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X-RAY COMPUTED TOMOGRAPHY OF FULL-SCALE CASTINGS

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Computed Tomography (CT) has been investigated for its potential to evaluate full-scale castings. Currently, casting manufacturers suffer from a number of shortfalls in inspection which affect the use of castings in the aircraft/aerospace industry.

An earlier task assignment indicated that CT has superior sensitivity to casting defects in small test coupons than conventional film radiography. But, as casting size and geometric complexity is increased, the CT sensitivity and measurement accuracy are reduced. In this task, CT testing was conducted to quantify the detection sensitivity and measurement accuracies possible on full-scale castings and to establish the CT system performance factors necessary for defect detection. The identification of cost-effective applications for CT in the casting industry was also sought.

This effort has identified four areas in which CT can be cost-effectively utilized in casting manufacturing. These areas are new product development, early screening, manufacturing of complex geometries and critical region inspection. A CT system may be cost effective if the foundry has: 1) a large production rate (> $100M/year), 2) a high percentage of parts requiring internal dimensional measurements, 3) a large percentage of complex aerospace castings, or 4) material review board (MRD) authority for engineering buy-off of rejected castings.

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SUMMARY

Under a preliminary testing task assignment of the Advanced Development of X-ray Computed Tomography Application program, computed tomography (CT) has been studied for its potential for improving the evaluation of full-scale castings. Currently, casting manufacturers suffer from a number of shortfalls in inspection which affect the utilization of castings in the aircraft/aerospace industry. The main drawback of current techniques is that they are subjective, qualitative and potentially ambiguous, and may not correlate to the actual service requirements of the components. Because CT is quantitative, it offers an inspection capability with potential to overcome some of the limitations of current inspection techniques. Additionally, where current techniques do not relate to quantitative damage tolerance criteria, CT has significant potential for use in effect-of-defect evaluations.

The results of an earlier task assignment indicated that CT has superior sensitivity to casting defects in small test coupons than conventional film radiography. But, as casting size and geometric complexity is increased, the CT sensitivity and measurement accuracy is reduced. In this task, CT testing was conducted to quantify the detection sensitivity and measurement accuracies possible for casting evaluation and to establish the CT system performance factors necessary for defect detection. The identification of cost-effective applications for CT in the casting industry was also sought.

This effort has identified at least four areas in which CT can be cost-effectively utilized in casting manufacturing. These areas are new product development, early screening, manufacturing of complex geometries and critical region inspection. Purchasing a CT system may be cost effective if the foundry has one or more of the following characteristics: 1) The foundry has a sufficiently large production rate (>$100 M/year), 2) produces a high percentage of parts which require internal dimensional measurements, 3) fabricates a large percentage of complex aircraft/aerospace castings, or 4) has material review board (MRB) authority for engineering buy-off of castings rejected by another inspection method. Some cost benefits may be realized without changes in acceptance specifications. However, the most significant benefits that CT can offer will require changes in engineering specifications and industry/government standards.

DISCLAIMER

1.0 INTRODUCTION

The goal of the Advanced Development of X-Ray Computed Tomography Applications demonstration (CTAD) program is to evaluate inspection applications for which X-ray computed tomography (CT) can provide a cost-effective means of evaluating aircraft/aerospace components. The program is "task assigned" so that specific CT applications or application areas can be addressed in separate projects. Three categories of task assignments are employed in the program, 1) preliminary tests where a variety of parts and components in an application area are evaluated for their suitability to CT examinations for their inspection, 2) final tests, where one or a few components are selected for detailed testing of CT capability to detect and quantify defects, and 3) demonstrations, where the economic viability of CT to the inspection problem are analyzed and the results presented to government and industry. This interim report is the result of a preliminary task assignment study on full-scale castings. Additional task assignment reports issued by the CTAD program are listed in references 1 through 6.

1.1 Computed Tomography

X-ray computed tomography (CT) is a powerful nondestructive evaluation technique that was conceived in the early 1960's and has been developing rapidly ever since. CT uses penetrating radiation from many angles to reconstruct image cross sections of an object. The clear images of an interior plane of an object are achieved without the confusion of superposition of features often found with conventional film radiography. CT can provide quantitative information about the density and dimensions of the features imaged. Appendix A compares the basic radiographic (RT), digital radiography (DR) and CT techniques utilized in the CTAD program.

Although CT has been predominantly applied to medical diagnosis, industrial applications have been growing over the past decade. Medical systems are designed for high throughput and low dosages specifically for humans and human sized objects. These systems can be applied to industrial objects that have low atomic number and are less than one-half meter in diameter. Industrial CT systems do not have dosage and size constraints. They are built in a wide range of sizes from the inspection of small jet engine turbine blades using mid-energy (hundreds of keV) X-ray sources to the inspection of large ICBM missiles requiring high (MeV level) X-ray energies. Industrial CT systems generally have much less throughput than medical systems. The CTAD program utilizes a wide range of CT systems, both medical and industrial.

1.2 Scope and Objective

This task assignment, designated "Task 6 - Full-Scale Castings," is a preliminary testing task directed at the evaluation of full-scale cast components. In a previous task (Task 3 - Castings) [3], castings defect samples were excised from larger cast parts and utilized to evaluate CT sensitivity to a variety of defect types and sizes relative to conventional film radiography. The defects were also inserted into larger cast structures, demonstrating a loss of sensitivity to feature detection as a function of geometry. The results of Task 3 showed that CT has excellent sensitivity to casting defects in small coupons. Also, the use of volumetric data sets to create three-dimensional models of flaws enables visualization of casting defects for more complete evaluation. Finally, CT dimensional measurements with excellent accuracies and precision better than 50 microns (0.002 inches) were demonstrated on test phantoms. However, as casting size and geometric complexity is increased, the CT sensitivity and measurement accuracy is reduced. Also, various CT system parameters affect defect detectability in an image. These issues have been addressed in this task assignment, along with an assessment of the benefits of CT for various stages of casting manufacture. This report describes this effort, including the components selected for study, the results of testing, and the conclusions which have been drawn.

The overall goal of this task assignment was to determine the technical feasibility and economic viability of using CT for the evaluation of full-scale cast parts. A specific objective was to evaluate the effectiveness of CT relative to the current practice of film radiography of castings for determining the cast component quality. Another objective was to determine CT system requirements for flaw sensitivity in castings. A third objective involved defining the technical and economic benefit of CT for castings during various stages of the manufacturing process. This last objective included discussions with foundries regarding their practice and the potential of CT to increase their productivity.

2.0 TEST PLAN

The Task 6 test plan included the acquisition of test samples, CT scanning, and data evaluation. It included fabricating CT penetrameters for defect sensitivity measurement in order to relate CT results with those obtained using film radiography. Also the use of data analysis for dimensional measurements and engineering analysis were performed. A defect sensitivity study was conducted which correlated signal-to-noise values and modulation with the ability to resolve small voids in various castings.

The scan plan for each component considered the material and size of the particular cast part in the selection of equipment to demonstrate CT performance on full-scale castings. Results were presented to various casting manufacturers to solicit their input on the technical and economic benefits of CT for castings. Finally, two interim technical report were prepared which describes the effort on this task and summarize the results. This report discusses CT imaging of castings and the economics of using CT for casting evaluation. A second report [7] discusses the use of CT data in casting analysis.

2.1 Component Selection

Representative cast components were sought from the Boeing Company and from several aerospace/aircraft casting manufacturers for use in studying CT capability. Figure 2.1-1 lists the parts investigated for this task assignment, along with their assigned part identification number (PID #) and known defects. All defects noted in Figure 2.1-1 exist in the cast part as a result of the casting process, not implanted defects. Results presented in this report are representative images of the CT data taken during the task assignment.

2.2 System Performance Characteristics

Figure 2.2-1 lists the measured performance characteristics of the CT systems used on this task assignment. The data in the table was obtained using the resolution and noise test phantoms described in Appendix B. The systems are designated by an arbitrary lettering assignment. CT images discussed in the report can be correlated to the resolution and contrast sensitivity capability of the CT system utilized by reference to Figure 2.2-1.

All systems displayed their image data on high-resolution video terminals, but hard copy image reproduction techniques varied. Some systems used standard black and white thermal printers, some photographic film and others, black and white or color laser printers. The best image reproductions were obtained by a film recorder or by manually photographing the video terminal; however, these options were not always available. CT data records on magnetic tape were obtained whenever possible and the data redisplayed on a photographic film recorder for reproduction. Image quality in this report is necessarily reduced from original image displays because of the reproduction processes.

PID #	Description	Defect Type
A. Sandcasting, Aluminum Alloy		
030106	Reservoir Manifold	Porosity
030117	Coupon	Porosity
030125	Coupon	Voids, Porosity
030166	APU Turbine Rotor Mount	Voids, Porosity
030175	Wheel Pulley	Porosity, Shrinkage
030181	Cable Drum	Voids, Porosity
030182	Sector	Voids
030183	ALCM Missile Body	Corrosion, Pitting
B. Magnesium Alloy Castings		
030201	Banjo Trim Mechanism	Linear Indications, Porosity
030204	Cover	Core Blowoff
030205	Gearbox Housing	Voids, Porosity
C. Titanium Alloy Castings		
030312	Test Plate	Voids
030313	Side of Body Joint	Inclusions, Weld, Microporosity
030314	Small Rod	Drilled Holes, Microporosity
030315	Wall Section	Shrinkage, Gas Holes
D. Investment Castings		
030501	Tongue	Mild Shrinkage
030502	Pipe Coupler	Dimensional
030503	V Plate	Mild Shrinkage
030504	Adapter	Unknown
030505	Collar	Mild Shrinkage
E. Investment Casting Shells, Ziron Sand and Silica		
030402	Shell Mold	Spalling of Internal Layers
030403	Shell Mold	Spalling of Internal Layers

Figure 2.1-1 Castings description.

Scan conditions				Results						
						Percent modulation				Signal to noise
						lp/mm				
System (6)	Energy kV	Slice thickness (mm)	Scan time	FOV (mm)	Std. used	0.5	1	2	4	
B	225	0.5	7.5 min 19 min	50 60	Steel Steel	86 92	49 69	5 17	1 5	6:1 (1)
I	2000	6 (4) 10 (5)	4.6 min	440	Steel	13 39	0 2	0 0	0 0	107:1(1)
J	410	0.25	53 sec	152	Steel	84	60	15	1	14:1 (1)
K	120	10 10 1.5	4 sec 4 sec 4 sec	100 100 100	Al	81 81 79	5 5 4	0 0 0	0 0 0	149:1(2) 22:1 (3) —
L	400	4	16 min	100	Steel	58	10	0	0	100:1 (1)
Q	420	0.25	1 min	64	Al	80	40	5	0	—
R	225	0.5	5 min	50	Steel	-	60	6	0	5:1 (1)

Notes: (1) Lg Al noise std 5.5"
(2) Sm Al noise std 2.75"
(3) Acrylic noise std 5.5"
(4) 512 reconstruction
(5) 1024 reconstruction
(6) Systems identified by arbitrary labels (ref [1 - 4], [6])

Figure 2.2-1 CT system performance data.

3.0 CASTING FEATURE SENSITIVITY

3.1 Inspection of Castings

Castings are used extensively in the aircraft and aerospace industry, and include aluminum, magnesium, titanium and steel alloys. Compared to forgings and billet machined parts, they are far less expensive by approximately a factor of four. Castings can be produced in complicated shapes that are impossible with machining techniques. Most castings contain imperfections to some degree or another, some of which are serious enough to affect their performance.

Castings for airplane or space vehicle applications must be classified according to MIL-STD-2175, "Castings, Classification and Inspection of." MIL-STD-2175 designates four classes of castings, 1 through 4, which are described in Figure 3.1-1. Inspection of the castings depends on the classification and the lot size of the castings. For aluminum castings, the inspection methods are visual and penetrant for surface defects, and film radiography for subsurface flaws. Defects which can commonly be found inside castings are gas porosity, gas holes, shrinkage (sponge and cavity), and foreign material (high or low density). Castings will therefore be specified with a radiographic grade for internal defects of A, B, C or D in addition to the class. Figure 3.1-1 lists the specification of radiographic grades. Aerospace design manuals state that class 1 castings are generally not used for aircraft applications [8]. Thus only class 2, 3 and 4 should be of concern. However, it is very common for aircraft designers to designate their castings as class 1 grade B or C for inspection purposes. This is a conservative approach which has the effect of requiring 100 percent penetrant and radiographic inspection to satisfy the class 1 inspection criteria of MIL-STD-2175.

3.1.1 Visual and Penetrant Inspection

Visual inspection is generally 100 percent, looking for surface defects and irregularities. Discontinuities such as cracks and evidence of shrinkage are of particular concern. Penetrant inspection is 100 percent on class 1, 2 and 3 and on a sample of class 4 castings. The penetrant inspection is to be in accordance with MIL-I-6866, "Inspection, Penetrant Method of", or MIL-STD-271, "Nondestructive Testing Requirements for Metals". An industry criticism of penetrant examination is that it often results in the rejection of castings for surface porosity indications that are difficult to differentiate from the naturally rough surface condition.

3.1.2 Radiography of Castings

Film radiography of castings is performed in accordance with MIL-STD-453 which states that castings designated class 1 will be 100 percent inspected. The 100 percent radiographic inspection means a large number of radiographs must be taken at a variety of angles in order to "cover" the casting completely. For class 2 and 3, the radiographic inspection is 100 percent on a sampling of the lot. If the reject level of the sample is too high according the MIL-STD-2175 directive, 100 percent radiography is required of all units in the lot.

In film radiography, IQIs (image quality indicators) are used to indicate sensitivity of the radiograph to features. The IQI most commonly used is the plaque penetrameter [9,10]. The penetrameter is a thin sheet of material (the same or very close to the part material) which is 2 percent of the thickness being tested and contains several small holes of diameter 1T, 2T and 4T (which are 1, 2 and 4 times the thickness of the plaque respectively). The minimum plaque thickness is 0.125 mm (0.005 inch) and the minimum 1, 2 and 4T holes sizes are 0.25 mm (0.010 inch), 0.5 mm (0.020 inch) and 1 mm (0.040 inch) respectively. The

MIL-STD-2175 Definitions for Castings	
Category	**Definition**
Class 1	A casting, the single failure of which would endanger the lives of operating personnel, or cause the loss of a missile, aircraft, or other vehicle.
Class 2	A casting, the single failure of which would result in a significant operational penalty. In the case of missiles, aircraft, and other vehicles, this includes loss of major components, unintentional release or inability to release armament stores, or failure of weapon installation components.
Class 3	Castings not included in Class 1 or Class 2 and having a margin of safety of 200 percent or less.
Class 4	Castings not included in Class 1 or Class 2 and having a margin of safety greater than 200 percent.
Radiographic Grade	**Definition**
Grade A	A highly stressed casting or area of a casting for critical application.
Grade B	A premium grade of casting for critical applications or specified area of a casting with low margin of safety.
Grade C	A high quality grade of casting or area of casting with average margin of safety.
Grade D	A casting or area of a casting subject only to low stresses.

Figure 3.1-1 Definitions of classes and radiographic grades of castings.

penetrameter is laid on top of the part that is being radiographed or on an adjacent block of equivalent material of similar thickness. The sensitivity of the radiographic image is indicated by the visibility of the holes in the penetrameter. The smaller the hole that is visible, the better the feature sensitivity of the image. Specifications generally call for the visibility of a 2 percent penetrameter's 2T hole, designated 2-2T sensitivity. A radiographic image of a part cannot be used to accept or reject a part without a proper penetrameter in the image showing the 2-2T sensitivity. Because castings usually involve complex shapes, the part thickness generally varies in each radiographic view, so no single penetrameter can accurately measure the defect sensitivity throughout the casting (See Section 3.3). Thus, several penetrameters are often used in an attempt to define the sensitivity in multiple thickness regions of a casting image.

The completeness of inspection in an area will depend upon the number and type of views taken, the complexity of adjacent areas (which can obstruct the views), and the validity of the penetrameter for a particular thickness to adequately represent the sensitivity to indications in a complex geometry. The thickness of a part influences the detectability of flaws, because a radiograph of a thicker part with the same flaw condition as a thinner part will produce a lower contrast image (Section 3.3). Also, film radiography may provide little or no useful information in critical inspection areas because of the difficulty of film placement or X-ray beam orientation on complex castings. All these factors tend to make "100 percent inspection" a misnomer because the quality of the inspection will be inconsistent.

The evaluation of casting radiographs is made by a comparison to ASTM reference radiographs and a judgement as to the relative level of defect that exists in the casting. The ASTM radiographic reference contains sets of frames (numbers F1 to F8) which are in ascending order of defect severity for the various types of defects found in castings. Different ASTM reference radiograph sets are available as a function of the casting material. Figure 3.1-2 lists the ASTM reference sets. MIL-STD-2175 provides tables which correlate the requirement of a casting radiographic grade to the appropriate reference radiograph frame number. The casting is accepted or rejected based upon the MIL-STD-2175 specification of allowable frame number level for the casting radiographic grade. However, the ASTM standard is not based upon any engineering criteria. It is only a radiographic reference to practical quality levels that can be achieved in the radiography of castings. Also, the reference radiographs are made from samples of specific thickness but which must be applied to the range of thickness that is found in complex castings. The evaluation of castings based upon this standard has never been correlated to part performance. Also, the method itself tends to be extremely subjective. It is not uncommon for two radiographers to select different frame numbers for the same region of a casting. For example, in one region of the wheel pulley casting (PID #030175), one radiographer selected F3, another saw F1, and a third did not identify any flaws!

The radiographic inspection is necessary to verify the internal quality of the casting, but the subjectivity of interpretation and lack of correlation to performance results in an overly conservative inspection criteria. The accepted product is cosmetically excellent, but at a very high cost to compensate for the high scrap rate of product which has adequate performance but contains anomalies. The somewhat paradoxical issues surrounding the current inspection of castings are summarized in Figure 3.1-3.

Reference Radiographic Sets	
ASTM Designation	Title
ASTM E 155	Reference Radiographs for Inspection of Aluminum and Magnesium Castings
ASTM E 186	Reference Radiographs for Heavy-Walled (2 to 4.5 in. (51 to 114 mm)) Steel Castings
ASTM E 192	Reference Radiographs of Investment Steel Castings for Aerospace Applications
ASTM E 271	Reference Radiographs for High-Strength Copper-Base and Nickel-Copper Alloy Castings
ASTM E 280	Reference Radiographs for Heavy-Walled (4.5 to 12 in. (114 to 305 mm)) Steel Castings
ASTM E 310	Reference Radiographs for Tin Bronze Castings
ASTM E 446	Reference Radiographs for Steel Castings Up To 2 in. (51 mm) in Thickness

Figure 3.1-2 ASTM Reference Radiograph Set for casting evaluation.

PARADOXES IN CASTING INSPECTION
• Class 1 castings are not to be used in aircraft design. • Engineers often call for class 1 inspection of aircraft castings
• Class 1 calls for 100 percent radiography. • 100 percent radiographic coverage to 2-2T is not strictly possible on complex castings.
• Criteria for acceptance is based on a subjective comparison to reference radiographs. • Reference radiographs are not correlated to performance.

Figure 3.1-3 Paradoxical issues surrounding the inspection of castings.

3.1.3 Computed Tomography (CT)

Computed tomography generally provides better flaw depth and flaw information in castings than RT [3]. This is essentially because the superposition of information in RT, which reduces sensitivity, is eliminated in CT scanning (see Appendix A). CT can precisely define the size and location of shrinkage, holes, porosity, and cracks within the inspected component. Depth information is useful in categorizing and evaluating defects. Because complete spatial information on part configuration and defect location is available from CT, an engineering assessment of fitness-for-service of the as-built component is possible, which could potentially reduce casting rejections significantly.

Digital radiography is a companion feature on CT systems and provides very similar information to film radiography. DR scans are commonly used to identify the CT slice plane location(s) prior to performing CT scans at the selected elevation on the component. An advantage of DR over film radiography is the dynamic range available in the digital image data. The grayscale window level and range can be adjusted to observe both radiographically light and dark regions from a single image. The fact that the data from CT and DR is in digital form is another advantage over film, because the image can be readily processed for display and enhancement. However, because of the mechanical equipment used in DR imaging, DR does not have the flexibility of film to be cut and inserted in complex castings for certain difficult to inspect regions.

Presently, neither CT nor DR are identified in MIL-STD-2175. Nonfilm techniques, which would include DR and CT, are acceptable only for screening of parts and if rejections occur, film radiography must be used to confirm the rejection and document it. The nonfilm technique must be "sufficiently sensitive to discriminate between parts in a borderline category which are considered to be rejectable using film methods." This does not allow the effective use of DR and CT because film radiography would ultimately be required to be used whenever rejectable conditions were detected in aerospace castings.

The design manual and MIL-STD-2175 both recognize that castings will have defects and so castings have large design factors of between 1.5 to 3.0 that are in addition to the standard safety factor of 1.5 used in structural applications [8]. Thus, designers are encouraged to identify critical stressed areas in the components and to specify inspection requirement that establish the quality of the casting needed to satisfy the function of the component. DR and CT can be used effectively for this design approach by using a rapid DR to establish an overall 100 percent check of a component and CT at selected critical regions for evaluation of critical size defects.

3.1.4 Correlation to Performance

Casting performance has historically been difficult to predict because of the metallurgical structure of castings and the existence of flaws. Safety factors used in the design of castings prevent their failure, but these factors increase material quantity, weight and costs. A primary reason for the inability to predict casting performance is that the nondestructive evaluation methods that have been used with castings have never been directly correlated with casting properties. Visual, penetrant, and film radiography have been used for years, but they are not capable of providing an adequate measure of the serviceability of the castings.

Examples of this are common knowledge in the industry, but one particular case is the "banjo" trim mechanism casting of Figure 3.1-4. This unit has been used in over 2000 aircraft without a failure since 1962. However, the rejection rate for the units has reached as high as 100 percent for various periods of time. A load test was devised to test rejected units under the service

Figure 3.1-4 Photograph of the banjo trim mechanism.

conditions that the part was designed to withstand. Testing showed that the units withstood over six times the ultimate design load and that the failure was always at a pin location and never was associated with any of the flaws used for rejection. This example points out the enormous waste caused by over specification of inspection criteria which results in the rejection of castings for anomalies in non-critical areas.

As was discussed in Section 3.1.2, ASTM radiographic standards for casting manufacture are not based upon engineering data. For example, Figure 3.1-5 shows that ultimate tensile strength in welded aluminum alloy tensile specimens is not correlated to the rejection criteria. Welding in these specimens was performed to simulate a casting process and allowed the inclusion of porosity defects [11]. The graph shows that specimens containing rejectable levels of defects always exceed the minimum utlimate strength requirement. The effect of porosity on the mechanical properties of castings has shown mixed results in various studies. McLellan and Tuttle [12] showed that porosity above 19 µm reduced ductility in Al-Si-Mg castings but that the combination of various cell sizes, chemistries and porosity could balance each other to arrive at desired mechanical properties. Eady and Smith [13] concluded that the effect of the porosity (in the range of 60 to 500 µm with percentages from 1 to 7 percent) was not straightforward and could be masked by other variables such as alloy content (Mg, in their study) and dendritic arm spacing. Porosity was found to not always be detrimental but depended on other parameters. As Figure 3.1-6 shows, degradation in tensile strength, for the system studied in reference [11], does not occur below 3 percent void area, which is in the regime of CT measurement sensitivity. Thus, the fine porosity defects should not be a necessary cause for part rejection. Rather, the application of the casting and the size of the defective area should be considered. The ASTM frame number becomes a cosmetic measure which may be useful for evaluating the "goodness" on a subjective qualitative scale of locations which are to be machined or drilled. Unfortunately, with film radiography, the specific three dimensional location of the features cannot be pinpointed to ensure that subsequent machining operations may not intersect the defects.

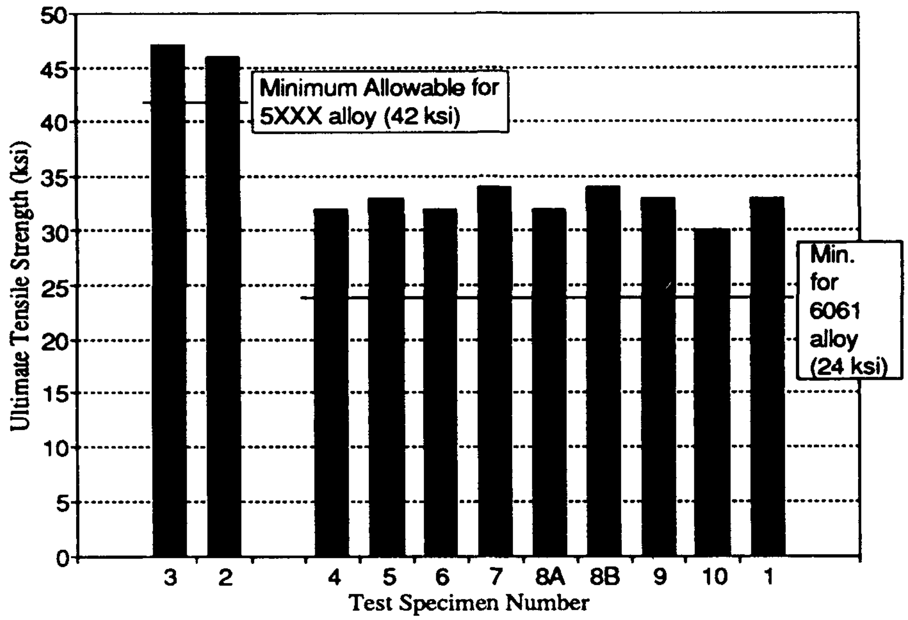


Figure 3.1-5 Welded Al test specimens with acceptable strength but rejectable radiographic porosity indications per BAC 5975, Class "A" or "B" welds.

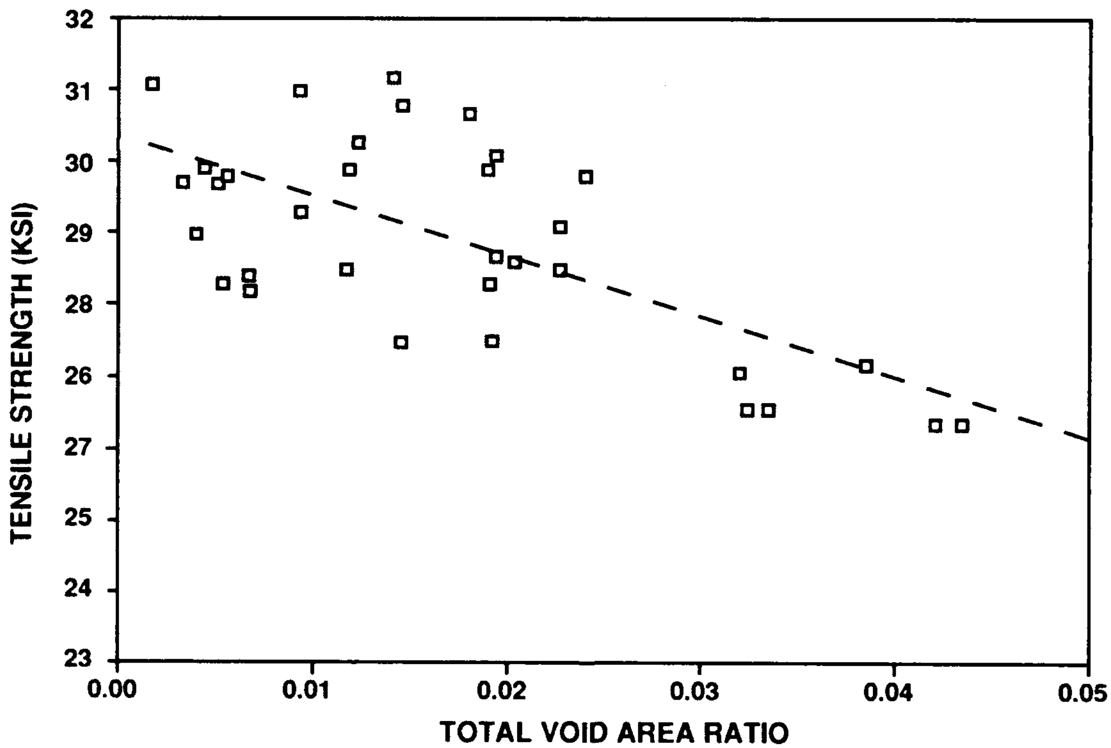


Figure 3.1-6 Tensile strength data for welded Al specimens with void/material ratios (as measured from failure surface) showing statistically significant degradation only above 0.03 (3 percent).

Another example is the 707 flap drive actuator housing casting shown in Figure 3.1-7. This aluminum cast part was fabricated, machined and a brass insert installed. Although the part passed early inspections, after final machining, penetrant inspection revealed potential porosity. The normal disposition of the component would be destructive analysis. However, due to the value of the component, several alternatives were considered to assess the severity of the penetrant indications. Radiographic inspection was very difficult to perform due to the orientation of the defect area and the presence of the brass material. The results were inconclusive, although they did not indicate any severe porosity near the lip of the part. Computed tomography was successfully used to show that the porosity throughout the part was minor. Based on the application of the component, engineers were able to conclude that the part could be safely put into service. The salvaging of the part was directly responsible for over $10K in cost savings due to the investment in machining, inspection and disposition. But, more importantly, the part was needed for an "aircraft on ground" (AOG) situation (a condition where an aircraft is unavailable for its scheduled mission). The cost of delays for AOG responses are significant in dollars and mission readiness. Computed tomography provided the interpretable evidence of the soundness of the component for service and avoided costly refabrication of the housing.

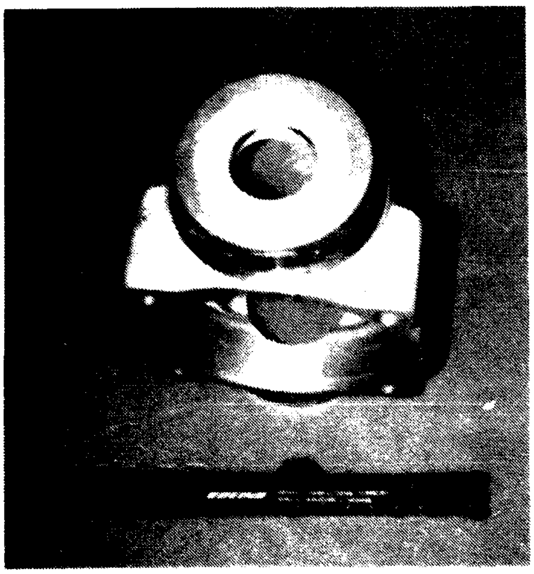


Figure 3.1-7 Photograph of the 707 flap drive actuator casting.

In light of these and what could be a multitude of other examples, it is appropriate to ask whether or not current inspection plans are reasonable requirements. Should one be spending time and money to thoroughly inspect regions of a casting that have no real effect on its performance? It has already been shown that the radiographic inspection quality can vary in a complex part, and that 100 percent radiographic inspection is a misnomer in many castings. It appears that it is common practice to inspect areas where inspection may not be necessary with a means whose effectiveness is poorly defined. Such a practice is a waste of time and effort.

A reasonable response to this problem is the proper assessment of the performance requirement of the casting and the utilization of inspection methods which produce data that correlate to part performance. It makes sense to obtain the highest quality data at locations which are critical to the component's function.

3.2 CT Casting Feature Sensitivity

3.2.1 CT Image Quality Indicators (IQIs)

As noted earlier IQI's are used in film radiography to indicate feature sensitivity in the image. A very similar IQI for use in CT casting studies has also been devised. Figure 3.2-1 is a photograph of the three pieces of a CT IQI. The CT IQI is a 19 mm diameter disk, containing 2 or 3 holes, of selectable thickness with a cylinder of material on both sides of the thin shim. The IQI thus represents cylindrical voids of a height equivalent to the shim thickness and diameters of 0.25 mm (0.010 inch), 0.50 mm (0.020 inch) and 1.0 mm (0.040 inch). In order for the IQI to be useful, the CT slice must be taken such that it covers the plane of the shim. The CT slice may be thicker than the shim and still be sensitive to the voids. Each cylinder may contain an angled slot cut into it to assist in centering the X-ray slice on the IQI. The partial volume effect of the slots allow one to calculate the actual X-ray beam slice width and location. Figure 3.2-2 illustrates how this takes place. Figure 3.2-3a shows a 0.25 thick CT slice taken on System Q that is located 1 mm high on the IQI. Figure 3.2-3b shows a slice that is centered on the IQI.

When one of these IQIs is placed in the scan plane near a region of the casting during a CT test, a direct measure of the detectability of volumetric feature size in that region is possible. These IQIs have been used to study the important variables involved in defect sensitivity, and to compare image quality and defect sensitivity with film radiography. This work is described in Section 3.3.

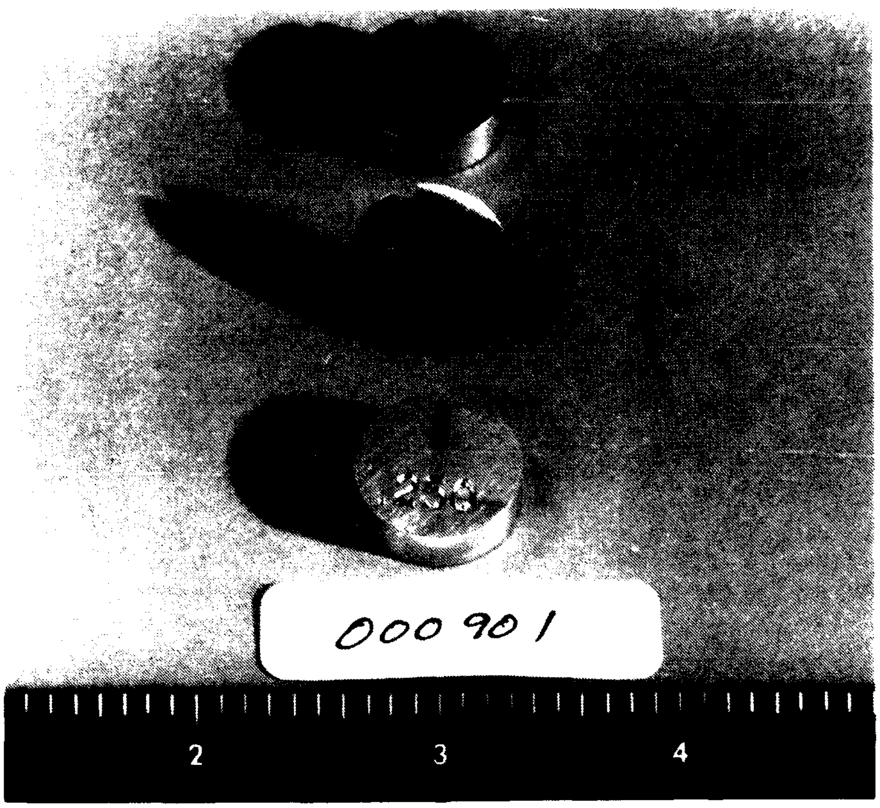


Figure 3.2-1 Photograph of a computed tomography IQI for castings.

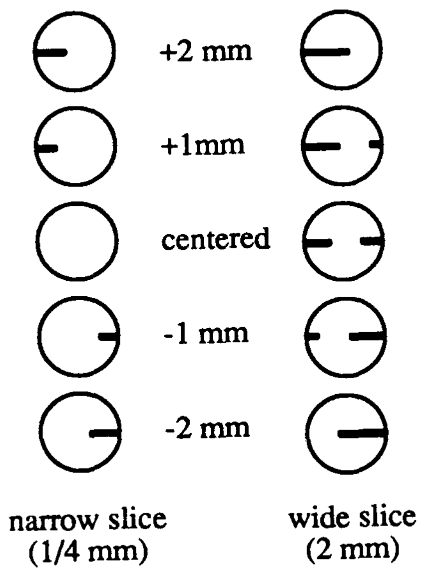
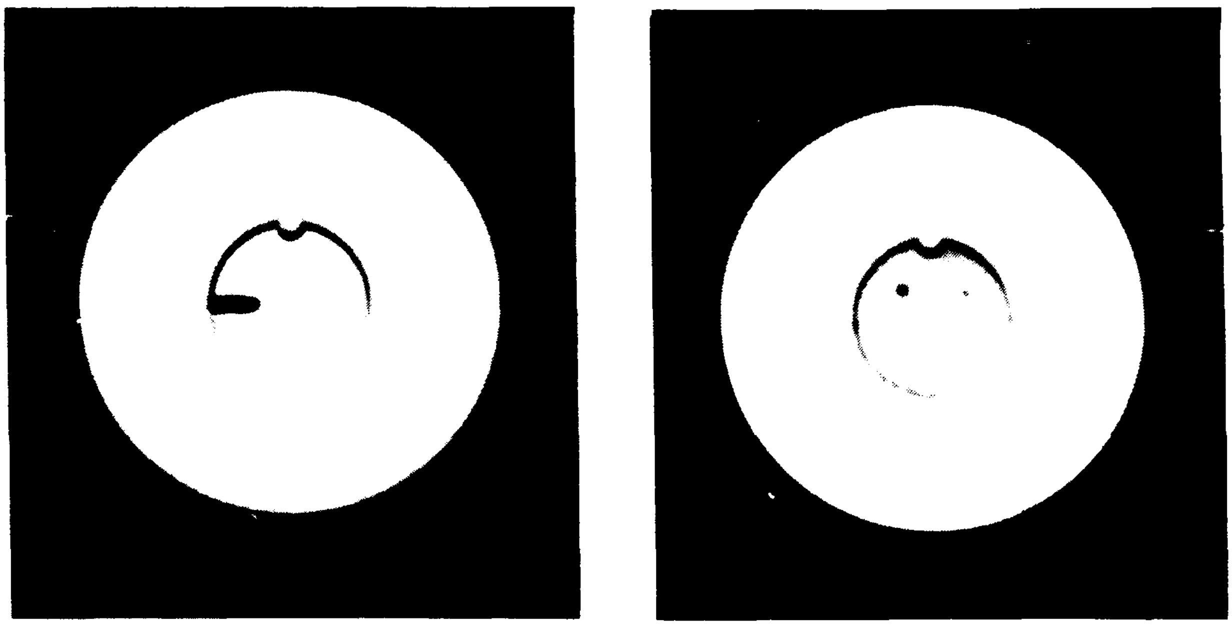


Figure 3.2-2 IQI images showing the centering indications.



a)

b)

Figure 3.2-3 CT image of IQI with 0.25 mm slice a) located 1 mm high and b) centered on IQI.

3.2.2 Part Thickness Effects on Defect Sensitivity

For any given CT system, the image resolution will depend (to the first approximation) on the X-ray optics of the design [14-16]. But, the noise will be affected by the operating parameters such as slice thickness, scan time, and X-ray energy. As the geometry of the object changes, so does the noise. An increase in the X-ray path length will cause an increase in the noise in the image.

A series of concentric rings was fabricated from aluminum for the purpose of studying the feature detectability in castings as a function of the operating parameters. These rings are shown in Figure 3.2-4. A CT IQI fits into the center ring to provide the measure of detectability.

Figure 3.2-4 Photograph of concentric aluminum rings for studying CT operating parameters.

The sensitivity to small defects as a function of X-ray path length was examined using measurements from the CT IQI at the center of the rings. The IQI contains right cylindrical voids of 0.012, 0.05, and 0.2 mm^3. Each void is 0.25 mm in height with diameters of 0.25, 0.5, and 1.0 mm respectively. Line plots through the CT image of the voids provide a numeric value for the image modulation. The noise in the data can be obtained by selecting a region of interest and measuring the variation of the CT values. In order for a feature (void) to be detected, the modulation must be greater than the noise.

Figure 3.2-5 shows the experimental measurements of the ratio of the modulation of the 0.2 and 0.05 mm^3 voids to the noise in the CT image as a function of the object size (path length) at two X-ray energies on System L. The path length has been changed by adding rings using the Figure

3.2-4 ring set. The higher energy CT scans tend to show a greater modulation-to-noise ratio. This should be due to increases in signal strength which reduce noise in the image. The Figure 3.2-5 plot allows one to predict the sensitivity that can be achieved as a function of the amount of material present. Obviously, to improve the detectability of fine detail, one needs to either increase the modulation or decrease the noise.

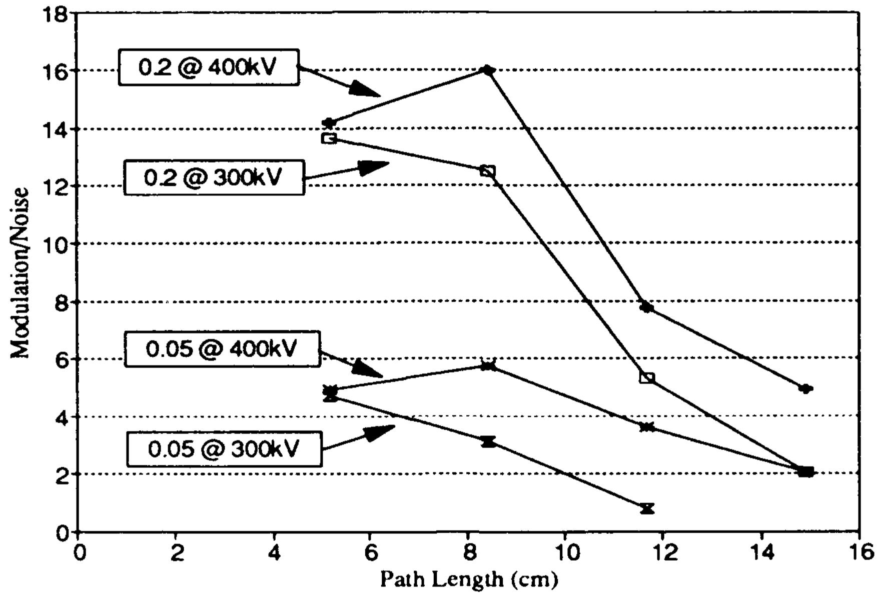


Figure 3.2-5 Modulation-to-noise ratio as a function of object size (path lenght) for voids of 0.2 and 0.05 mm^3 at 200 kV and 400 kV.

3.2.3 Slice Thickness Effects on Defect Sensitivity

The thickness of the CT slice will also affect the detectability of small voids. Figure 3.2-6 shows the effect of changing the slice thickness for voids of 0.012, 0.05, and 0.2 mm^3. This data was taken on System L. Noise in an image is affected by the slice thickness. As the slice thickness increases, greater signal is present, which reduces the noise. Normally, reduced noise would increase detail sensitivity. However, the voids are right cylinders of only 0.25 mm in height. When the slice thickness is greater than the void height, partial voluming occurs in the imaging which reduces the modulation of the void signal. Thus, a curve of detectability is formed for optimizing sensitivity as a function of slice thickness. In this particular case, a 1 mm slice would provide the best defect sensitivity. By correlating the noise and resolution with the partial voluming for the anomaly size of interest and the part size, it should be possible to predict CT system requirements for casting inspection.

A thin slice width can provide excellent sensitivity to defects, but the thinner the slice width, the more slices are required to cover the entire part. Thus, CT can be used very effectively for high sensitivity in critical region inspection. However, this same sensitivity may be prohibitively time consuming to apply on 100 percent of the part, and so a less sensitive approach may be used in non-critical areas.

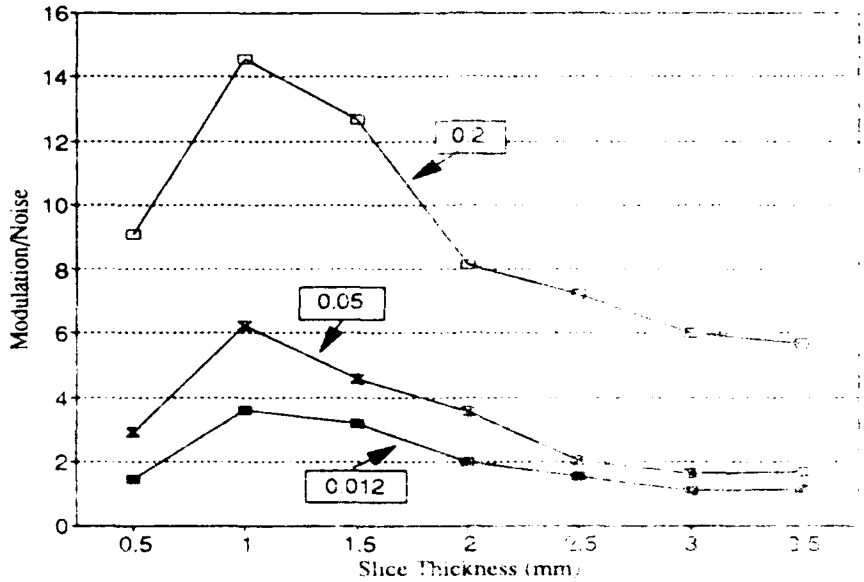


Figure 3.2-6 Modulation-to-noise ratio as a function of CT slice thickness for a 5 cm aluminum path length at 300 kV.

3.3 Part Thickness Effects on Radiographic Sensitivity

Film radiography of large, thick castings will be less sensitive to defects than of small, thin castings. This relationship between the amount of material and the ability to identify defects is of importance when comparing film radiography with CT evaluation, because the defect sensitivity of each method is affected differently by object geometry. For example, Figure 3.3-1 shows a cylinder of height 'h' and diameter 'd', which would probably be radiographed through its height, but CT scanned across its diameter. A change in 'd' would not affect the sensitivity of the radiograph, but would affect that of the CT image, as discussed in Section 3.2.2 (The change in 'd' was produced by adding concentric rings). A change in 'h', however, will affect the radiographic sensitivity, but not the sensitivity of the CT image. (One must, however, either take more or thicker slices to cover the whole cylinder.)

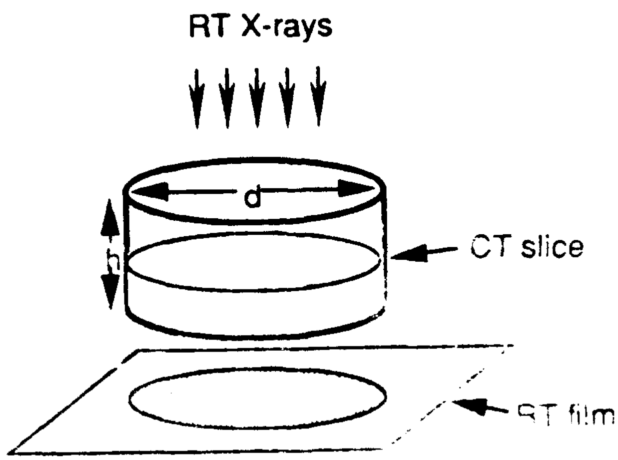


Figure 3.3-1 Example of RT and CT inspection of cylindrical object.

To examine the relationship of part thickness to defect sensitivity in film radiography, a small cylinder containing porosity (PID# 030117) at one end was cut into three 6 mm (0.25 inch) thick disks. The disk containing the flaws was radiographed alone, with the second disk added on top of it that did not contain flaws, and finally with the third disk added on top of that. The resulting three film images were digitized for computer analysis using a light box and a video camera. Figure 3.3-2 shows a CT slice of the disk taken on System J, showing the internal porosity. The large void, visible in the CT image, is also visible in each of the film radiographs, and was chosen as the means of comparing the defect sensitivity of each. The modulation (drop in signal intensity) of a line that passes through the void in each image was measured. The results of these measurements are shown in Figure 3.3-3. There is clearly a linear relationship between object depth and the modulation. This test was repeated for another coupon (PID# 030125) with equivalent results as shown. (In this particular study, the noise in the images was due to the digitizer and not the film; the film noise is assumed to remain constant. Thus, the modulation itself is a measure of detectability.) In the example of the cylinder in Figure 3.3-1, if 'h' doubles, the sensitivity of the film is dramatically reduced. The sensitivity of a CT image is unaffected by the change in 'h', and can be chosen by selecting the slice width and energy.

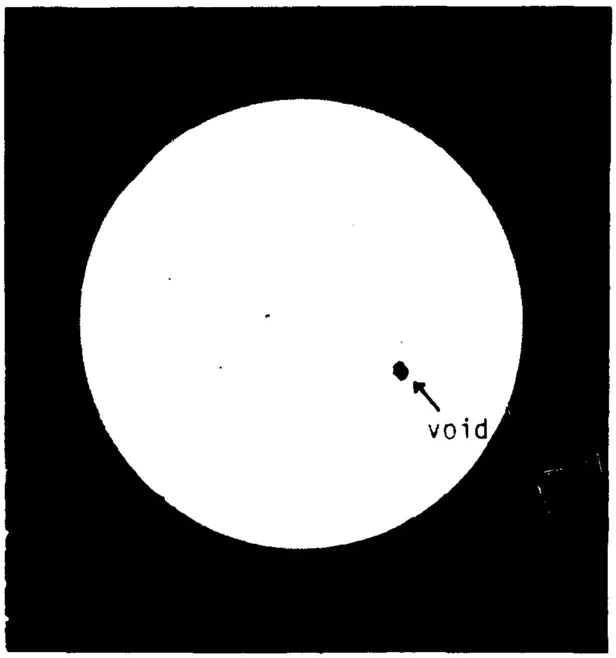


Figure 3.3-2 CT image of aluminum disk showing the large void used for the sensitivity study.

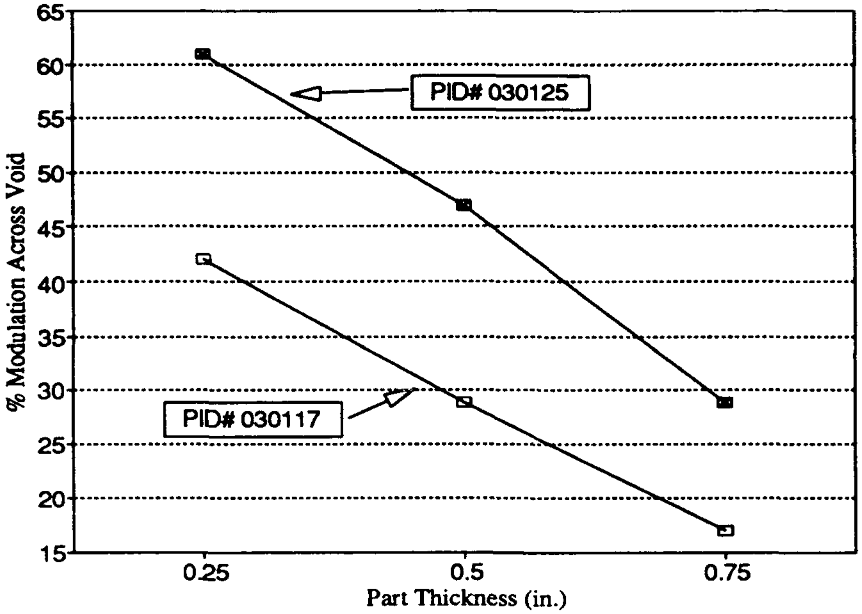
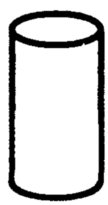
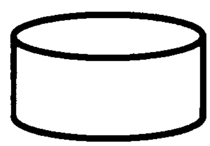
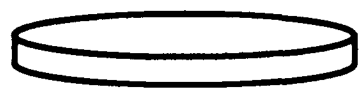


Figure 3.3-3 Graph showing the effect of thickness (path length) on RT defect sensitivity in cast coupons PID# 030117 and 0301125.

These results show that film radiography can become ineffective in defining actual defects in thicker castings. Film works best with thin, flat shapes. Thick objects of complex shape are more effectively inspected with CT. Figure 3.3-4 shows which type of object geometries work best for CT and RT inspection.

● Computed Tomography (CT)
○ Film Radiography (RT)

Object Shape				
excellent		●	●	○
satisfactory	○* ●			
poor		○	○	●

* with film parallel to long axis

Figure 3.3-4 Comparison of RT and CT inspectability as a function of object shape.

3.4 CT Artifacts

One of the concerns that users must face with CT images is the characterization and understanding of artifacts present in CT reconstructions [17,18]. Artifacts are features that do not correspond to physical structures in the object. The combination of polychromatic X-rays, long material path lengths (particularly along straight edges) and significant material density variation (between cast material and air) present computational problems than can create streak artifacts in the image data fielo of castings. An example of an image with artifacts is the CT slice of a gearbox housing (PID# 030205, see Section 4.4-1) shown in Figure 3.4-1, which was taken on System L. The thin regions of the casting and the corners show variations in CT value that are not due to variations in the casting. Interpretation of images containing artifacts is relatively easy for experienced personnel, but there are times when artifacts can obscure important data.

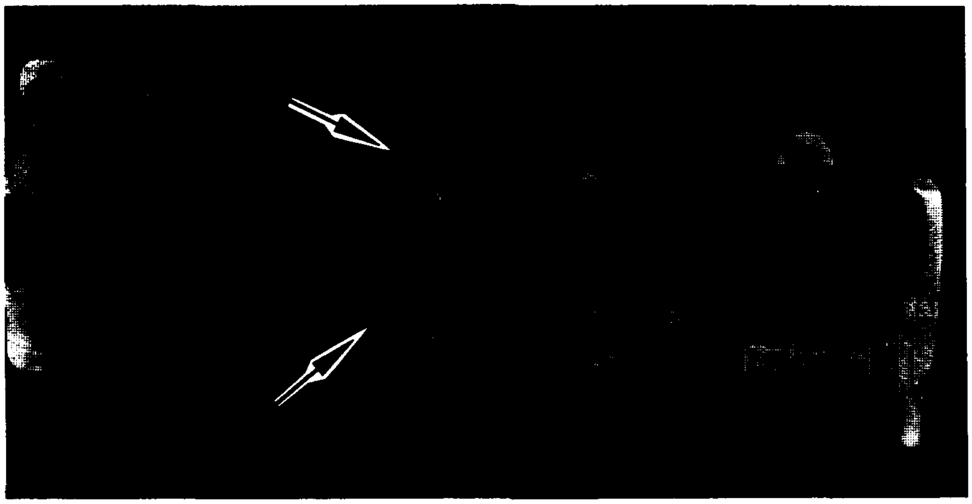


Figure 3.4-1 CT slice of gearbox housing showing streak artifacts caused by the long material path length along certain straight edges.

Fortunately, artifacts can be reduced or accounted for in a variety of ways. The casting can be scanned at a higher energy, which increases the signal and reduces the contrast, thereby reducing artifacts. A bolus material such as granular borax soap, sand or other material can be packed around the object to lessen the discontinuous change in material density. Adding bolus material will also add to the X-ray path length, and will tend to increase the noise and reduce the general detectability of defects. Thus, sensitivity is a tradeoff with this method, and should be considered when attempting to reduce artifacts.

If doubt exists about the presence of an artifact, one possible approach is to displace the object on the inspection table by half of the detector spacing and the CT scan repeated. Some types of artifacts will be shifted in the image, but a true defect will remain in the same location on the part. Another way to separate artifacts from defects is by image subtraction. A CT image from a "good" casting can be subtracted from the image produced from the casting being evaluated. The artifacts will tend to cancel out, and the defects will remain. This method has application outside of artifact reduction, in manufacturing quality control with CT. Image subtraction allows variations from a standard to be emphasized and then measured quantitatively.

A beam hardening artifact, caused by a spectrum shift to the higher energies as the X-ray beam penetrates the object, creates an artificial density variation in an image. This gives an apparent higher density reading on the outer surfaces of an object, and a lower density reading in the interior. Pre-filtering the X-ray beam to remove the lower energy X-rays can reduce the effects of beam hardening in the image. Correction for beam hardening can also be done in the computer software, with the help of a calibration standard. A correction matrix is determined from the calibration which is then applied to subsequent scans of the object.

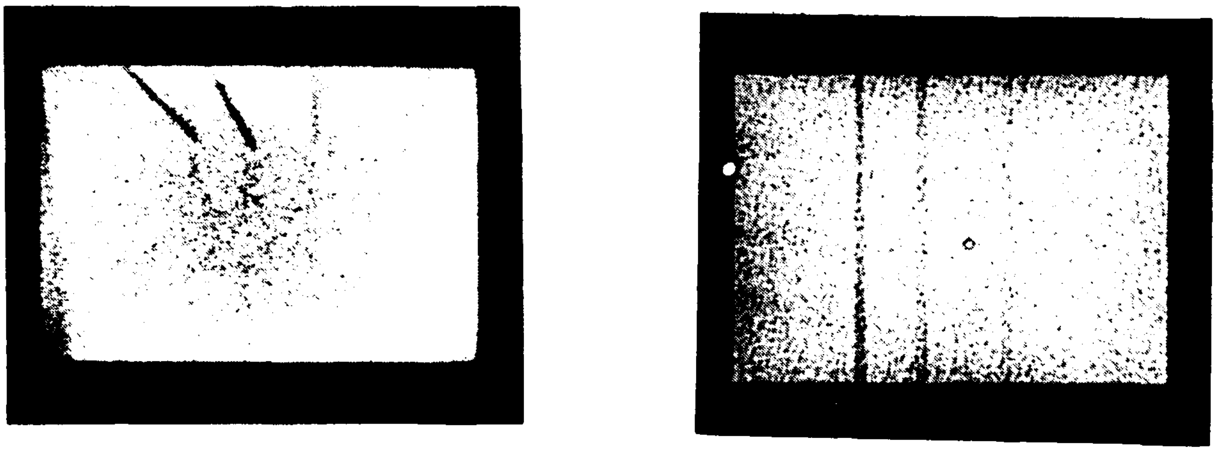
3.5 CT Crack Sensitivity

Because X-ray inspection methods function on the basis of X-ray attenuation through material, crack detection requires that there be some type of air gap in order to be seen. Small, closed cracks would not be expected to be identified with CT or RT. Penetrant is of course the method preferred for the detection of surface cracks. However, many cracks are detectable by X-ray methods under certain conditions.

For film radiography, crack orientation is important. The plane of the crack must be within a few degrees of the direction of the X-rays in order for the crack to be imaged. The likelihood of finding randomly oriented cracks with conventional radiography is relatively low, unless multiple-angle exposures are taken in each region of interest.

In order to examine the effect of crack orientation on CT detectability, a small crack test block was made. This test block, shown in Figure 3.5-1, contains three approximately 0.025 mm (0.001 inch) wide gaps to simulate cracks which lie at angles of 0, 30 and 45^{o} relative to the short sides of the block. The test block consists of three machined sections and bolted together. It was scanned with the scan plane through all three gaps and parallel to the block face which is visible in the photograph. The CT images, taken on System Q are shown in Figure 3.5-2. All three gaps can be seen. Fiugre 3.5-2a shows a slice in the plane of Figure 3.5-1. Figure 3.5-2b is a slice perpendicular to the palne of Figure 3.5-1, close to the surface. In Figure 3.5-2b the higher angle gaps are shown as broader indications. These results show that CT is able to image gaps independent of the their orientation. Radiographic images of the gaps only show the gap which is oriented such that it is along the X-ray beam. When the block is oriented properly, radiography is able to detect the machined assembly interfaces which are not visible in the CT image.

Figure 3.5-1 Photograph of the test block for measuring crack sensitivity as a function of direction.



a)

b)

Figure 3.5-2 CT slice of test block containing gaps, a) parallel to Figure 3.5-1, b) perpendicular to Figure 3.5-1.

4.0 TESTING RESULTS

The results of CT testing of various castings revealed that there is potential for significant benefit for CT in casting manufacture in support of specific categories of foundry operation or casting needs. Figure 4.0-1 summaries these categories. Examples from the Figure 2.1-1 parts list are used to represent the application of CT in each area.

Benefit Area	CT Advantages
New Product Development	Spatial location of voids, shrink, etc. in 3D Dimensional measurements without sectioning Position and effect of cores
Early Screening	Acceptance of otherwise rejectable components Reduced "Dead End" costs Better repair planning
Complex Geometries	Direct dimensional measurements No superposition of features Less difficult than film radiography
Critical Region Inspection	Quantitative defect measurement Improved sensitivity

Figure 4.0-1 Potential benefit areas for CT of castings.

4.1 CT for New Product Development

CT can be used by a foundry to reduce costs of developing new castings. The 3-D spatial information on voids, shrinkage, and porosity from CT data can reduce the time for casting and mold design cycles by helping the designer better define the casting process of a part. Decisions about riser, chill, and gate changes can be made without taking a large number of film radiographs or cutting the part as presently required and used in common practise. Dimensional measurements can be made without spending the time and money to cut up the part.

4.1.1 Titanium Alloy ATF Plate

An example of the use of CT for new product development is the titanium alloy test plate (PID# 030312) which was used to study the manufacturing process of this alloy for use in the Advanced Tactical Fighter program (Figure 4.1-1). The particular manufacturing method for this plate produced some large flat voids in the interior of the plate, which were identified with film radiography. The plate was then subjected to hot isostatic pressing (HIP) in order to eliminate the voids. HIP, which involves subjecting a component to a high temperature, high pressure environment, is often used to heal internal porosity in castings. At this point, it was difficult to determine with film radiography how successful the HIP process was. The plate was then scanned with CT at the previous locations of the voids. The CT images indicated not only that some voiding was still present, but showed the actual extent and depth of the remaining voids. Figure 4.1-2 shows a CT slice taken on System L which passes through two voids. This information could then be used to help optimize the process by adjusting the appropriate manufacturing parameter. Although the plate example is a very simple geometry, the benefit of CT for new product development should only increase with increasing casting complexity.

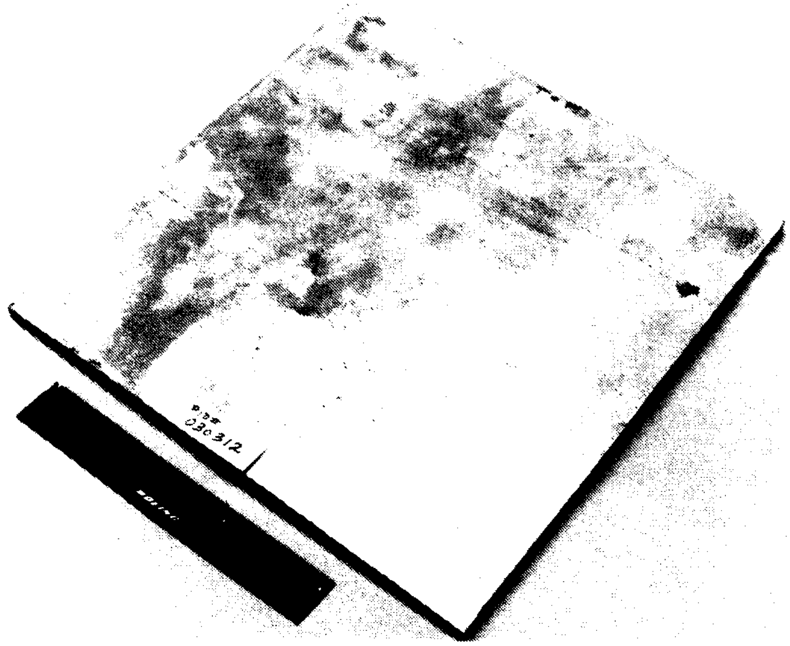


Figure 4.1-1 Photograph of titanium alloy test plate.

Figure 4.1-2 CT slice of titanium alloy test plate showing two voids which were not eliminated through the HIP process.

4.1.2 Investment Casting Molds

In investment castings, the quality of the product is strongly dependent on the mold condition. It has been estimated that 80 percent of rejections in investment castings can be attributed to problems in the mold. Figure 4.1-3 is a photograph of a typical investment mold. The mold is formed around a wax model using an initial layer of zircon or similar material and then multiple outer layers of silica material. Problems with the initial layer, such as peeling or spalling, will result in problems in the final casting. Figure 4.1-4 is a CT slice of the mold taken on System [illegible]. This imaging can be used to show how the inner layer is forming and its interaction with outer layers. Any indications of missing material is indicative of a potential problem. CT could be applied in the analysis of problem molds and as a process control tool to assure that molds are being consistently formed with the desired material present.

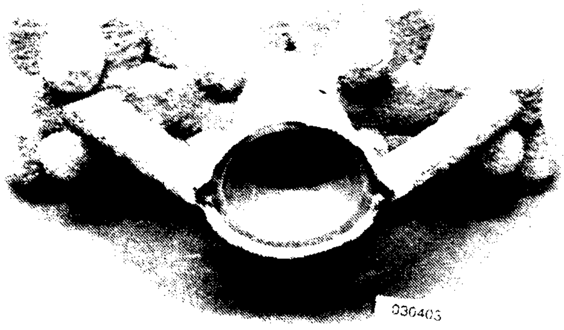


Figure 4.1-3 Photograph of an investment casting mold.

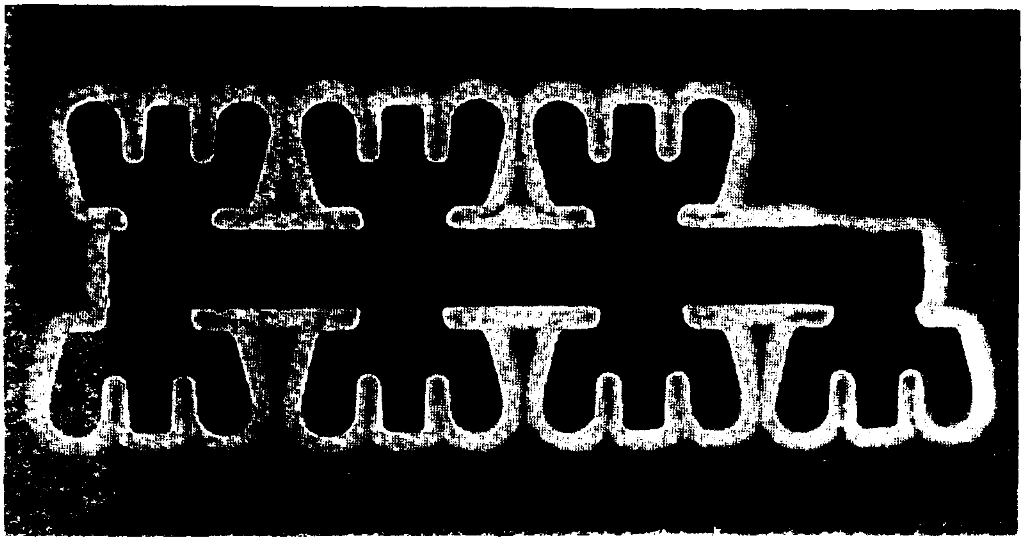


Figure 4.1-4 CT slice of the investment mold [illegible] layer (white) [illegible] gray)

4.2 CT for Early Screening

CT can contribute to improving the economical product flow of a foundry by allowing early screening of the casting at various stages to determine the optimum selection of subsequent operations or disposal. Parts rejected by radiography, penetrant, or visual can often be saved because the defects are in a region that will be machined away anyway. The exact location of defects can be revealed by CT, showing which castings will pass post-machining inspection and which will not.

CT also reduces "dead end" costs because parts containing defects that may pass early inspections but, will fail at a later stage, may be detected by CT and rejected before further costs have incurred. It is not uncommon for a casting to pass radiographic, penetrant, and visual inspection, and then to fail inspection after it has been machined. Porosity that was acceptable before machining either comes to the surface after machining, or becomes a more significant effect due to the reduced part thickness after machining. At this point, the casting has to be thrown out or subjected to costly repair. CT can provide defect location and size information which would reveal defective parts before any more costs are incurred.

CT can also assist with repair planning of castings that are salvageable. A better definition of the problem (as compared to RT) can reduce over-grinding or improper welding. One casting manufacturer described a scenario in which an area of a part was ground down and radiographed over a half dozen times in an attempt to remove some voids. The expense of such work can be reduced by using CT, which can define defect locations in three dimensions. Time and money can also be saved by reducing the number of aborted repair attempts, which are often undertaken without enough information on the real extent of the defect.

An aluminum sector casting (PID# 030182) provides an example of how the use of CT can potentially save parts which might be rejected by other methods. This part is shown in Figure 4.2-1. This casting has several large gas holes which were identified with film radiography, and were the causes of its rejection. A DR of a section of the part taken on system R is given in Figure 4.2-2 clearly showing the defects. The two lines show the location of the CT slices chosen, which cut through some of the gas holes. The image of these slices, shown in Figure 4.2-3, reveal the location of these flaws to be right at the surface. These flaws would have most likely been machined away as part of the manufacturing process, and if not, could easily have been weld repaired. Slices taken at other gas hole locations revealed that they all were at the top surface of this casting. This type of information provided by CT on the exact location of the flaws can help reduce unnecessary scrap.

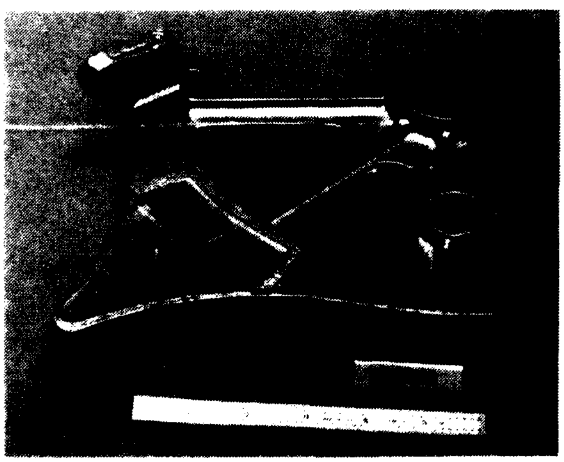


Figure 4.2-1 Photograph of aluminum sector casting.

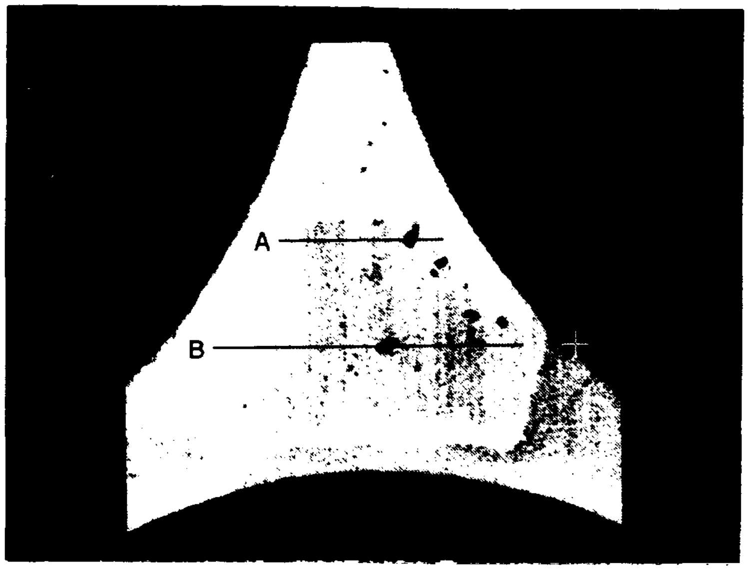
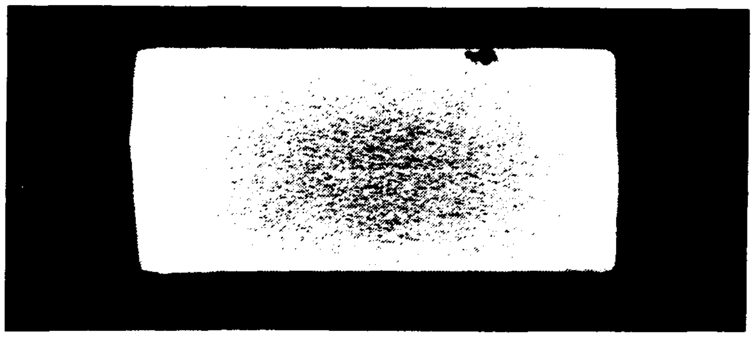


Figure 4.2-2 A digital radiograph (DR) of a section of the sector casting showing porosity. Some CT slice locations are indicated.

a)



b)

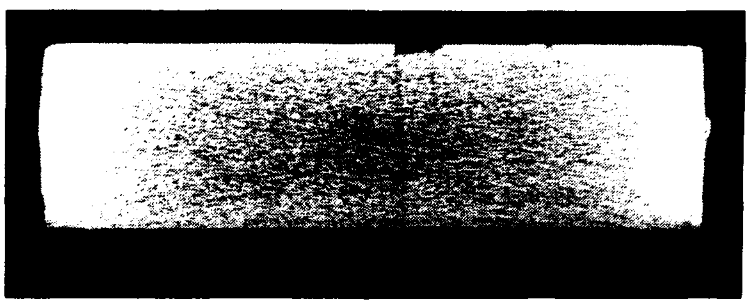


Figure 4.2-3 CT slice of sector a) at location A revealing that the porosity is at the surface, b) at location B revealing that the prosity is at the surface.

4.3 CT for Complex Geometries

There is a trend in casting manufacturing toward greater complexity, especially in investment castings [19]. The increase in complexity has rendered current inspection methods, such as film radiography, more difficult, and often inadequate.

CT can be more effective than film radiography for inspecting complex geometries because CT provides better quantitative technical information that is useful in assessing part quality. CT can reduce time and cost over film radiography when the geometries require a large number of exposures.

When CT is applied to a complex casting, it is possible to perform direct comparisons with a standard of the casting. This approach can be a very easy way to interpret the data.

4.3.1 Reservoir Manifold

Complex castings, such as the reservoir manifold (PID# 030106) shown in Figure 4.3-1, can be difficult to inspect with film (Figure 4.3-2). However, CT slices anywhere in the part can provide easy-to-understand images with accurate defect and dimensional information. Examples of CT slices taken on System L are shown in Figure 4.3-3. In each case, the dimensional results are easy to interpret as compared to film radiographs. Although reproduction in this report does not allow visualization, the CT images also show porosity at various internal locations in the manifold.

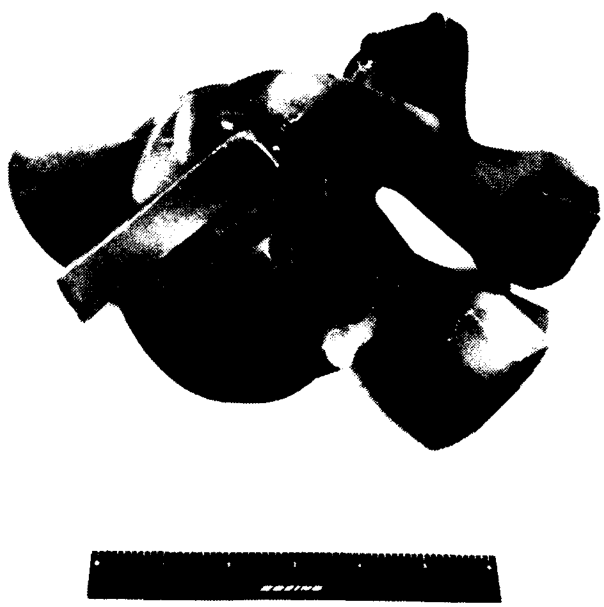


Figure 4.3-1 Photograph of reservoir manifold.

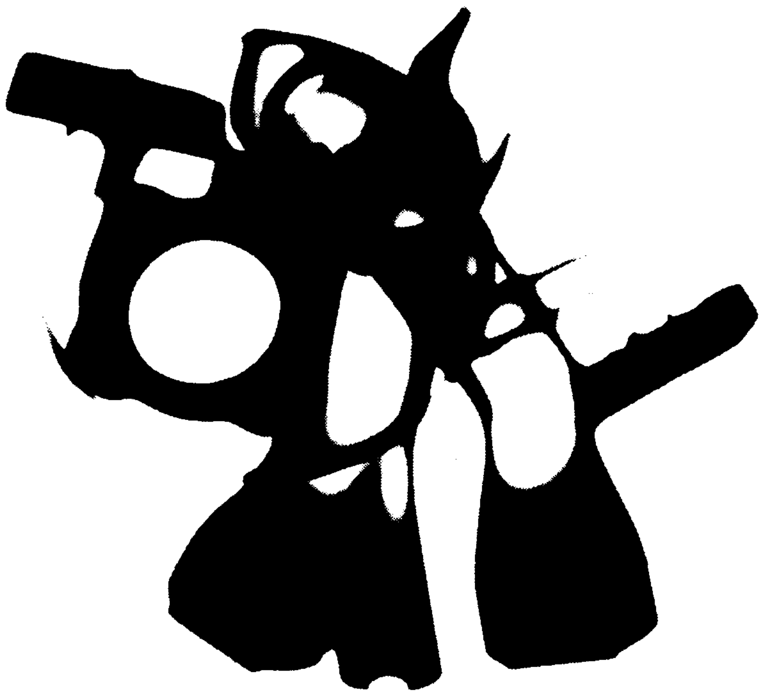


Figure 4.3-2 Image from a radiographic examination of the reservoir manifold.

a)

b)

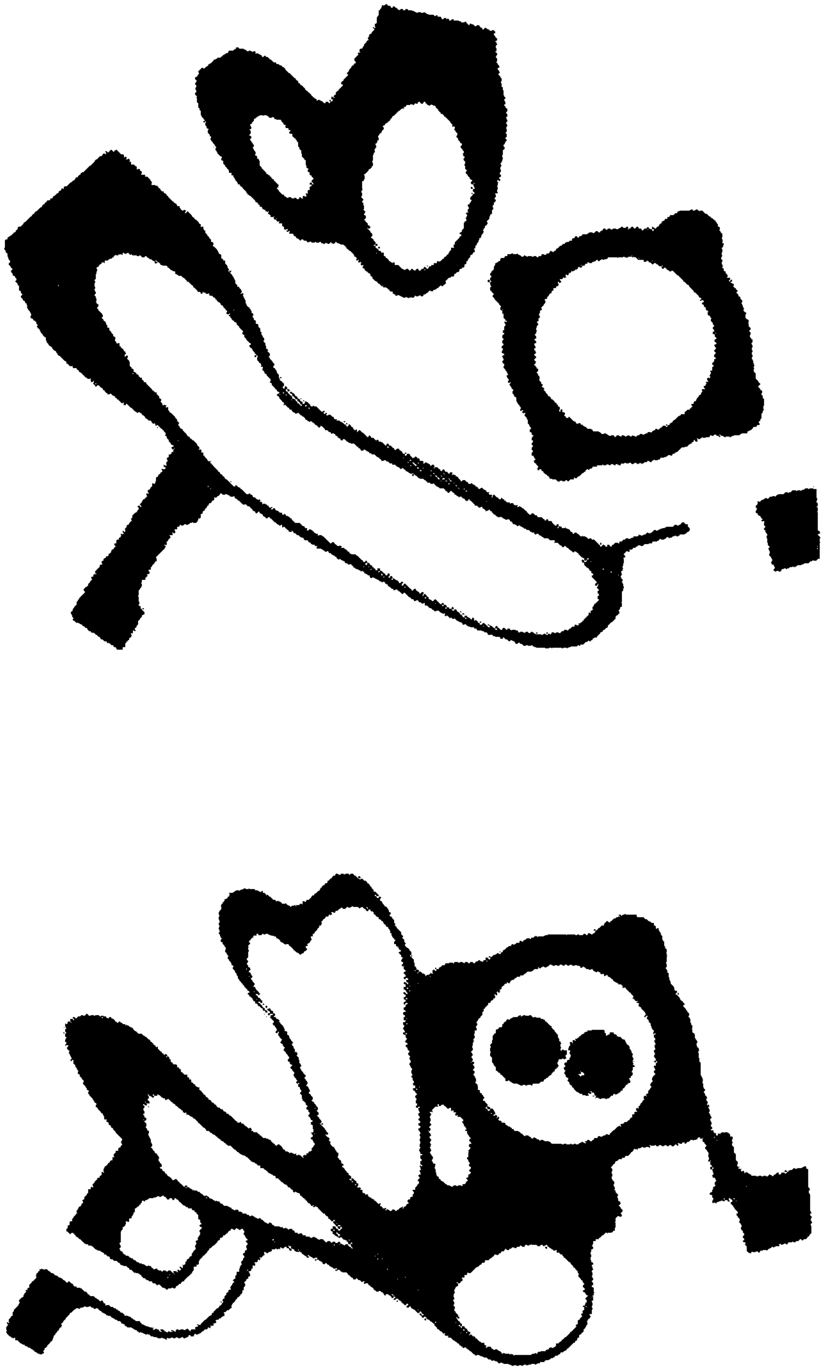


Figure 4.3-3 CT examination of reservoir manifold a) at height 509 mm, b) at height 529 mm.

4.3.2 APU Turbine Rotor Mount

The turbine rotor mount for the 757 auxiliary power unit (APU) (PID# 030166) is shown in Figure 4.3-4. Due to its complexity, a large number of film shots are required to assess the quality of the entire part. It remains questionable whether or not a part of this shape can be truly 100 percent inspected by radiography to appropriate quality levels, or whether that requirement is necessary. Figure 4.3-5 is a CT slice taken on System L through the lower pedestal, which reveals a defect whose location would make it difficult to "see" or to assess with film radiography. The location and extent of this defect is defined in this CT image. CT simplifies the assessment of defects in complex components.

4.4 CT for Critical Region Inspection

CT allows thorough inspection of specific regions which are associated with part performance, and can reduce wasted inspection effort. When CT is applied to specific areas it can provide high sensitivity to features. This, combined with defect criteria for the component, provides a better means for qualification than is presently employed by quantification of the inspection results and analysis of the critical performance requirements.

The magnesium alloy gearbox housing shown in Figure 4.4-1 is an example of CT for critical region inspection. A CT slice over the entire gearbox was shown in Figure 3.4-1. This gear box is being developed for use in the Advanced Tactical Fighter program. CT examination prior to vibration testing has been used in a critical region (see arrow in Figure 4.4-1) of the gearbox, after the gearbox was loaded with components. This was of interest to ensure that no flaws were present in regions that would see high stress loads. One of several slices of this region, taken on System L, is shown in Figure 4.4-2. These scans detected no anomalies in the region of interest. Artifacts due to higher density metallic component assemblies in the magnesium housing were present in the image, but did not restrict interpretation. CT is effective for this type of focussed inspection on critical regions.

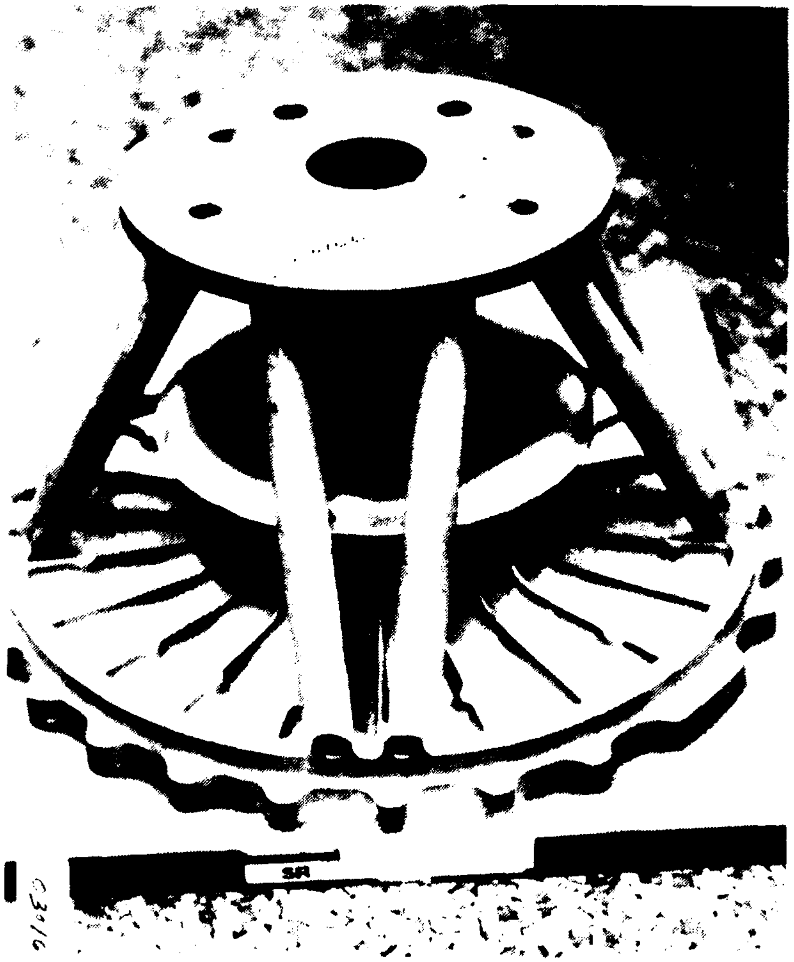


Figure 4.3-4 Photograph of APU turbine rotor mount.

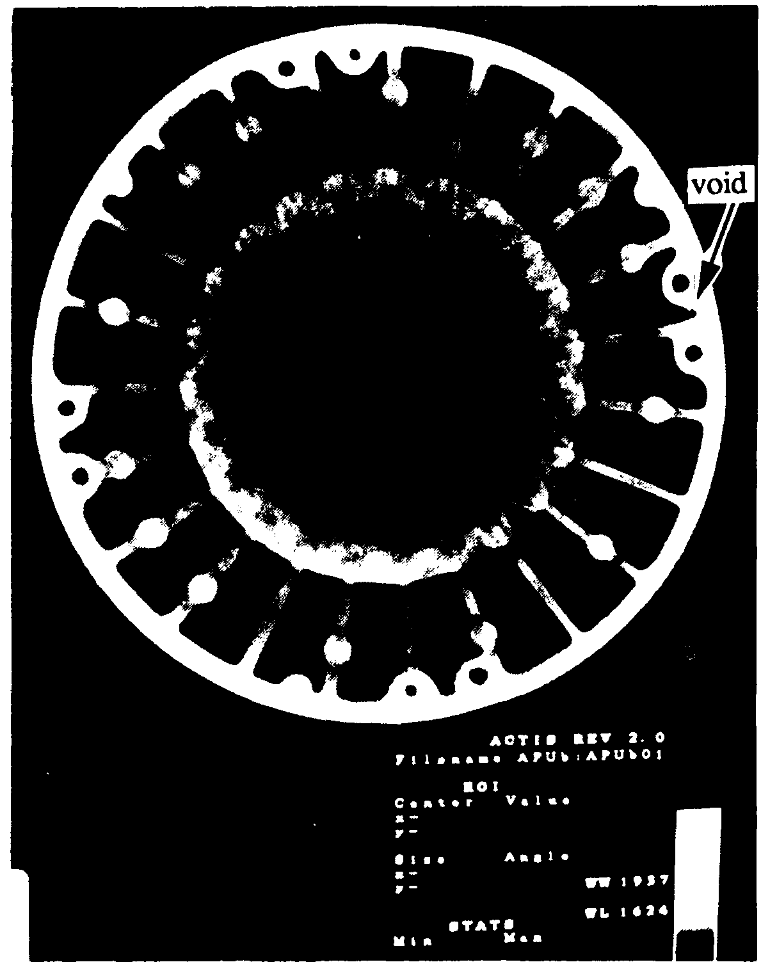


Figure 4.3-4 CT slice of lower pedestal of turbine rotor mount.

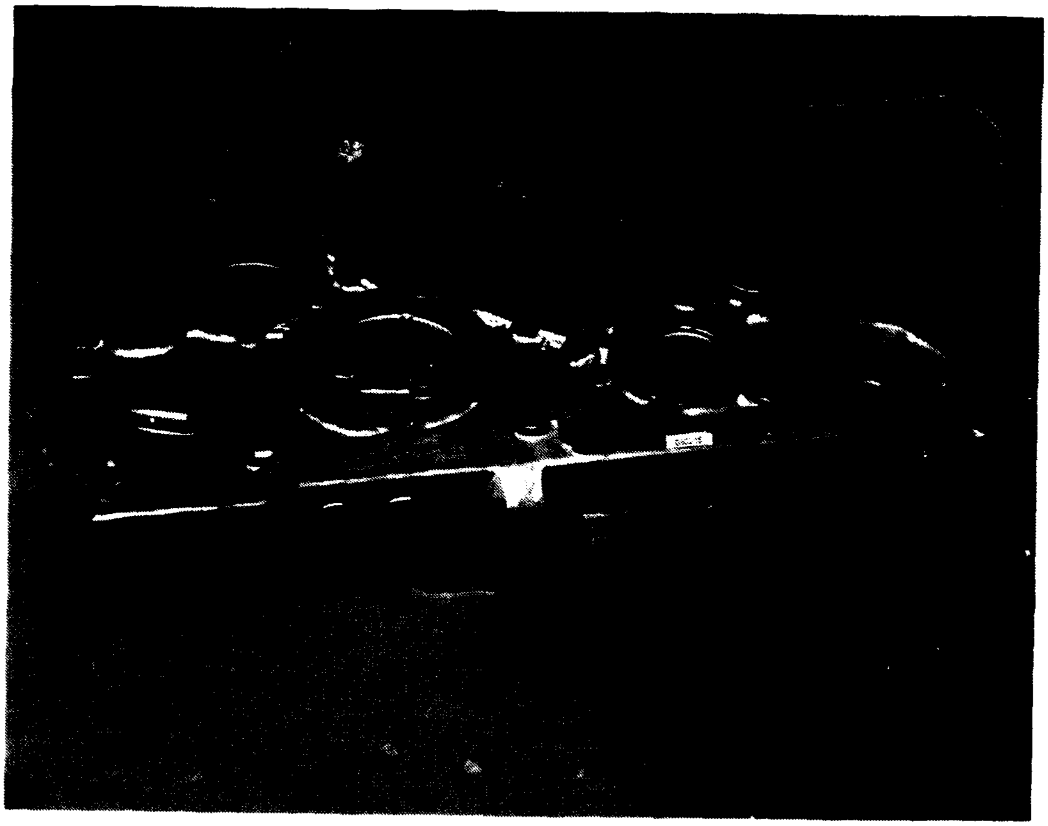


Figure 4.4-1 Photograph of magnesium alloy gearbox housing.

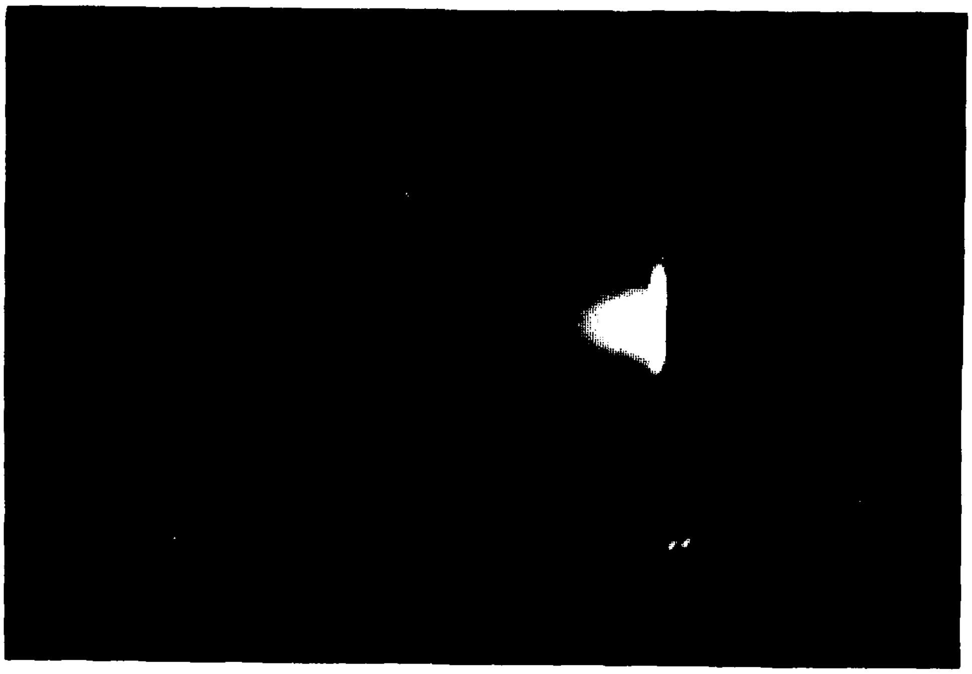


Figure 4.4-2 CT slice of critical region of gearbox housing.

5.0 COST BENEFIT ANALYSIS

Three areas of CT application which will provide an economic return in full-scale castings are 1) new product development, 2) production inspection (early screening, complex geometries, and critical region inspection), and 3) engineering analysis for acceptance. The economic implementation of a CT system for a foundry, however, depends on the foundry size, process control approach, CT inspection sensitivity requirement and CT throughput capabilities specific to any particular foundry's product line.

5.1 New Product Development

CT holds the greatest near-term payback potential for castings in new product development. Production costs are generally high, creating an incentive for implementing productivity improvement techniques. Also, CT will not be inhibited in the new product development area by the existing inspection specifications, which dictate the inspection methodology that can be applied in the product acceptance area.

The development of a new casting is a multi-phase process. If the casting is aluminum, it will usually be required to conform to MIL-A-21180 and the inspection requirements of MIL-STD-2175. The development process will include preliminary design, cost trade-off studies, structural analysis, design modification, source evaluation, and NDE technique selection. A fabrication process is selected, and test castings are then made which are extensively nondestructively and destructively inspected to establish the optimum manufacture method. It is at this stage that CT will allow a foundry to reduce costs of developing new castings. The 3-D spatial information on voids, shrinkage, and porosity from CT data can reduce the time for casting and mold design cycles by helping the designer more efficiently choose the casting process of a part. Decisions about riser, chill, and gate changes can be made without taking a large number of film radiographs or destructively sectioning.

Also, the first casting articles fabricated must often undergo stringent nondestructive and destructive measurements. Besides being expensive, such tests often result in the loss of one or more castings, the cost of which can be substantial if the casting is large or complex. Computed tomography provides feature location and geometry information which can be useful for dimensional measurements. This information has economic value as an alternative to comprehensive measurements on castings that may require destructive sectioning. For complex parts, CT is often a better inspection method than RT, and can be utilized to get more accurate data. In many cases, RT can be supplemented with CT in critical or hard-to-inspect regions. Computed tomography can reduce these costs significantly if the defect sensitivity or dimensional measurement accuracy of CT is sufficient for the casting.

On average, a foundry will expend roughly 5 percent of its effort on new product development. For example a foundry that does $100 M/year will likely have approximately 50 full-time equivalent staff involved in developing new products. These numbers scale very well for all sizes of foundries and even for different types of foundries such as sandcasting and investment casting. If the overhead cost of one person in the new product area is estimated at $100K/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 pruchase 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 5.1-1 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.

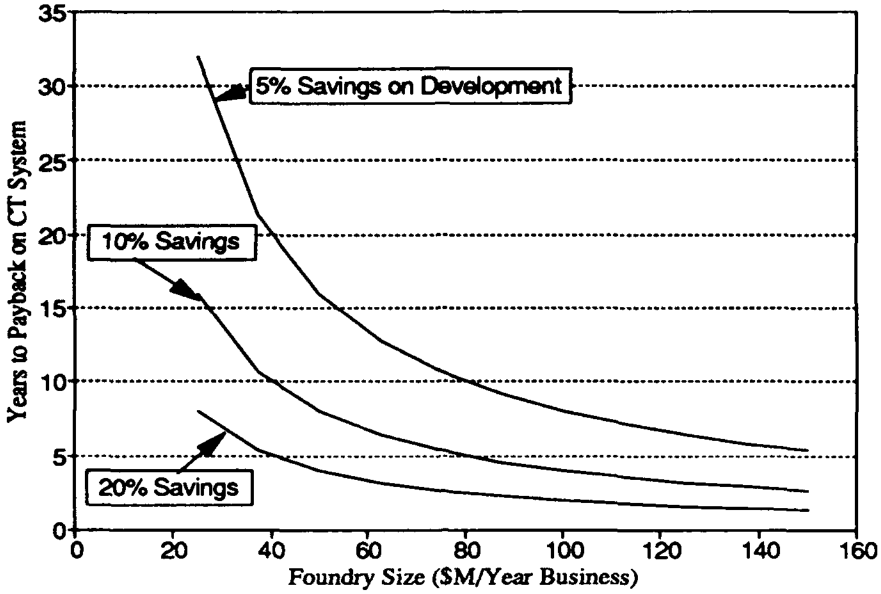


Figure 5.1-1 Estimated time for return on investment on $2M CT system used for new product development in foundries of various size. Values given for 5, 10 and 20 percent savings on development.

5.2 CT for Production Inspection

As a general inspection method, CT cannot currently replace film radiography for production inspection of internal defects in aerospace/aircraft castings. Several reasons for this are 1) current specifications for castings inspection, however inadequate, are tied to film radiography, 2) for many applications, the cost of a CT system is currently too high to justify its purchase and, 3) the defect sensitivity required by some of the most stringent specifications cannot currently be met with CT in large castings.

However, there are particular inspection categories in which it can be economically viable to utilize CT. Early screening of castings, inspection of castings with complex geometry, and critical region inspection are significant areas where CT can help with production inspection. These areas are discussed in Sections 4.2 - 4.4. The economic incentive to use CT is to reduce scrap. Foundries typically operate with a 5 to 10 percent scrap rate on well maintained production but often have scrap rates of over 20 percent on new products. Scrap loss is serious because it comes directly out of profit. Also, disputes between the foundry and the customer over who should absorb certain scrap costs can be time consuming. The use of CT in the production cycle for information about the process that can reduce the generation of scrap would be cost effective. For example, a $100M/year foundry is losing roughly $10M to scrap. A $2M CT system could pay for itself in 2 years if it were able to save 1 percent of product (reduce scrap from 10 percent to 9 percent). Figure 5.2-1 estimates how long it would take for such a CT system to pay itself off if it were able to reduce scrap rates in different sized foundries.

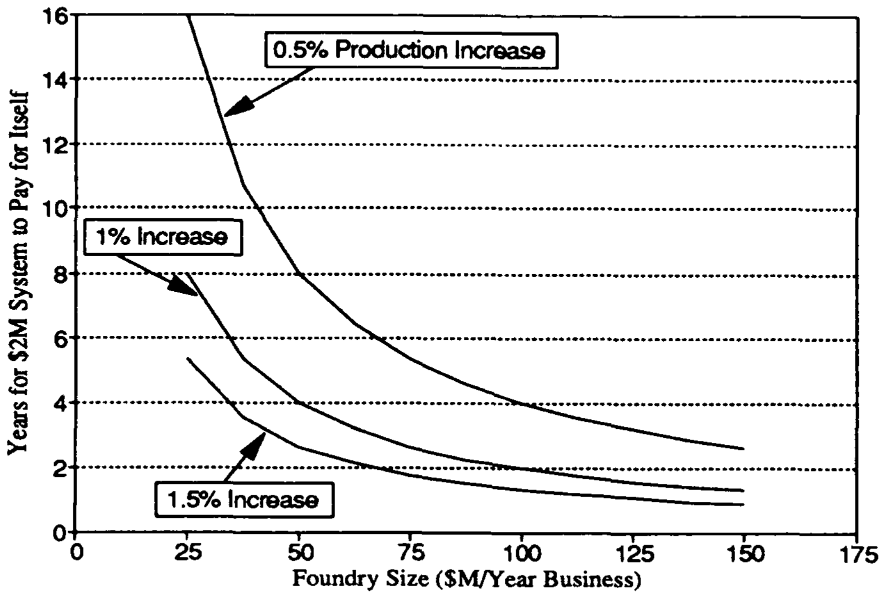


Figure 5.2-1 Estimated time for return on investment on a $2M CT system if production were increased by 0.5, 1 or 1.5 percent (by reducing the scrap from 10 percent to 9.5, 9 and 8.5 percent respectively) in foundries of various size.

5.3 Engineering Analysis for Castings Acceptance

Computed tomography can provide important information about casting features that will allow an engineer to determine whether or not a part may be suitable for service in spite of internal defects. Most castings are overdesigned for their mission, but fail inspection due to defects in noncritical areas. Because CT can determine the three-dimensional position of a defect and size, the information can be used to assess the suitability of the part for service. Considerable savings are possible, as shown earlier for the case of the 707 flap drive actuator housing casting (Section 3.1.4). In this case, the savings were significant because of the investment in the machining of the component. Computed tomography can play a large role in assisting in Material Review Board (MRB) decisions on the disposition of a component. The MRB is called on to decide the disposition of components that do not meet the inspection specification but which are believed to be suitable for service. Often these decisions involve critical, high value castings for which the expense of CT evaluation would be cost effective.

Engineering analysis using the CT data to input to finite element analysis codes is also possible. This has been effectively applied by General Electric [20] and an example will be reported in a companion report to this task assignment effort [7]. If, during the design stage, the engineer is able to determine the critical loadings on a component it is possible to define critical regions for inspection. Computed tomography systems can perform very effectively in support of this approach. The DR capability of CT systems can be used to provide a general overview of the component to check for gross anomalies. Precision CT images can be taken in critical areas. This has been the cost effective approach for turbine engine blades where the DR is used for flaw detection and CT slices are used to measure critical internal dimensions.

5.4 CT for Foundry Use

A foundry will probably find a purchase of a CT system for evaluating castings to be cost effective if it has at least one of the following characteristics:

1) The foundry has a sufficiently high production rate to support the large capital investment of a CT system. In the example given in Section 5.2, a CT system could pay for itself in 2 years in a $100M/year foundry if production scrap rates were decreased by only 1 percent (scrap reduced from 10 percent to 9 percent).

2) The foundry produces a high percentage of castings which require internal dimensional evaluation. Stringent inspection specifications on dimension in complex castings can be difficult or impossible to meet with current inspection methods. CT is ideal for this area, as the growing practice of CT inspection of turbine blades indicates.

3) Most castings produced in the foundry are complex, and not easily inspected with film radiography. This means that, on the average, a larger number of films and greater time is required to inspect each part, the complexity of which mitigates against an effective film radiograph inspection anyway. One casting manufacturer estimated a labor and film cost of conventional radiography at $45/exposure, and said that castings which require 20 exposures are not unusual. In this case, the costs for film radiography are high enough to consider CT as an alternative. Specifications will need to be modified for this to be possible.

4) The foundry has MRB authority, allowing the possibility of a CT-based engineering buy-off, thus saving many castings which would otherwise be scrapped. If a manufacturer is bound to a specification, better information about a part's fitness for service is of little value. However, if a rejected casting can be reviewed with CT and passed, considerable savings can be made, depending upon the value of the casting.

Industrial CT systems are continuing to be improved for higher sensitivity and greater throughput. A thin CT slice width can provide excellent sensitivity to defects that may lie in a critical region of a part. However, the thinner the slice width, the more slices are required to cover the entire part. Thus, CT defect sensitivity will often, in practice, be limited by the amount of time and money one is willing to spend on the inspection. If one is just inspecting critical regions with CT, the method can be cost-effective. The use of cone-beam CT (see Appendix A) can overcome the difficulties of taking many individual CT slices. This capability can lead to the effective use of CT in production applications. Cone-beam CT sensitivity must be matched to the inspection goals. Foundry applications of CT will require rugged, easy to operate systems. These developments are currently taking place as indicated by the purchase and use of CT systems for the support of turbine blade and automotive casting evaluation.

6.0 CONCLUSIONS AND RECOMMENDATIONS

This preliminary task assignment on CT for full-scale castings has illustrated that CT can be cost-effectively utilized in casting manufacturing. Although 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.

6.1 Conclusions

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.

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 thickness will affect the detectability of small voids. Once the correlations between system parameters, casting dimensions, and defect sensitivity are determined, one can then choose the optimal CT settings for the most effective casting inspection.

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. Also, since CT data provide quantitative volumetric measures of dimensions, CT dimensional information on anomalies derived from CT data can be used in finite element analysis codes for product development and determination of the effects of defects.

6.2 Recommendations

Casting manufacturers whose foundries have the characteristics which enable economically viable CT usage should consider purchasing a CT system as a cost-reduction measure. With standards and methods similar to the ones described in this report, it would be relatively simple to define the optimum CT operating variables for particular castings inspection needs. Digital radiography and CT should be implemented in combination to allow a rapid DR evaluation followed by selective CT scanning at critical locations.

It will 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.

We recommend that CT be applied to new casting product development as a final testing task under the CTAD program. Under the task, we would work with a foundry to try to identify more clearly the parameters in casting development that CT could cost effectively monitor. Also, we would look for criteria in foundry process controls that CT measurements could satisfy for ultimate reduction of scrap.

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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 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 castings which often vary 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.

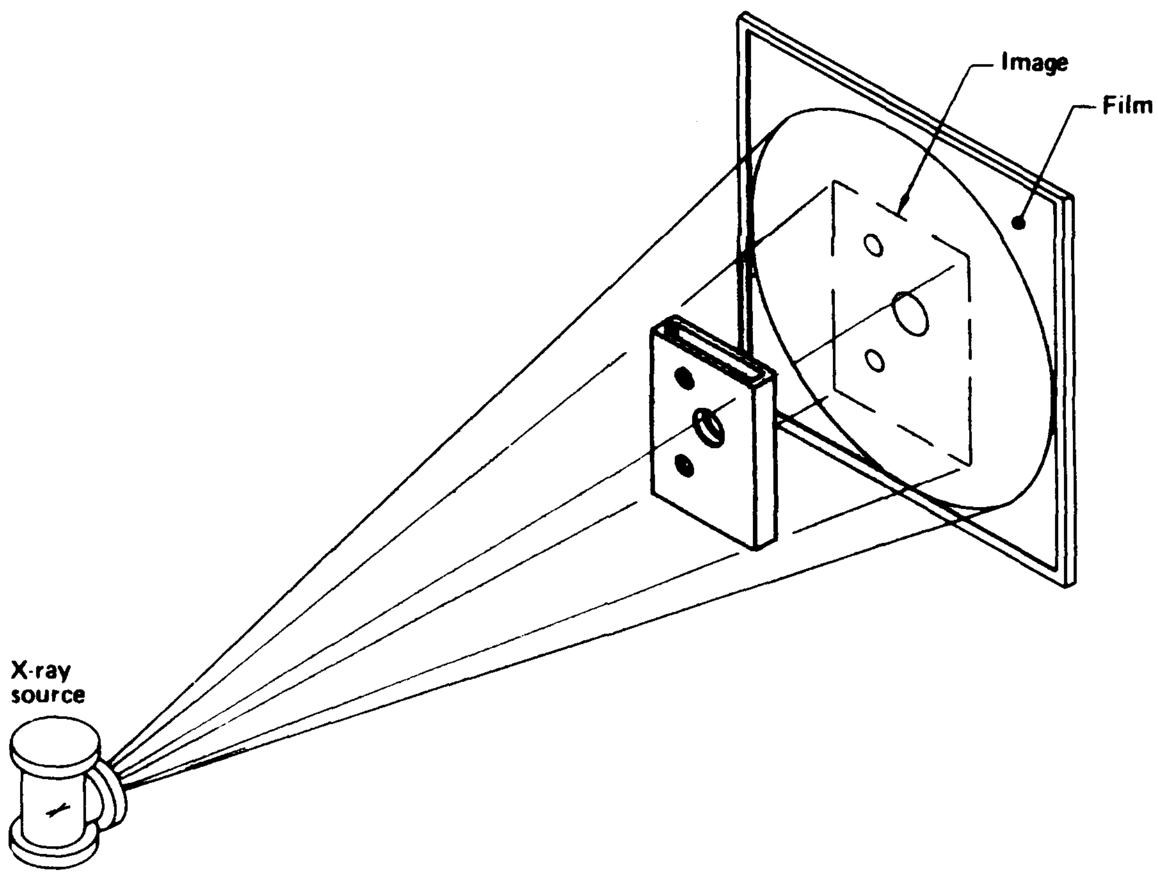

Figure A1-1 Film radiography.

A2 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 casting to be imaged at suitable signal to noise with one scan.

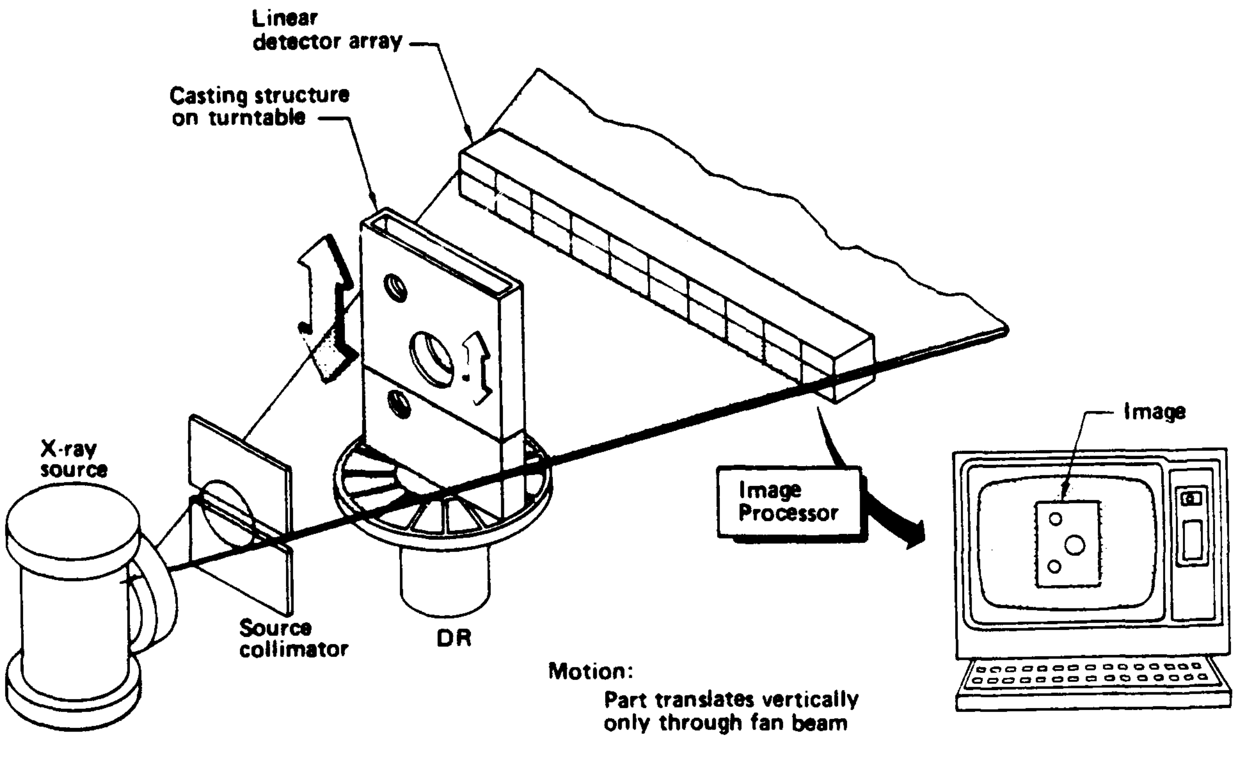

Figure A2-1 Digital radiography.

A3 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, thus making it 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.

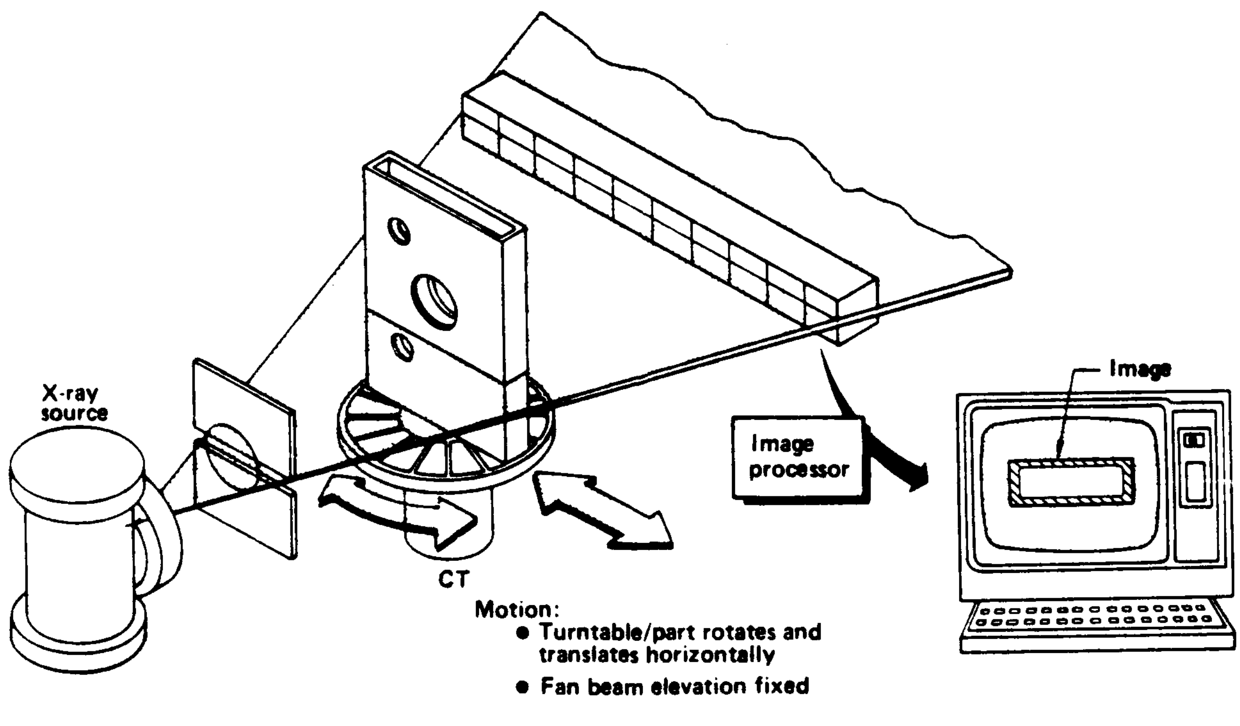

Figure A3-1 Computed tomography.

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.

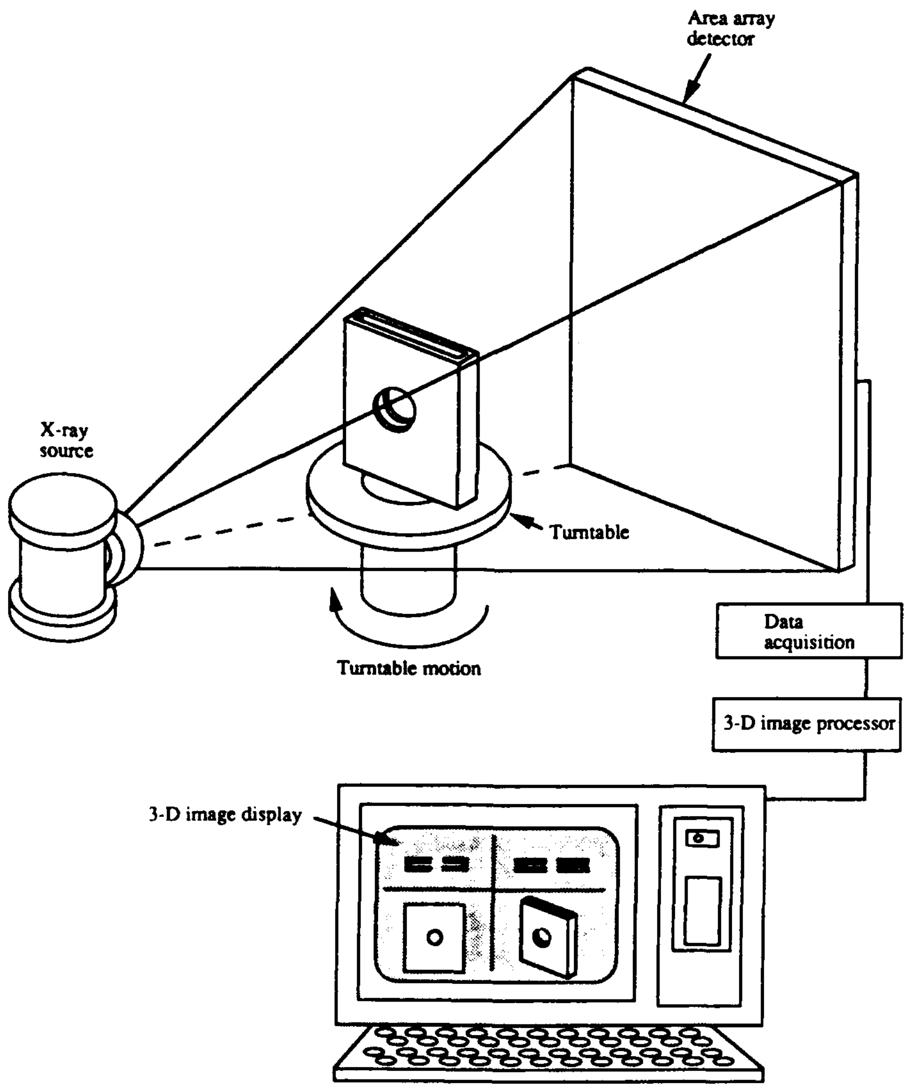

Figure A3-2 Cone beam CT.

APPENDIX B - CT PHANTOMS

A set of CT phantoms was developed for the Advanced Development of X-ray Computed Tomography Applications program in order to provide consistent evaluation of results from various CT systems. The phantoms serve several purposes. First, they provide a quantitative measure of the CT machine capability that can be used repetitively to assure consistent performance. Second, the quantitative measurements can be used in conjunction with part images to assess a quality level necessary to achieve desired detection or measurement levels in the inspected parts. Third, the phantoms can be used to select CT systems based on the desired sensitivity level for the CT application.

The use of phantoms for CT is complicated due to the wide range of parameters in any CT inspection. Therefore, caution must be used in extrapolating phantom data to suggest a "best" overall CT system. In fact, CT systems have varying designs that result in a range of performance characteristics. The phantoms allow the user a quantitative measure of quality level that, combined with other operating parameters, may suggest an optimum system. While the phantoms used in this program measure line pair resolution and contrast sensitivity, there are several other important parameters a user must be concerned with in selecting a machine for scanning: scan time, field of view, object penetration, data manipulation, system availability and cost.

Three basic CT performance phantoms and two dimension measurement phantoms have been constructed. The CT performance phantoms are line pair resolution phantoms, contrast sensitivity phantoms and a density standard phantom. The resolution and contrast sensitivity measurements are fundamental measures of a system. The density measurement is more of a calibration. The dimensional measurement phantoms are of two types: one for general small CT system gap measurements and one for larger CT system wall measurements.

B1 Resolution Phantom

Figure B1-1 shows the line pair resolution phantom. The phantom consists of sets of metallic and acrylic plates of specified thickness. Line pairs of 0.5, 1, 2 and 4 lp/mm are formed by the phantom.

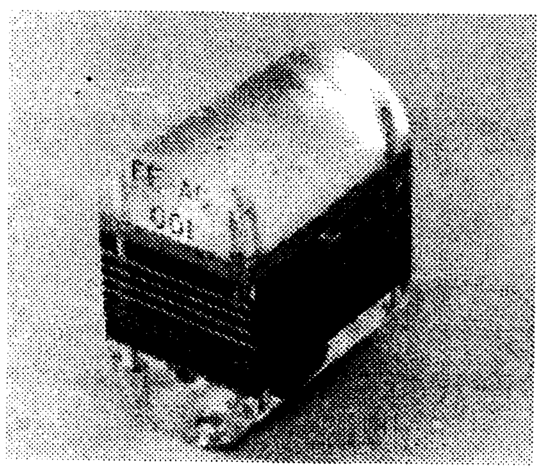

Figure B1-1 **Photograph of the resolution phantom.**

The entire assembly is bolted together, and the line pair plates can be changed if additional or a different range of line pairs is desired. Following CT scanning the reconstructed image is analyzed by measuring the modulation of the CT numbers resulting from a trace across the line pairs. The modulation at each line pair set is measured as a percentage of the modulation, where the modulation measured between the 3 mm (0.12 in) thick metal and 3 mm (0.12 in) thick acrylic steps is 100 percent. Operating parameters such as field of view, slice thickness, integration time and detector collimation will affect the results. It is desirable to obtain data at CT machine parameters that are the same as that used for part scanning. The resolution phantom has been fabricated in two forms: steel/acrylic and aluminum/acrylic. The steel/acrylic phantom is for systems of 300 kVp and up, the aluminum/acrylic phantom is for systems under 300 kVp.

Figure B1-2 shows a CT image of the steel resolution phantom obtained from a high-resolution CT machine. The CT image density contour line across the gauge indicates modulation for the respective line pair measurements at approximately 82 percent at 1/2 lp/mm, 46 percent at 1 lp/mm, 4 percent at 2 lp/mm, and 0 percent at 4 lp/mm.

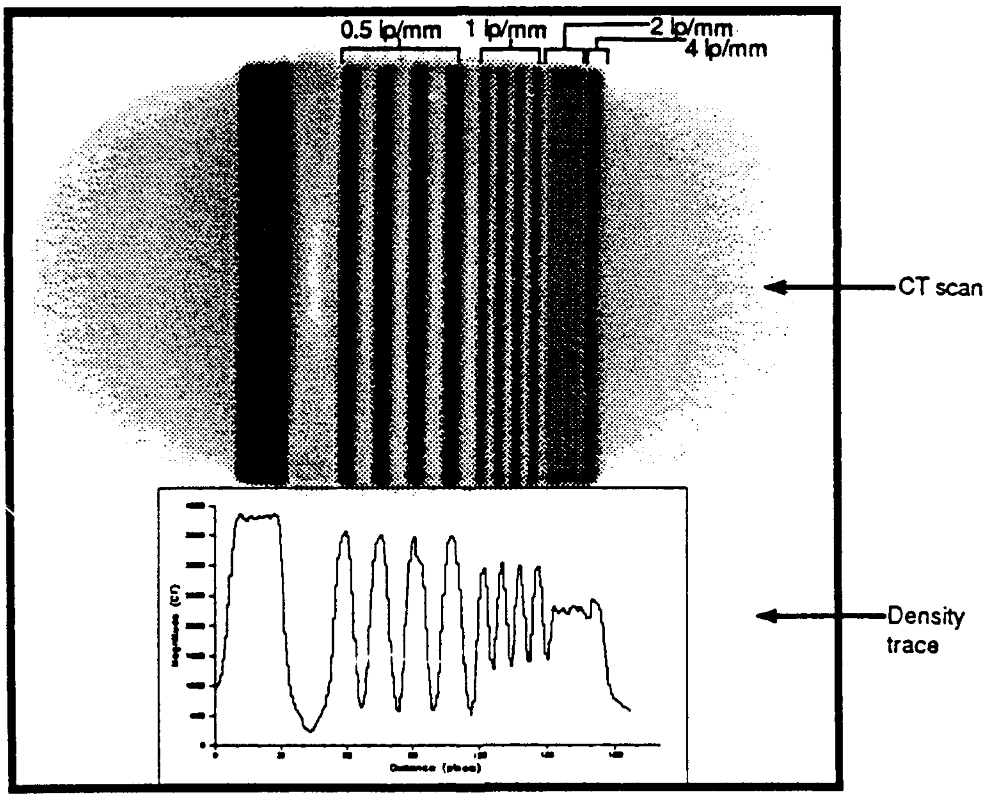

Figure B1-2 CT slice of the resolution phantom.

B2 Contrast Sensitivity Phantom

The contrast sensitivity phantom is a uniform disc of aluminum, 25 mm (1 inch) thick. Two sizes were made: one is 140 mm (5.5 inch) in diameter and the other is 70 mm (2.76 inch) in diameter. The smaller diameter size is used on systems with small fields of view or low kVp. Figure B2-1 shows an example CT slice of the large aluminum contrast sensitivity phantom with the corresponding density trace.

The measurement of contrast sensitivity is obtained by taking a region in the reconstructed image and determining the average and standard deviation for all CT numbers in the region. A typical region size of 1 cm (0.39 inch) diameter is used. Readings are usually taken at the center of the disk. The ratio of the average to the standard deviation is used as a signal-to-noise measurement. The inverse is a measure of contrast sensitivity. The signal to noise measurement for the density trace shown in Figure B2-1 is approximately 6.

The signal-to-noise ratio measurements are an important measure of system performance. The values improve with higher signal strengths. They also improve with smoothing algorithms in the reconstruction; however, this will decrease the resolution. Thus, the signal to noise and resolution must be considered together in assessing a quality level for performance.

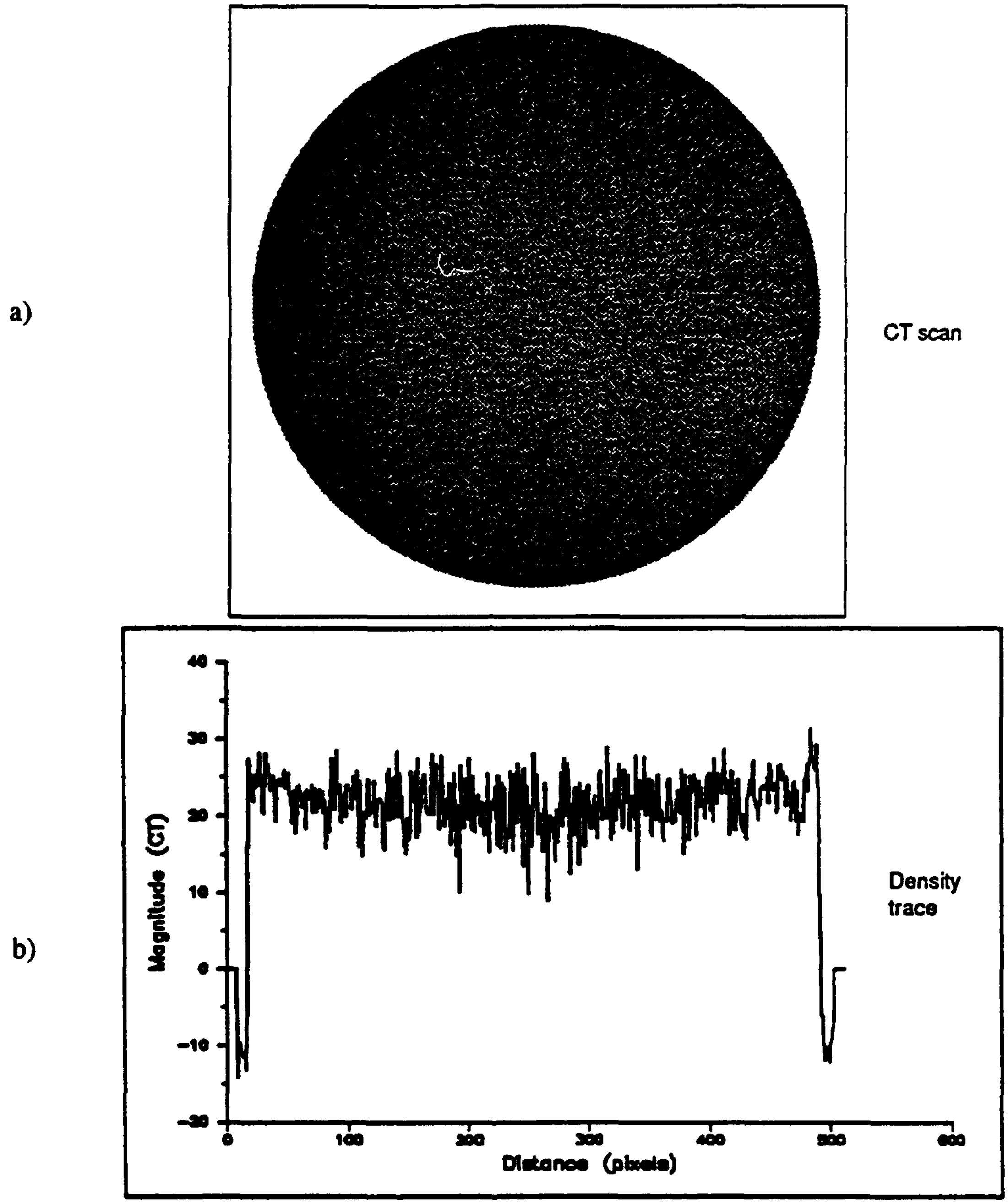

Figure B2-1 CT slice of the contrast sensitivity standard a) image, b) density trace through center.