braids/Weaves
	04 08 xx	Other
Advanced Materials and Processes	05 01 xx	Metal Matrix Composites
	05 02 xx	Ceramic Matrix Composites
	05 03 xx	Carbon Carbon Composites
	05 04 xx	Plastics
	05 05 xx	Coatings and Insulation
	05 06 xx	Alloys/Metals
	05 07 xx	Superplastic Forming (SPF)
	05 08 xx	General/Miscellaneous
Metal Joining	06 01 xx	Welds
	06 02 xx	Adhesive Bonds
	06 03 xx	Mechanical Fastening
	06 04 xx	Brazes and Solders
	06 06 xx	Other Metal Joining
Structural Components	07 01 xx	Landing Gear Components
	07 02 xx	Engine Components
	07 03 xx	Structure
	07 04 xx	Miscellaneous
Whole Engines	08 xx xx	Small Jet Engines