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X-RAY COMPUTED TOMOGRAPHY FOR CASTING DEVELOPMENT

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Computed tomography (CT) has been used to evaluate specific sand casting product examples for technical and economic benefits. The representative results are applicable to other casting technologies as well. CT has been shown to be cost effective in the development of new castings. The areas which would benefit include internal dimensional measurements (eliminating destructive sectioning), specific region inspections, flaw characterization in critical regions (to allow passing or informed repair of castings), and geometric acquisition for CAD/CAM.

The quantitative capability of CT allows an engineering evaluation of castings based upon a correlation with performance. This quantitative measurement capability has also been used to measure the benefit of hot isostatic pressing in casting production. CT is also cost effective for engineering design and analysis by providing rapid geometry acquisition for input to computer aided design systems. This is particularly beneficial for components that do not have existing drawings or cannot be adequately defined until they are made for any reason.

Presently CT can serve as an engineering aid to casting manufacturing. In order for CT evaluation to become routine in foundry applications, however, casting designers need to call it out as a measurement technique in the original casting deisgn drawings, specifications on the application of CT must be written, contracts must include CT evaluation as a means for accepting casting quality, and lower cost CT systems must be available.

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SUMMARY

Computed tomography (CT) has been investigated as a tool to assist the manufacture of castings. Earlier task assignment activities identified that CT could be cost-effectively utilized in casting manufacturing and in the quantitative analysis of castings, particularly during development. In this report activity CT has been used to evaluate specific sand casting product examples for technical and economic benefits. The representative results are applicable to other casting technologies as well.

CT is a cost effective tool in the development of new product in which internal dimensional measurements or specific region inspection are required. The benefits of eliminating destructive sectioning as a means of inspection have been demonstrated. CT provides flaw characterization capability in critical regions that allows passing or informed repair of castings rejected by qualitative inspection methods. The quantitative capability of CT allows an engineering evaluation of castings based upon a correlation with performance. This quantitative measurement capability has also been used to measure of the benefit of hot isostatic pressing in casting production.

CT is also cost effective for engineering design and analysis by providing rapid geometry acquisition for input to computer aided design systems. This is particularly beneficial for components that do not have existing drawings or can not be adequately defined until they are made for any reason. An example is ergonomically designed castings, such as an aircraft control wheel.

Although CT can be used cost effectively for engineering evaluation of specific casting problems, a number of things need to happen for CT to gain wide acceptance. In order for CT evaluation to become routine in foundry applications, casting designers need to be educated on the value of CT so they can call it out as a measurement technique in the original casting design drawings. Specifications on the application of CT must be written and contracts must include CT evaluation as a means for accepting casting quality. There is a need for lower cost CT systems that can be used in the foundry on the size and types of product manufactured.

ACKNOWLEDGEMENT

The authors acknowledge Sunset Foundry for contributing the castings for this study and providing constructive feedback on the CT results. Thanks are due to Ted Reinhart, Wes Graham, Bob Boeger and Mike Shimmels of Boeing for the cast aluminum tensile specimens and, their material property, die penetrant and radiographic data. Scanning assistance from Scientific Measurement Systems and General Electric is also gratefully acknowledged.

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 computed tomography (CT) can provide a cost-effective means of inspecting aircraft/aerospace components. The program is task assigned so that specific CT applications or application areas can be addressed in separate task assigned projects. Three categories of task assignment 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 final task assignment study on the use of CT for castings. Additional task assignment reports that have been issued by the CTAD program are listed in references 1 through 12.

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. The CT images are maps of the relative linear X-ray attenuation coefficient of small volume elements in the object. The X-ray linear attenuation coefficient measurement is directly related to material density and is a function of the atomic number in the small volume elements. The volume elements are defined by the reconstruction matrix (in combination with the X-ray beam width) and by the effective CT slice height. The CT results can provide quantitative information about the density/constituents and dimensions of the features imaged.

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 12 - CT for Casting Development," was a final testing task directed at evaluating the applicability of CT to assist the product/process development cycle of castings used in the aircraft/aerospace industry. The specific focus was on aluminum sand castings as test examples for employing CT evaluation in various steps of their development cycle. The results from these examples can be extrapolated to other foundry applications. This study utilized the capability of CT to provide quantitative measurements on castings for dimensional and material property evaluation. The study includes an assessment of the economic potential to employ CT in the foundry.

2.0 TEST PLAN

The Task 12 test plan involved working with a local foundry to select castings for study, conducting CT scanning at various stages of manufacture, evaluating the CT data, and assessing the value of the information provided. A scan plan was developed for each component based on its specific requirements, with the goal of determining the capability of CT to provide pertinent information. The CT results for each component were evaluated for both their technical benefit and economic payback potential.

Additionally, a number of casting tensile samples were excised from various Al castings by Boeing for use in a destructive testing program. Some of these samples were provided to the CTAD program for comparative analysis by CT both prior to and after destructive testing. A demonstration of CT as a cost effective tool for computer aided design (CAD) geometry acquisition was conducted using an ergonomically designed aircraft control wheel. At the conclusion of this study, this technical report was written to describe the effort on this task and to summarize the results.

2.1 Component Selection

Several castings were chosen for use in studying CT for product development. Table 2.1-1 lists the castings investigated, which were acquired from Sunset Castings of Kent, WA, a manufacturer of aluminum sand castings. The tensile specimens tested in this task were acquired from the Boeing Allowables Group (after destructive testing) and Boeing Materials Technology (before destructive testing). An ergonomically designed cast flight control wheel used to demonstrate the viability of CT for creating CAD models was obtained from a Boeing Flight Control Group.

Table 2.1-1 Components Selected For Evaluation

PID#	Number of Samples	Description	Purpose of Evaluation
030189	6	Discharge Fitting	Internal dimensional measurement
030184/6	10	Hydraulic Manifold	Characterization of flaw region
030188	6	Flap Control Unit Housing	Evaluation of critical stress region
030187	7	Boeing Allowables	Establishment of CT tensile Ssecimen correlations
030191	30	Boeing Materials Tech.	Establishment of CT tensile specimen correlations

2.2 CT Testing

CT testing was performed at appropriate facilities based on the capability of the systems, the availability and cost. The quality of the CT imaging is not unique to any particular system utilized but in fact should be obtainable by alternative CT systems that have nearly equivalent resolution and contrast sensitivity for the component size under examination. In general the system types are categorized as medium resolution industrial CT (400 kV_{peak}, roughly 1 line pair/mm and 20 to 100 signal-to-noise ratio), high resolution industrial CT (400 kV_{peak}, 2 to 4 line pair/mm and 5 to 20 signal to noise ratio) and medical CT (120 kV_{peak}, roughly 1 line pair/mm and 50 to 150 signal-to-noise ratio).

The example CT image results presented in this report allow the reader to extrapolate the potential of CT on other systems which may provide greater or lesser detail sensitivity. Depending on the features or characteristics that are desired in a material examination with CT it is possible to make trade-offs of resolution and S/N (choosing higher resolution and lower S/N or vice versa) while maintaining sufficient feature sensitivity. In many cases though, high resolution may be the determining factor in providing sensitivity to fine feature details while in other cases high S/N may be the requirement for material consolidation measures. In general, high contrast features such as small voids and inclusions benefit from high resolution imaging while low contrast material variations such as microshrinkage an sponge porosity benefit from high S/N.

In most cases for the casting evaluations a CT IQI was employed. The CT Image Quality Indicator (IQI) has been discussed in earlier reports [7,8]. The IQI provides a visual indication in the image of the sensitivity to small voids.

2.3 Data Evaluation

Data evaluation of the CT results on the casting components primarily consisted of assessment of the detail sensitivity to features of interest and the usefulness of that information to the casting manufacturer. In some cases comparison with destructive testing was made.

All the CT systems used on this program displayed their data information on a high-resolution video terminal but hard copy image reproduction techniques varied. Image quality in this report is necessarily reduced (often significantly) from original image displays because of the reproduction process.

The nature of the CT data allows for a quantitative measure of features in terms of dimensions and X-ray attenuation. Dimensional measurement can be made directly on the CT image display or the data transferred to a computer aided design/computer aided manufacturing (CAD/CAM) workstation. In addition to dimensional measurement on some cast products, the CT image value mean and standard deviation on individual scans of the cast tensile specimens were measured. Although X-ray linear attenuation would not be expected to be directly related to microstructural strength of materials, measurement of the variability in the X-ray attenuation coefficient from CT can be used to establish uniformity and under certain conditions can be correlated to performance measurements.

A full 3-D set of CT scans can be used to create a complete model of a component. The CT data can be conditioned by appropriate edge finding routines and the data transferred into a CAD/CAM system. This data can be further reduced to contours, and a wireframe model for CAD manipulation and part drawings can be created.

3.0 CT FOR PRODUCT DEVELOPMENT

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 nondestructive evaluation (NDE) technique selection. A fabrication process is selected, and test castings are then made which are nondestructively and destructively inspected to establish the optimum manufacture method. 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. The iterative cycle of modifying the casting mold design, casting and testing to arrive at a suitable product costs time as well as money.

Computed tomography provides feature location and geometry information which can be extremely useful to establish the dimensional measurements tolerances and any defect location in three dimensions. This information has economic value as an alternative to comprehensive measurements on castings that may require destructive sectioning. Computed tomography aids in the reduction of the iterations required to achieve the optimum product by providing the casting engineer with greater insight into defect position and orientation, and dimensional measurements.

The following sections discuss three examples which demonstrate the possibilities of using CT. The examples are all aluminum sand castings, but the results can be applied to other metals and casting processes. The CT systems of course that would be used to accommodate potential castings other than the aluminum examples, may vary in physical size and X-ray penetration for the density of product that can be evaluated.

3.1 Discharge Fitting, PID# 030189

An aircraft discharge fitting manufactured by Sunset Foundry is an excellent example of the usefulness of CT for dimensional measurements in castings. A completed fitting is shown in Fig. 3.1-1. This fitting, like many castings, has specified internal dimensional tolerances which cannot normally be measured without destructive sectioning of the part. Thus, "good" castings must inevitably be destroyed in order to obtain the required information during both the development and production phases.

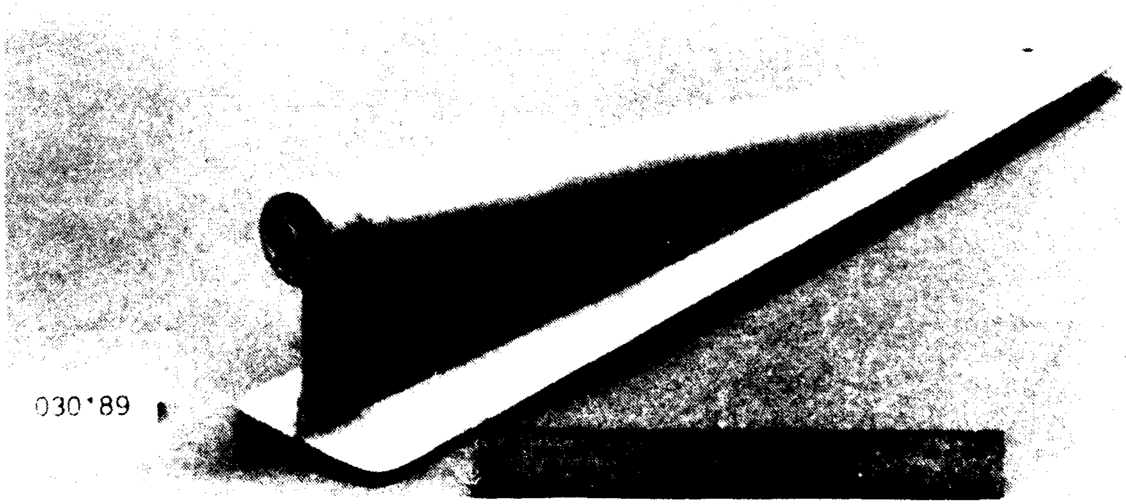


Figure 3.1-1 Photograph of a cast aluminum discharge fitting.

CT evaluation was utilized to help establish the manufacturing process for the discharge fitting casting. CT scanning and analysis was performed on the first and second articles, as well as subsequent articles which did not pass radiographic inspection. Figure 3.1-2 is a digital radiograph of the first fitting that was cast, showing the locations (at the vertical white lines in the image) where the specifications require internal measurements. Normally, destructive sectioning would be performed at these locations, and the measurements would be made with a micrometer after the excess material around the saw cut is ground off. Alternatively, a CT slice was at each location. Both industrial and medical CT systems were compared for cost and technical benefits.

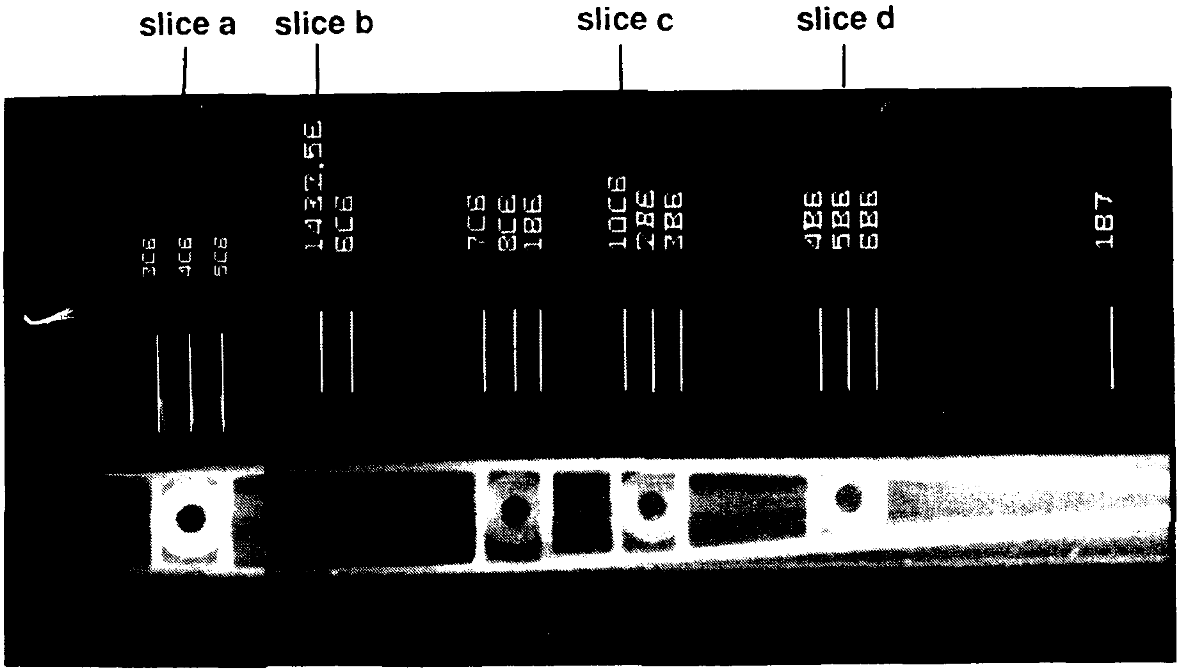


Figure 3.1-2 Digital radiograph of a cast aluminum discharge fitting.

Figure 3.1-3 shows several of these slices taken on a high resolution (2 to 4 lp/mm) industrial CT system. All the required measurements (as indicated in Figure 3.1-2) could be made right from the video monitor using software developed for this purpose. The dimensional information provided was more precise than required, and allowed the foundry engineers to bypass destructive sectioning for this part as part of their development cycle. The CT information showed that several internal dimensions were out of tolerance due to manufacturing problems (core shifting and/or warping), and changes were made in the process to eliminate these problems.

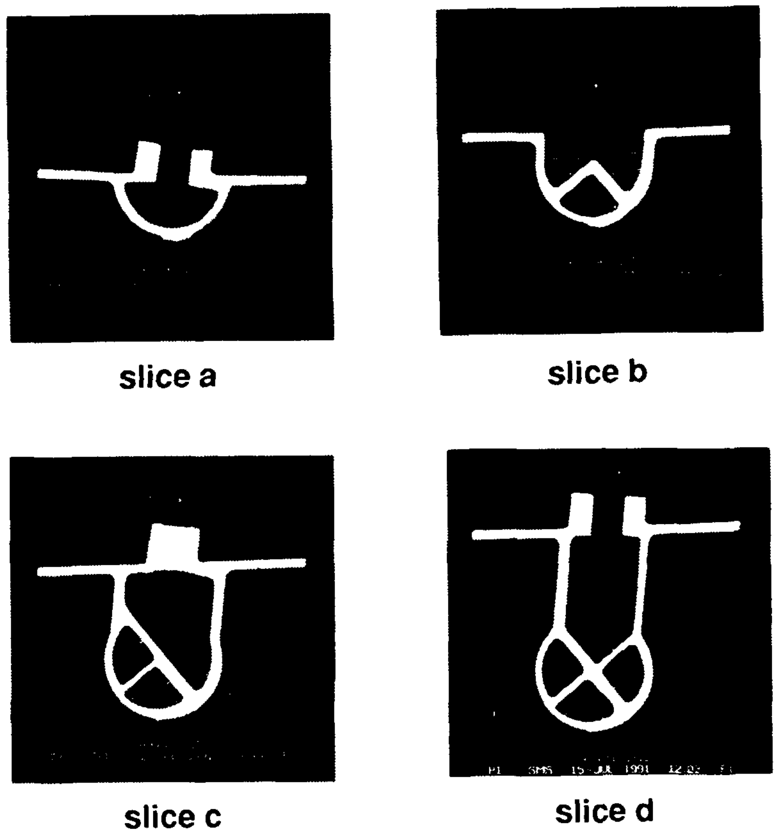


Figure 3.1-3 Series of CT slices through the discharge fitting.

In order to verify the accuracy of the CT measurements, destructive sectioning and subsequent dimensional measurement were done on the first article as part of this study. Figure 3.1-4 is a photograph of the fitting, showing the locations where it was sectioned. Normally, internal measurement of the fitting dimensions would require more than fifteen cuts. Figure 3.1-5 shows the cross-sections of individual pieces of the fitting along with several CT images taken at the locations sectioned. The wall dimensions measured with CT and a micrometer are listed in Table 3.1-1. The micrometer measurements were taken several times at each location and averaged because variations in the measurement, greater than 0.25 mm (0.010 inch), can occur because to the differences in the position and orientation of the micrometer relative to the fitting wall. The measurements show excellent correlation between CT and physical measurement. The differences are nearly all with 0.25 mm (0.010 inch). CT internal dimensional measurements along the length of the fitting were used in the first article report for the discharge fitting casting.

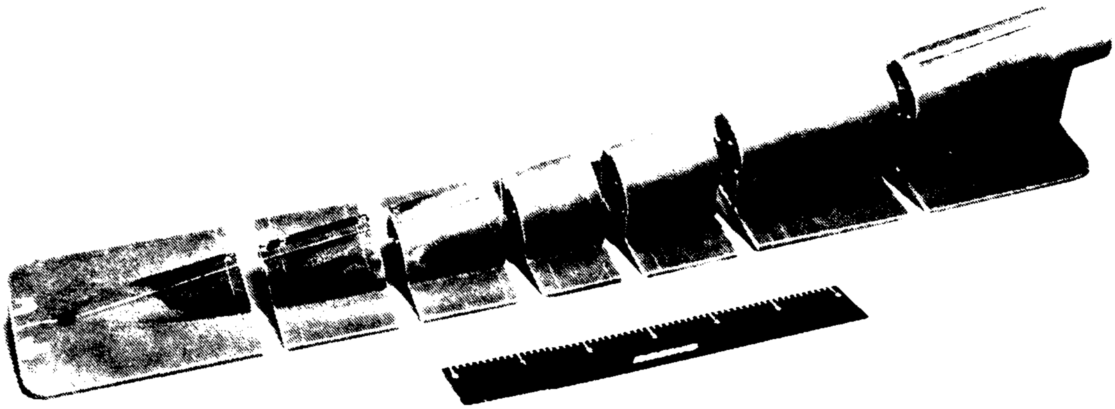
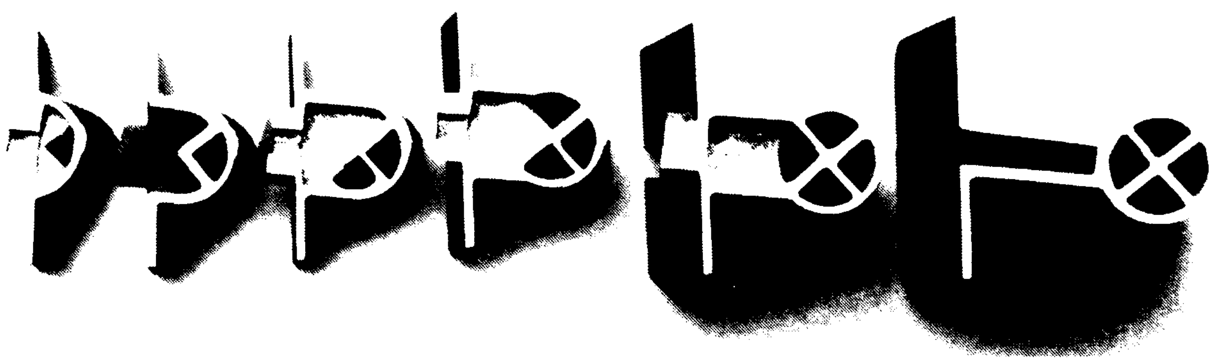


Figure 3.1-4 Photograph of the sectioned discharge fitting.

(a)



(b)

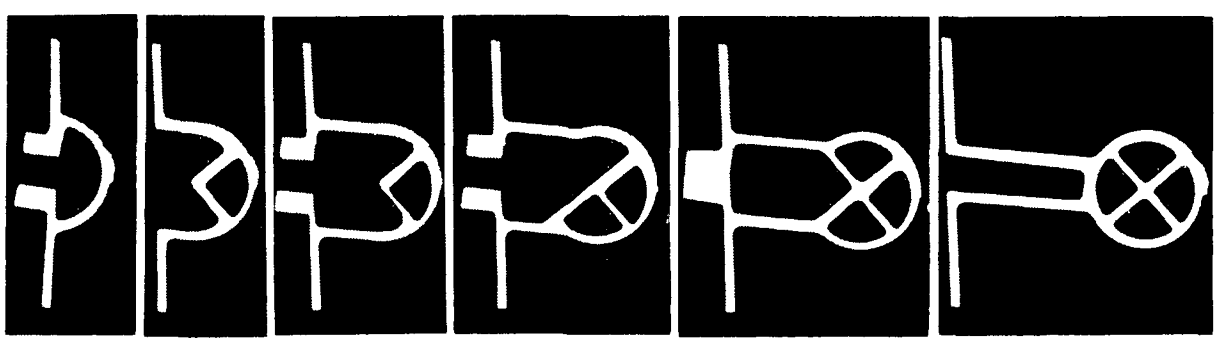


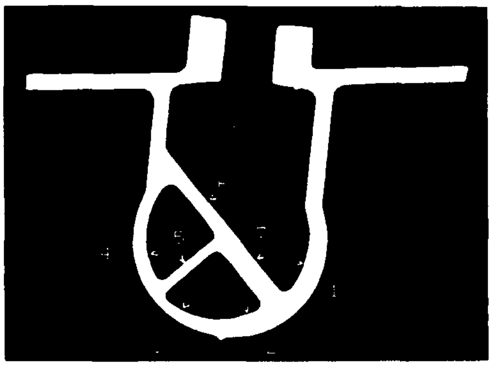
Figure 3.1-5 Discharge fitting a) photograph of sections of the discharge fitting and b) CT slices of corresponding to several sections.

Table 3.1-1 Discharge Fitting Dimensional Measurements

Part ID	Position	CT Measurement		Physical Measurement		Difference	
		(mm)	(inch)	(mm)	(inch)	(mm)	(inch)
4C6	1	2.43	0.0957	2.51	0.0987	-0.076	-0.0030
	2	2.51	0.0988	2.47	0.0973	0.038	0.0015
	3	2.75	0.1083	2.79	0.1097	-0.036	-0.0014
6C6	1	3.36	0.1323	3.58	0.1408	-0.217	-0.0085
	2	2.91	0.1146	3.05	0.1200	-0.138	-0.0054
	3	1.86	0.0732	1.98	0.0780	-0.121	-0.0048
	4	1.95	0.0768	2.01	0.0790	-0.057	-0.0022
	5	2.54	0.1000	2.83	0.1113	-0.286	-0.0113
	6	2.55	0.1004	2.63	0.1037	-0.083	-0.0033
	7	3.21	0.1264	3.32	0.1307	-0.109	-0.0043
8C6	1	2.99	0.1177	3.23	0.1270	-0.236	-0.0093
	2	2.93	0.1154	3.30	0.1298	-0.368	-0.0145
	3	1.91	0.0752	2.21	0.0868	-0.296	-0.0116
	4	2.69	0.1059	2.78	0.1093	-0.087	-0.0034
	5	1.38	0.0543	1.62	0.0638	-0.241	-0.0095
	6	2.99	0.1177	3.01	0.1185	-0.020	-0.0008
2B6	1	3.07	0.1209	3.11	0.1225	-0.041	-0.0016
	2	3.32	0.1307	3.49	0.1373	-0.168	-0.0066
	3	1.91	0.0752	2.16	0.0850	-0.249	-0.0098
	4	2.25	0.0886	2.29	0.0900	-0.036	-0.0014
	5	1.64	0.0646	1.73	0.0682	-0.091	-0.0036
	6	2.17	0.0854	2.26	0.0890	-0.091	-0.0036
	7	3.31	0.1303	3.39	0.1333	-0.077	-0.0030
4B6	1	2.46	0.0969	2.51	0.0990	-0.055	-0.0021
	2	2.94	0.1157	3.06	0.1205	-0.121	-0.0048
	3	1.89	0.0744	2.11	0.0830	-0.218	-0.0086
	4	1.95	0.0768	2.02	0.0795	-0.069	-0.0027
	5	1.88	0.0740	1.99	0.0782	-0.105	-0.0042
	6	2.83	0.1114	2.84	0.1120	-0.015	-0.0006
	7	1.79	0.0705	1.82	0.0718	-0.035	-0.0014
	8	2.66	0.1047	2.58	0.1015	0.082	0.0032
1B7	1	3.05	0.1201	3.10	0.1221	-0.051	-0.0020
	2	3.07	0.1209	3.20	0.1262	-0.135	-0.0053
	3	2.09	0.0823	2.15	0.0847	-0.061	-0.0024
	4	2.41	0.0949	2.49	0.0982	-0.083	-0.0033
	5	3.06	0.1205	3.13	0.1234	-0.074	-0.0029
	6	1.84	0.0724	1.94	0.0765	-0.103	-0.0041
	7	2.5	0.0984	2.54	0.1002	-0.044	-0.0017
	8	2.25	0.0886	2.37	0.0932	-0.116	-0.0046
	9	2.34	0.0921	2.40	0.0943	-0.056	-0.0022

Following the CT data analysis on the first article, a second prototype was cast, which was again CT scanned and analyzed. The information from the analysis of the second fitting was used to make final adjustments for the production castings. Slight changes were made in the mounting of the cores which produced the internal passageways in the fitting. Because of CT, destructive sectioning of the part was not required. At this point, production runs were made, and the fittings were delivered. Though it was not done in this case (and it was not contractually required), CT could have been used as a quality assurance tool to verify the dimensions of the final product on all or a selected number of the delivered fittings.

The cost of CT evaluation can vary greatly depending on the selection of the CT system and method of scanning. The scanning time per article and amortized CT system cost are the driving factors. Figure 3.1-6 shows a CT image from a high resolution industrial system along side one from the medical system taken at the same location. The first article examination on a medical scanner provided sufficient resolution for the required dimensional measurements. This result is important because medical CT is much faster and can be less expensive than industrial CT, and therefore can be more cost effective if it does the job satisfactorily. Cost can also be reduced by simultaneous scanning several parts at the same time, provided the scanner has a large enough field of view and sufficient X-ray penetration. Figure 3.1-7 is a CT slice of four discharge tubes scanned at the same time on a medium resolution CT system. The purpose of the scan was to determine if multiple components could be scanned without reducing the resolution required for accurate measurements. The results demonstrated that simultaneous scanning can reduce evaluation costs and provide sufficient measurement accuracy.

a) 

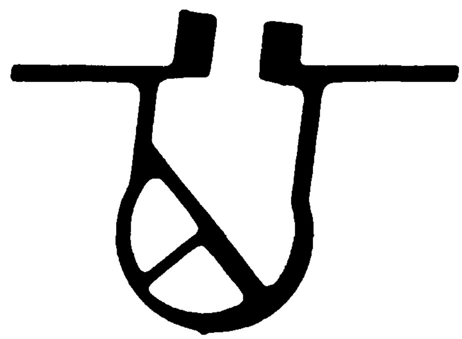
b) 

Figure 3.1-6 CT image of discharge fitting from a) industrial CT system b) medical CT system.

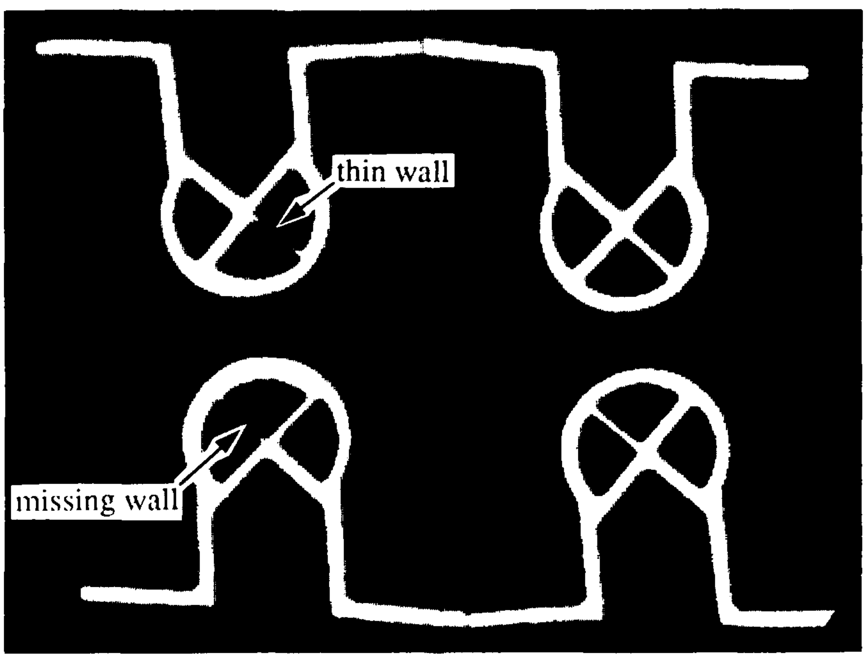


Figure 3.1-7 Multiple discharge fittings evaluated in a single CT scan from a large field of view industrial CT system.

3.2 Hydraulic Reservoir Manifold, PID# 030184,6

The need often arises for the evaluation of a particular region of a casting because of a high incidence of manufacturing flaws in that region. This is a very common problem when a new casting is being developed, requiring an iterative cycle of manufacturing and testing. The cycle involves identifying and evaluating flaws, so that the process can be altered or refined to eliminate them in succeeding castings. An area that tends to have a high incidence of defects can be labelled a "critical inspection" region and the elimination of the defects in that region becomes the highest priority in the production of the casting. By default, it becomes the region of interest to the casting manufacturer. CT evaluation of these selected areas is less costly and time consuming than evaluation of the entire part, and can provide information that cannot be obtained through other inspection methods.

An hydraulic reservoir manifold is shown in Figure 3.2-1. The manifold is a complex aluminum sand cast component that is not easily inspected with standard radiographic methods. The first manifolds that were cast in the product development cycle contained flaws in a particular region. There was a tendency in the manifolds to have small voids in the region indicated by the arrow in Figure 3.2-1.

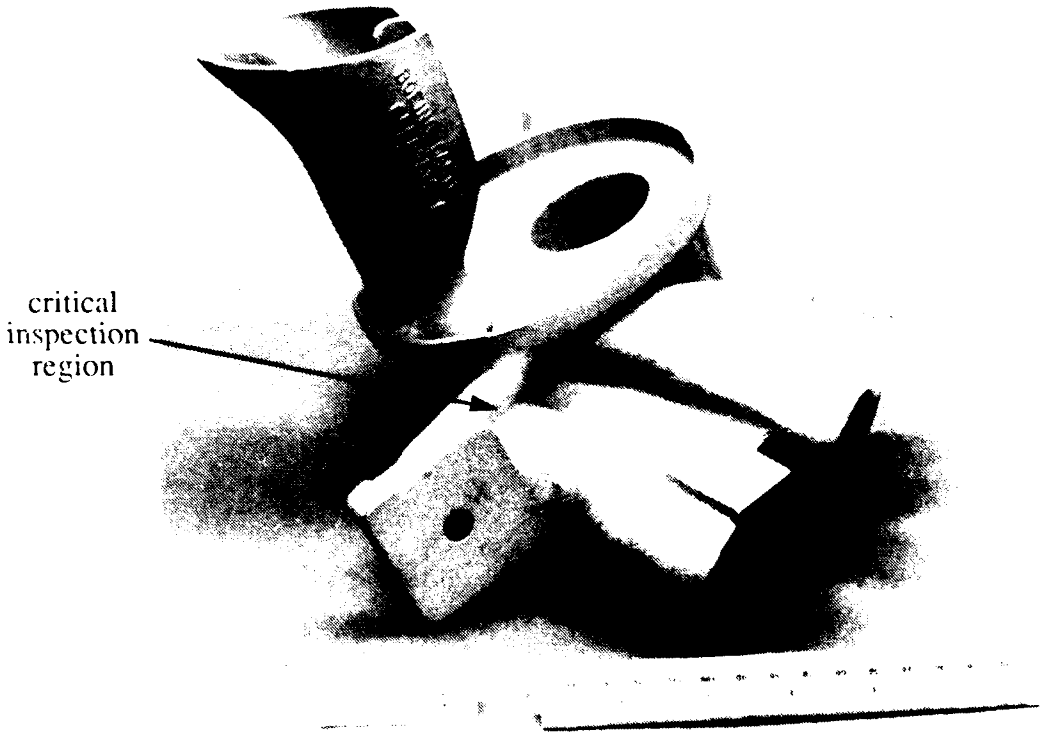


Figure 3.2-1 Photograph of an hydraulic manifold casting.

Figure 3.2-2 is an image produced from a film radiograph of a manifold. The complexity of this casting does not allow an adequate evaluation with film radiography, particularly in interior regions. A superior approach is to utilize the capability of a CT system. A digital radiograph (DR) from the CT system can be used to provide a general radiographic examination of a component and to select the best locations for CT slices. The DR can provide a higher dynamic range image than a single film. This allows the adjustment of viewing intensity to optimize the evaluation of all regions of the casting.

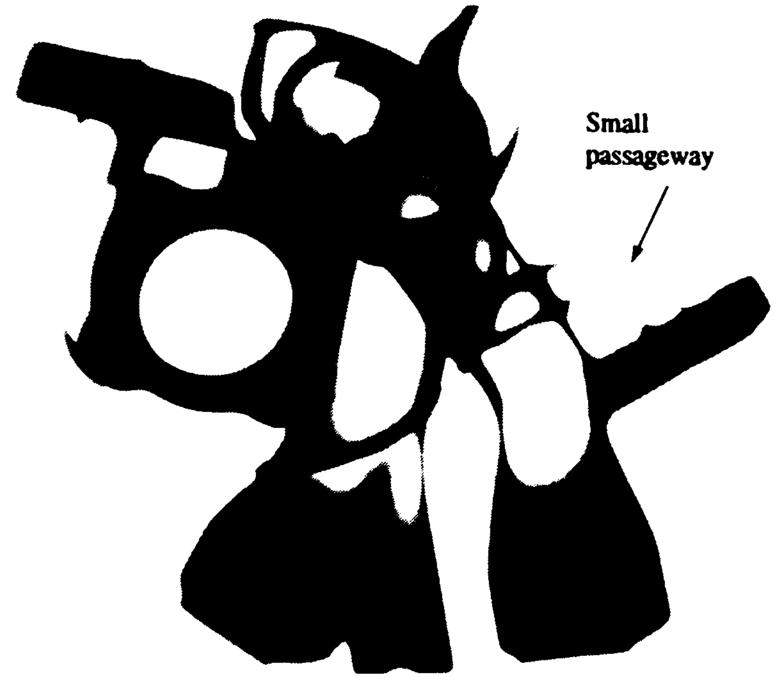


Figure 3.2-2 Print from a film radiograph of an hydraulic manifold casting.

Table 3.2-1 lists the individual manifold castings evaluated with CT in this study, and where in the casting process they were scanned. CT scanning was performed on four just-cast manifolds (030184A-D) to evaluate the critical region and to provide a dimensional measurement of the wall thickness in a small passageway in the same region. The CT evaluation was able to verify proper core placement for this passageway and to provide a quantitative measure of the porosity in the critical region. Each of the manifolds showed low levels of porosity in the region examined. It was expected that the hot isostatic pressing (HIPping) process of these castings (as part of their manufacture) would reduce this level of porosity.

Table 3.2-1 Manifold Castings Studied

Manifold PID#	Process Stage	CT Evaluation Results	Benefits Provided By CT Evaluation
030184A 030184B 030184C 030184D	Just Cast	small porosities large porous region out of tolerance small porosities	Eliminated dead-end costs with manifolds B & C
030184E 030184F 030184G 030184H	Ground	small porosities small porosities small porosities small porosities	Define material quality in critical region before next process step
030186A 030186B	Sandblasted	flaw in tube defined flaw in tube defined	Allows for informed assessment for repair
030184F 030184G 030184H	Post Hipped	reduced porosity, new void reduced porosity reduced porosity	Identifies potentially critical flaw Quantifies process step

CT analysis of manifold 030184B indicated that there was an anomalous region (approximately 10x5x5mm) between the two largest channels. The region appeared to be less dense than the surrounding material, and it was postulated to be a region of sponge porosity. Because of the apparent defect, the casting was pulled out of production, ground, sandblasted, and radiographed. The anomaly did not appear in the radiograph. The casting was then destructively sectioned so that a 30 mm (1.18 in) section containing the apparent defect could be evaluated. Figure 3.2-3 is a CT image of one of the slices taken through this area. The casting was then sectioned at the location of the anomaly so that it could be verified visually. Figure 3.2-4 is a photomicrograph of the anomaly region which shows the presence of the defect.

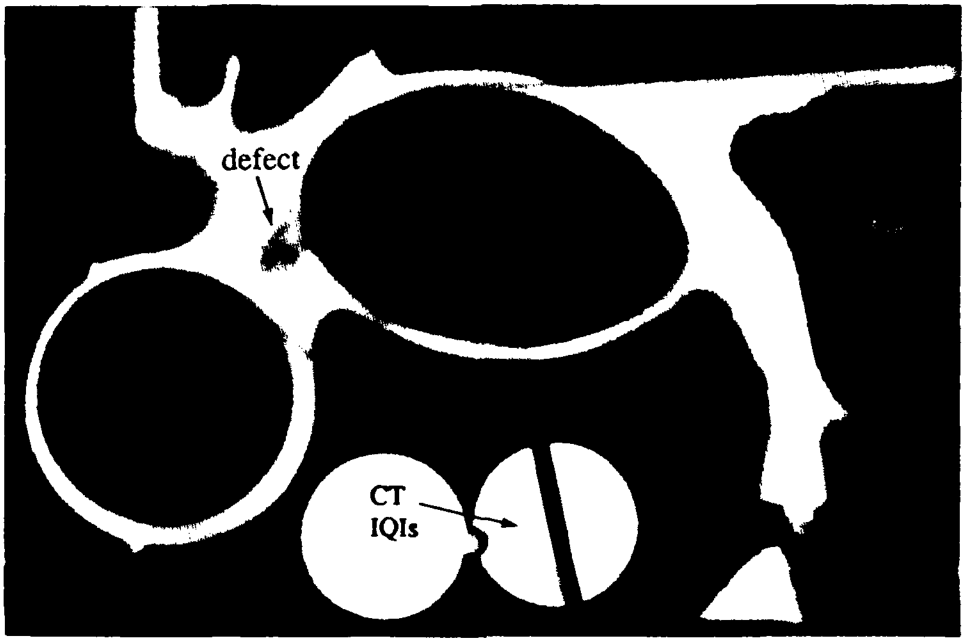


Figure 3.2-3 CT image of a section of the hydraulic manifold casting.

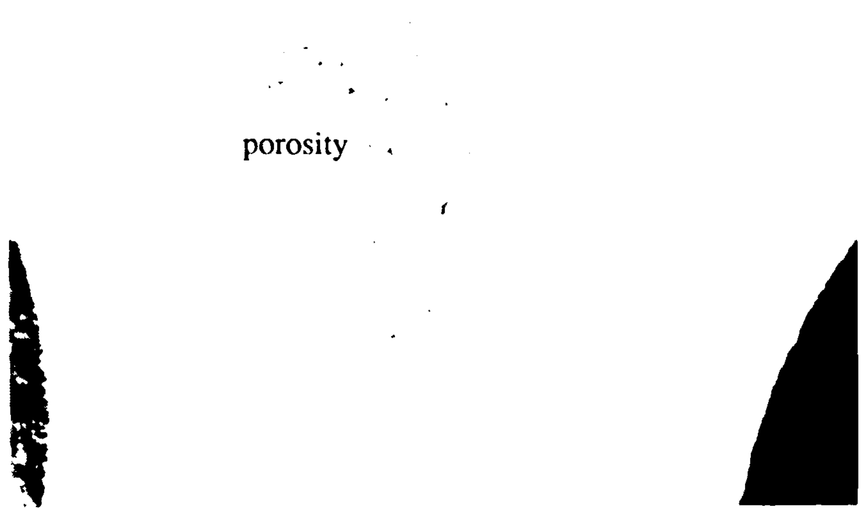


Figure 3.2-4 Photomicrograph of the anomaly region of the hydraulic manifold casting.

In the case of manifold casting 030184C, the wall thickness in the small tube was out of tolerance. The manifold was taken out of the production line before any more work was done on it. The information provided by CT eliminated the additional costs associated with completing the manufacture of this casting.

Four other manifolds (030184E-H) were examined with CT after they were "cleaned up" with a grinder to remove much of the excess material associated with the sand casting process. Film radiography requires such surface preparation for best sensitivity. CT is not necessarily affected by the as cast, unground state, so this evaluation could be performed earlier in the product cycle. Each of these manifolds showed low levels of porosity similar to the other manifolds in the region examined. Figure 3.2-5 is an example of one of the CT images taken of manifold 030184-H. In this study, the evaluation of the castings at the ground stage provided baseline data for the effect of HIPping on the casting quality.

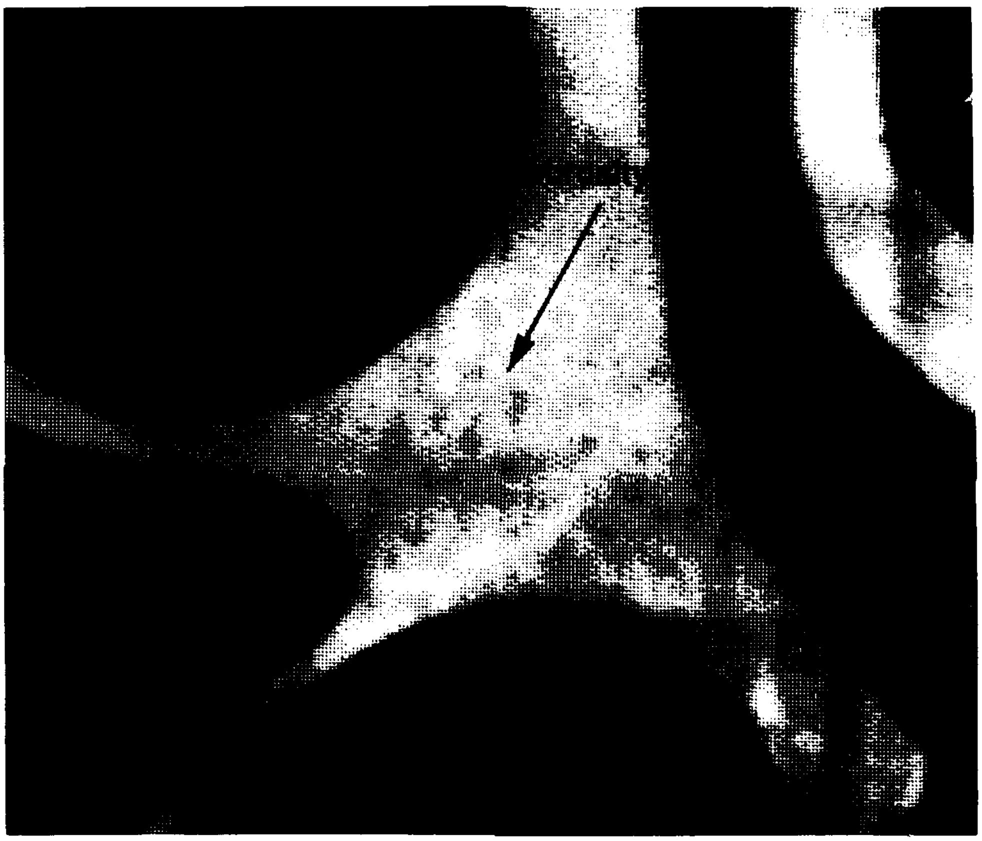


Figure 3.2-5 CT image taken from manifold 030184-H.

Two manifolds (030186A,B) were examined with CT after they had been ground, sand blasted, and film radiographed in final inspection. Radiography revealed small defects in both of these castings in the small passageway shown in Figure 3.2-2. Two CT slices of manifold 030186A are shown in Figure 3.2-6. The slices were taken perpendicular to one another, and reveal the size, shape, and exact location of the void in the passageway. Similar CT data were obtained for manifold 030186B. In general, the benefit of CT for these castings over film radiography is that CT can quantify anomalies that can often only be indicated qualitatively by radiography. In this case, the defects could not be repaired, and the castings had to be rejected. In many cases, however, regions with anomalies or defects can be successfully weld repaired with the help of CT data.

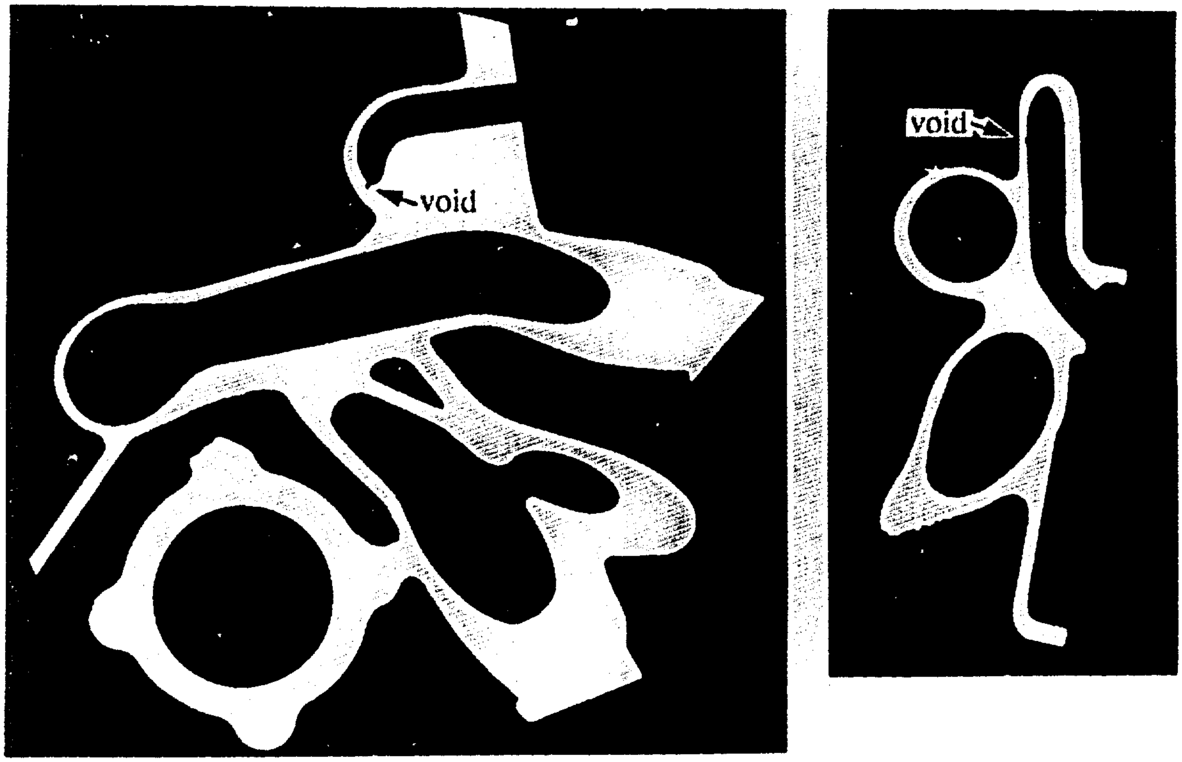


Figure 3.2-6 Two CT slices of manifold 030186A taken perpendicular to one another to evaluate the defect region.

Manifolds 030184F-H were CT evaluated before and after being subjected to the HIPping process. A comparison of pre- and post-HIPped manifolds revealed that the HIPping process greatly reduced the porosity in the critical region in these castings. The CT data in a 20-mm (0.8 in) thick section of the region was analyzed before and after HIPping. Table 3.2-2 lists the mean and standard deviation of the CT values (relative linear X-ray attenuation coefficients) before and after HIPping in all three manifolds. These values were measured by taking region-of-interest statistical measurements of the CT values in the area between the large passageways (area where the porosity was identified in the pre-HIPped castings). The level of the mean indicates how dense a casting is at the location scanned, and the standard deviation is a measure of the uniformity of the density at the same location. A highly porous material will have a low mean CT density and a high standard deviation

Table 3.2-2 CT Evaluation of HIPped Manifold Castings

	Before HIPping		After HIPping	
Manifold "F"				
Slice	CT mean	CT STDEV	CT mean	CT STDEV
2	658	11.2	660	7.0
4	655	8.5	662	9.4
6	649	11.5	662	7.4
8	648	9.7	663	7.2
10	645	9.3	660	9.0
12	638	8.8	657	9.6
14	636	9.0	656	10.8
16	635	11.0	659	8.8
18	641	10.8	666	7.3
20	634	12.4	664	11.0
Manifold "G"				
2	651	9.2	657	10.7
4	646	9.4	661	7.7
6	638	8.0	663	7.3
8	637	9.3	661	8.2
10	633	10.3	657	9.6
12	633	12.2	656	11.0
14	640	11.0	661	8.4
16	631	6.9	666	6.5
18	632	9.5	666	9.3
20	627	9.4	656	8.2
Manifold "H"				
2	656	11.0	663	8.4
4	656	9.6	666	6.2
6	656	9.2	665	7.4
8	652	9.6	662	8.9
10	647	10.7	660	9.8
12	644	10.1	660	10.7
14	643	9.5	664	8.6
16	646	7.7	667	6.1
18	641	9.4	660	7.9
20	640	6.5	657	6.8

Figures 3.2-7 through 3.2-12 show the Table 3.2-2 results in graphic form for the three examples. In general, the mean CT value increases and the standard deviation of the CT values decreases because of the HIPping process. The width of each casting (and therefore the amount of material at that location) decreases from left to right on each graph. The increase in density (reduction in porosity) was greater for the thinner areas than the thicker.

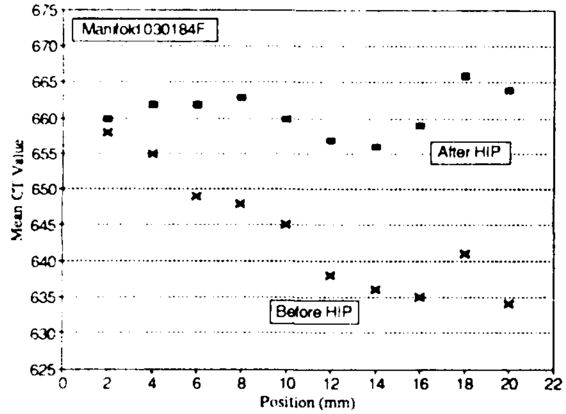


Figure 3.2-7 Graph of CT value versus position for manifold 030184F

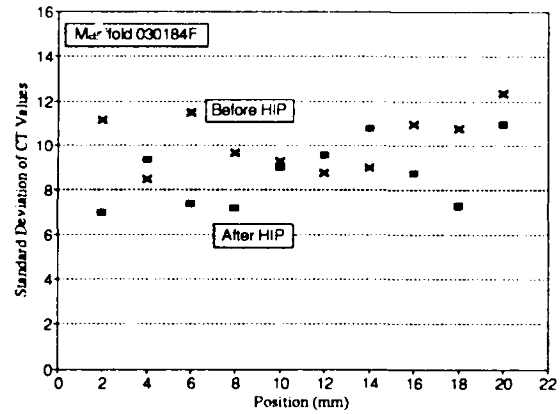


Figure 3.2-8 Graph of CT standard deviation versus position for manifold 030184F.

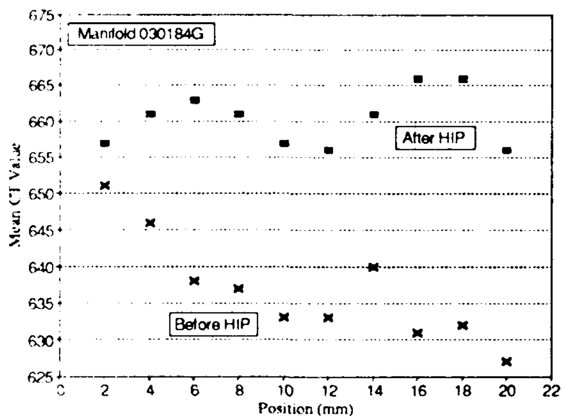


Figure 3.2-9 Graph of CT value versus position for manifold 030184G.

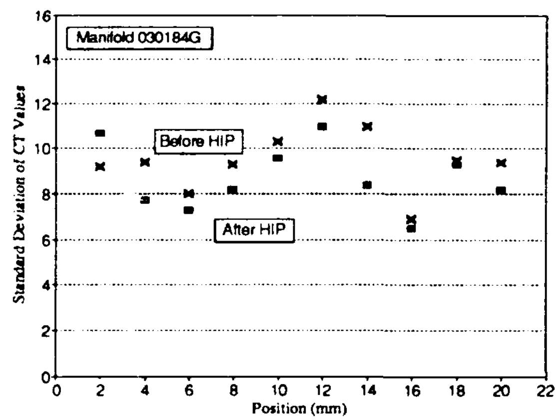


Figure 3.2-10 Graph of CT standard deviation versus position for manifold 030184G.

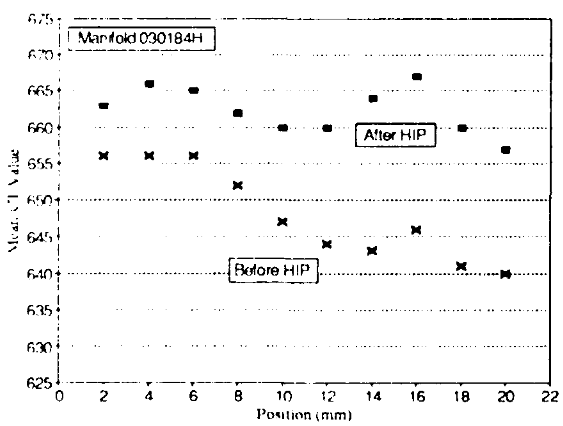


Figure 3.2-11 Graph of CT value versus position for manifold 030184H.

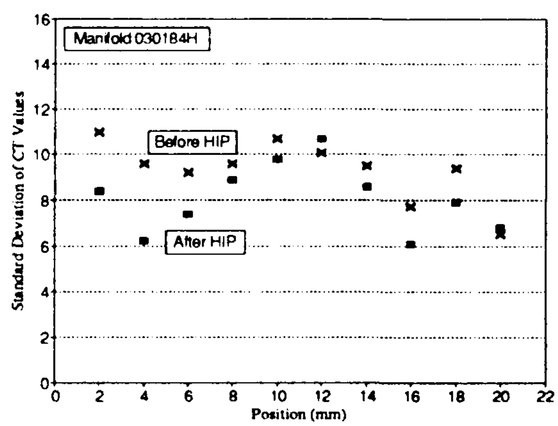


Figure 3.2-12 Graph of CT standard deviation versus position for manifold 030184H.

The CT data obtained before and after HIPping allows the examination of the migration of porosity due to this process. Besides measuring the mean and standard deviation in regions of interest on each CT slice, each set of images were evaluated before and after for qualitative changes. In manifold 030184F the HIPping process reduced the overall porosity in the region examined, but produced a single, larger void. This void is most likely due to the repreceipitation of hydrogen gas, during post-HIP treatments, which coalesces into gas bubbles in the aluminum [14]. Figure 3.2-13 is the CT image of the post-HIPped casting that contains the void, which was not in the CT slice (or adjacent slices) of the pre-HIPped casting. This void is located near a thin wall where it could be of concern.

Figure 3.2-13 CT image of manifold 030184F showing the void that appeared after HIPping.

The CT evaluation of this product cycle not only allowed us to quantify the effects of the HIPping process, but also called out attention to this potential drawback of HIPping. Several general trends are clear from these CT results, (a) HIPping of these castings significantly reduces their porosity (increase of 2-5% in overall material density in the region examined) and increases their uniformity, (b) the effectiveness of HIPping is inversely proportional to the amount of material at any given location (since HIPping produces diffusion of gas bubbles out of a casting under high temperature and pressure, one would expect it to be thickness dependent), and (c) if the pores are filled with a gas that does not dissolve easily in the alloy, HIPping can cause the coalescence of small voids into larger ones or produce the migration of voids to more critical locations.

3.3 Flap Control Unit Housing, PID# 030188

Regions of a casting that are expected to "see" critical stresses often require more thorough inspection than the rest of the casting. It was concluded in an earlier report [7] that CT could provide thorough inspection of critical regions of a component. The flap control unit housing is an excellent example of a casting with a critically stressed region. It was chosen to determine whether or not CT would be effective in improving the process development of such a casting.

Six flap control unit housings were pulled from the production line to be evaluated with CT. Each of the six control unit houseings required weld repair in one or more locations on the casting to repair visual defects. Figure 3.3-1 is a photograph of one of the housings. The critically stressed region, as called out on the engineering drawing, is the raised "H" section on the top of the housing. This region has requirements for interior wall thickness. A series of CT scans were taken through this section to look for manufacturing defects such as thin walls and shrinkage porosity. Figure 3.3-2 is an example of one of the scans, showing a cross section of the critically stressed region. When appropriate, CT scans were also taken through the regions called out for weld repair in order to assess the extent of the defects.

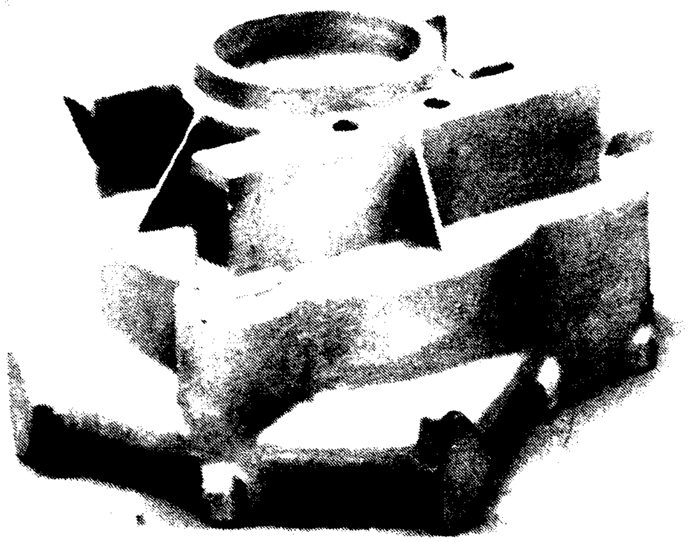


Figure 3.3-1 Photograph of a flap control unit housing.

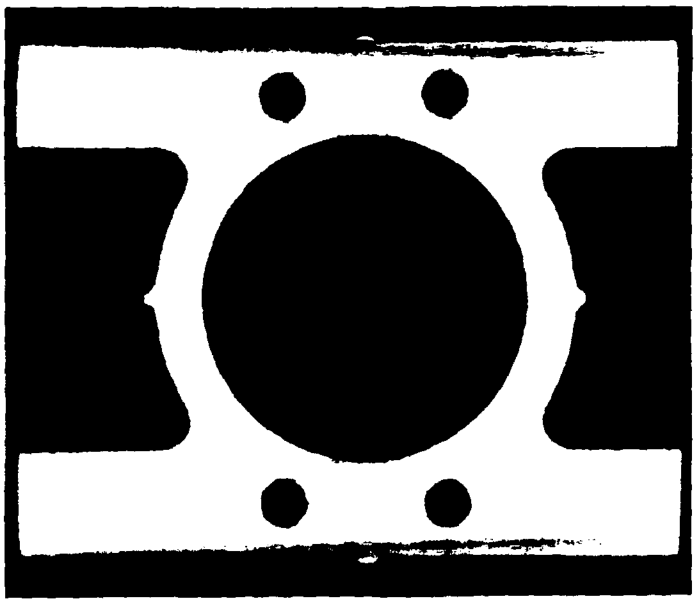


Figure 3.3-2 CT image of flap control unit housing.

CT evaluation revealed a common shrinkage defect in the "H" section in five of the six castings in a location and of a similar nature in all five housings. Several other equivalent locations in the "H" section contained similar flaws. The information provided by CT was used to reevaluate chill placement for the casting for the purpose of eliminating the shrinkage flaws. The casting engineers agreed that the particular location of the shrinkage reduced the likelihood that it would have been revealed using film radiography. In fact, they admitted that the entire critical region comprising the "H" section is very difficult to radiograph effectively.

Housing 030188B contained a large hole that could not be repaired because of its location. Therefore, it was chosen as the casting to destructively section and radiograph to verify the extent of the porosity. The casting was sectioned near the regions where porosity was indicated to allow film to be placed on the other side of the section opposite the x-ray source. Figure 3.3-3 is a photograph of the section. Radiographs of the sectioned region containing the anomalies did not reveal any noticeable porosity. The section was analyzed again with CT, and the porosities were again identified, as shown in Figure 3.3-4. Comparison with a CT slice in this scan set which passes through the center of the CT Image Quality Indicator (IQI) revealed that the porosities were larger than the 4T void of the finest radiographic requirement. It was very surprised that radiography was unable to image the apparently substantial porosity indicated by CT. The most probable explanation for this is that much of the porosity lies in line with web sections which attach the "H" section to the larger body of the casting. The webs would tend to "hide" the porosity. CT scanning of the web area also indicated porosity. Figure 3.3-5 is a CT image of a scan 4 mm (0.16 in) below the previous slice. Although reproduction has decreased the sensitivity to details, the porosity in the webbing can be compared to the 4T hole in the CT IQI.

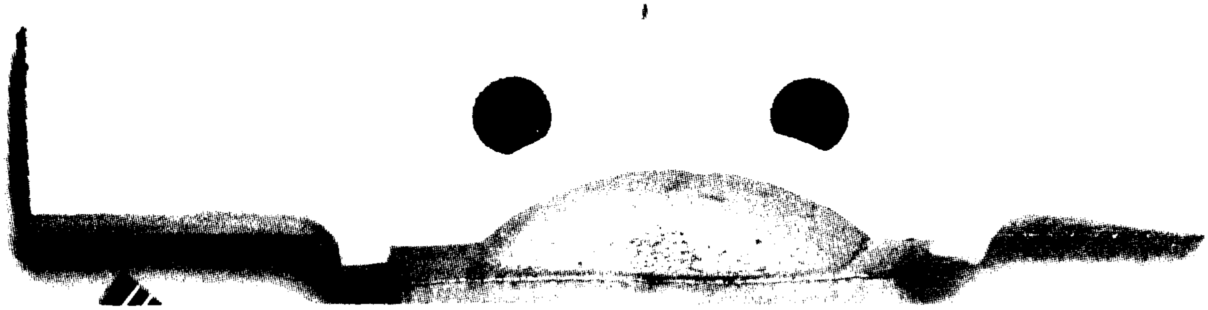


Figure 3.3-3 Photograph of a section from the flap control housing 030188B containing defects.

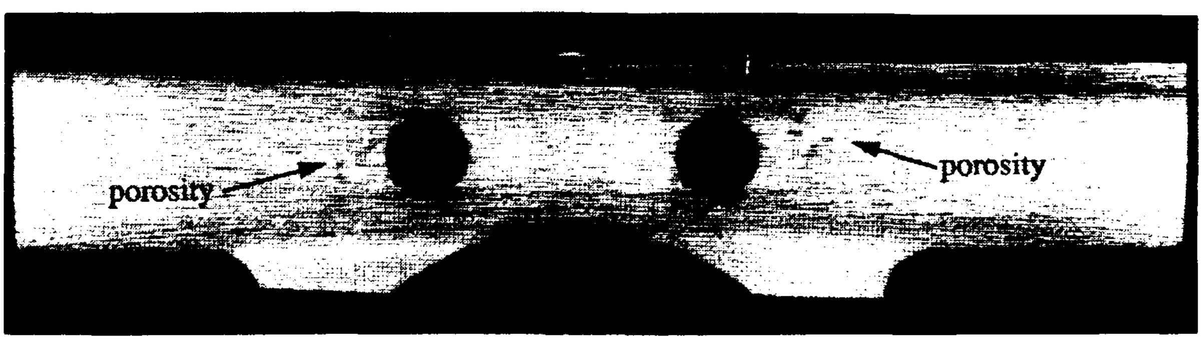


Figure 3.3-4 CT image of the section from the flap control unit housing 030188B indicating porosity.

porosity

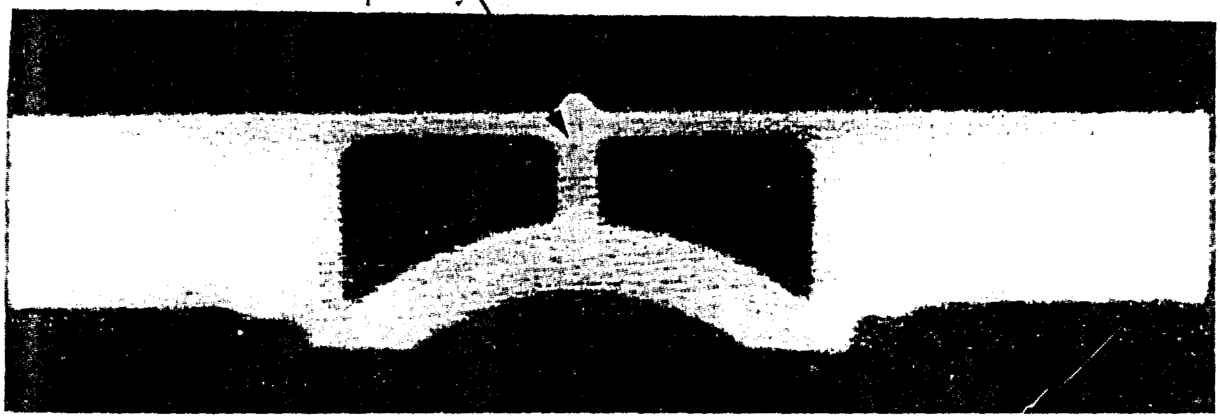


Figure 3.3-5 CT image of the section of the flap control unit housing 030188B at a location 4 mm lower than Figure 3.3-4 showing porosity in the webbing.

These results demonstrate that (a) CT provides an accurate measure of casting quality, even in complex structures, and (b) film radiography of complex castings may allow defects to go unnoticed. CT slices through the middle of the "H" section also provided accurate measurement of the interior wall thickness and verified that they were within dimensional tolerance requirements. Figure 3.3-6 is an example of one of these slices with the threshold set to show the dimensions on the casting.

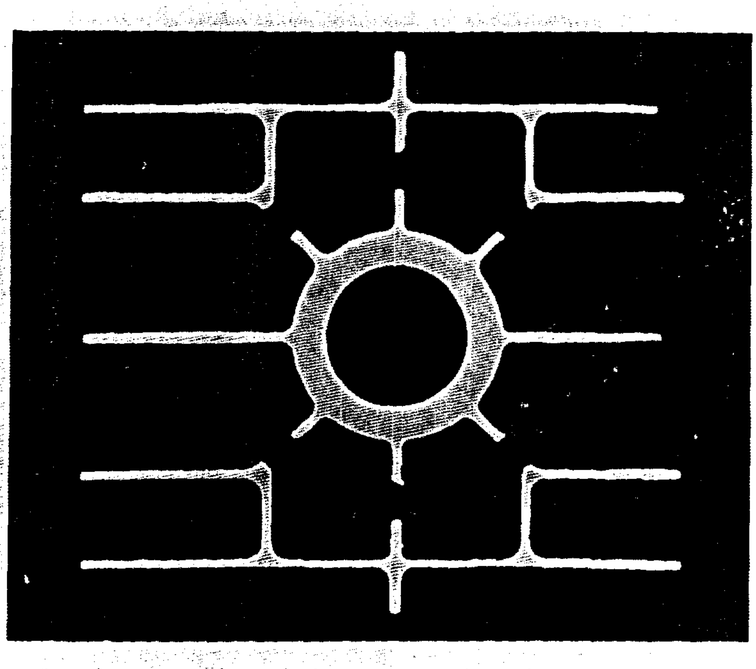


Figure 3.3-6 CT image of the flap control unit housing for dimensional measurements.

CT slices though various areas requiring weld repair were of value when the depth of the flaw was uncertain. If a flaw extended entirely through a wall, its extent was obvious by sight. On the other hand, the depth of a flaw visible from only one side could not be certain. Figure 3.3-7 is a CT image of the ring at the center of the "H" section in one of the housings. The defect requiring weld repair is easily seen. A series of CT slices through the ring revealed that the flaw was 5 mm (0.2 in) below the top of the ring. In this case, the flaw region was small enough that it could be ground out and repaired by welding. However, in another case, the time and money wasted on an abortive repair could be eliminated if CT revealed that the flaw was too large to successfully repair. This case did not occur in any of the five housings which were examined.

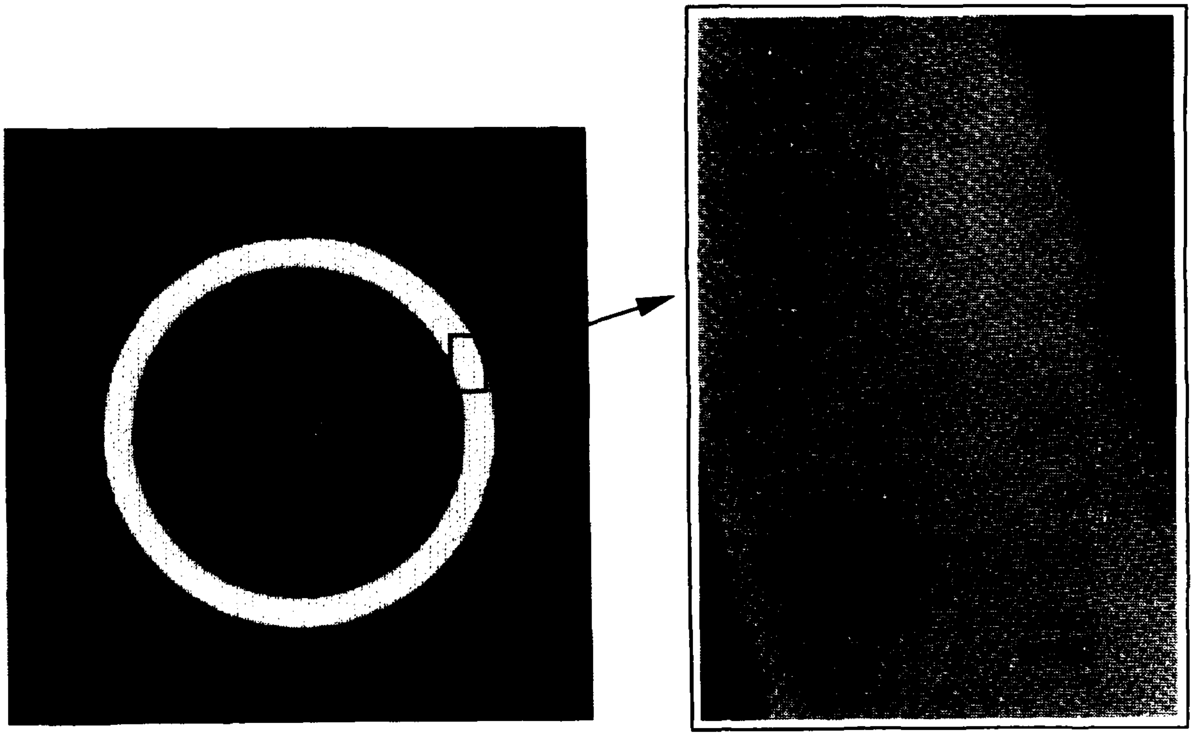


Figure 3.3-7 CT image of the flap control unit housing for evaluation of the depth of a defect.

4.0 CT FOR ENGINEERING ANALYSIS

Computed tomography allows for a quantitative measure of features in terms of dimensions and X-ray attenuation. Geometry acquisition from CT can be useful for dimensional measurements directly on the CT image display or for transfer to a CAD workstation for use in drawing definition and even engineering analysis. In addition to dimensional measurement, the CT value mean and standard deviation can be used to assess the quality of a casting. These values are useful for defining the extent of microporosity in a casting. The measurement X-ray linear attenuation in volume elements of a casting do not directly relate to the physical principles of microstructural strength of materials. However, these measurements can be used correlate to material uniformity and will correlate to macrostructural strength measurements that are dependent on material macrostructural conditions, such as voids.

4.1 CT for Materials Testing

4.1.1 Boeing Allowables Tensile Test Specimens

Castings have experienced significant rejection levels in manufacturing due to penetrant inspections. However, it has been suggested that the rejections are not indicative of the ability of the casting to actually maintain strength in its design application. This hypothesis was examined as part of an evaluation of a number of tensile specimens taken from castings manufactured by various foundries to a material and process specification. The tensile specimens were penetrant examined and submitted to mechanical testing. Figure 4.1-1 shows a histogram of the yield strength of the tensile specimens from one manufacturer. The curves show that penetrant rejection has no correlation to a reduction in yield strength for a family of tensile specimens. This result holds true for ultimate strength and elongation for this experiment. There is a variation in the material performance as a function of the manufacturer.

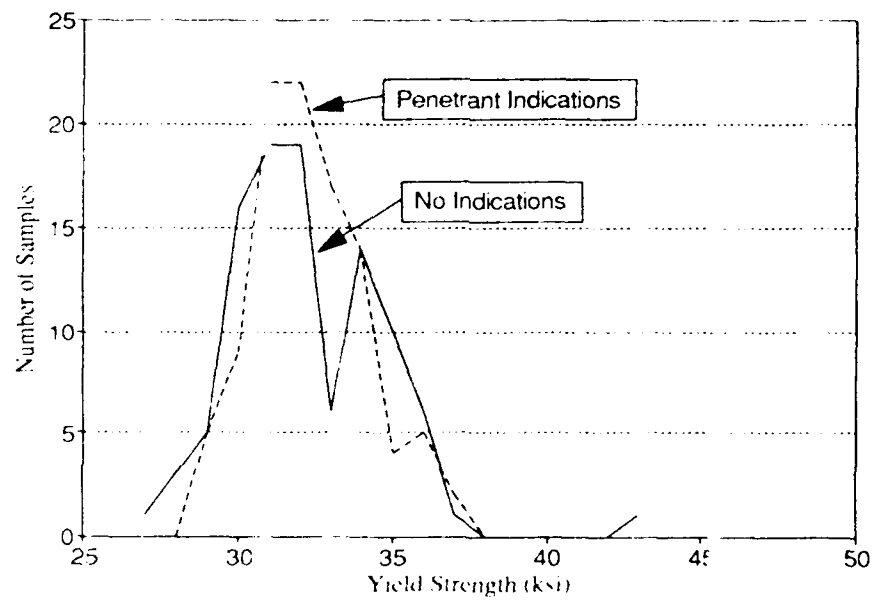
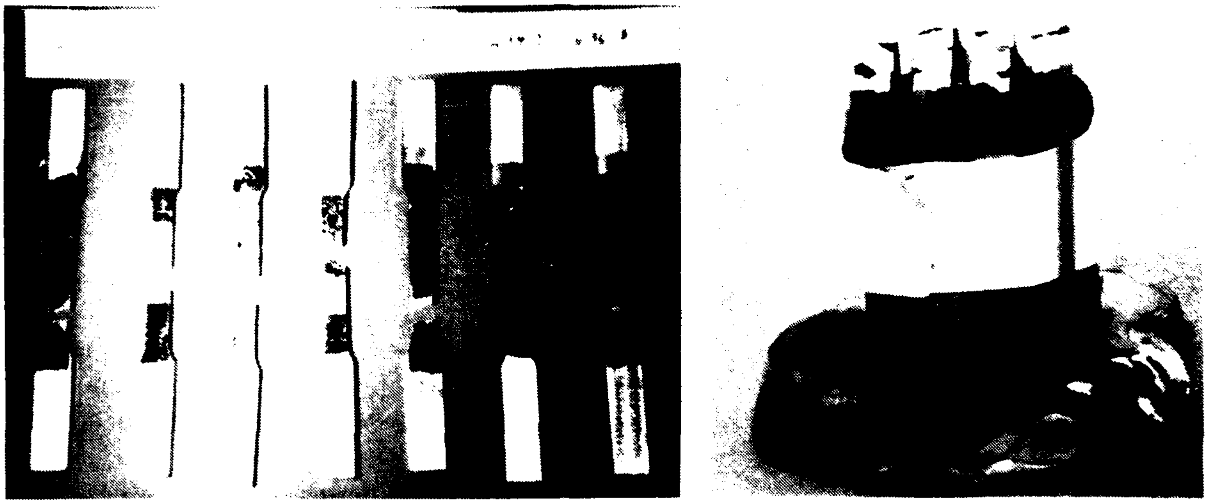


Figure 4.1-1 Histogram of the yield strength of tensile specimens for samples that contained penetrant indications and those that did not.

Seven of the tensile specimens from this experimental study were obtained for evaluation with CT. The selected specimens were all cut from the same 345-T6 sand casting and machined to the same geometry. The specimen halves were stacked together so that their fracture surfaces would be at approximately the same CT slice height. Figure 4.1-2 shows the broken tensile specimens.



(a) (b)

Figure 4.1-2 Photographs of the tensile specimens a) individually and b) assembled for CT examination.

CT slices were taken over the 7 mm (0.28 in) of material (in steps of 1 mm (0.04 in)) adjacent to the failure surfaces. Figure 4.1-3 is one of the images. The mean and standard deviation of the CT values over the CT cross section of each specimen was measured for a region-of-interest (ROI) just smaller than the cross sectional size of the samples. These measurements were made for each slice and also averaged together for each specimen. Table 4.1-1 lists the average CT mean and standard deviation measurements for each specimen along with their respective destructive testing results. There is less than a one-half of one-percent spread in the mean CT values, but the standard deviation (which represents the variation in the material density) of less than 20 percent.

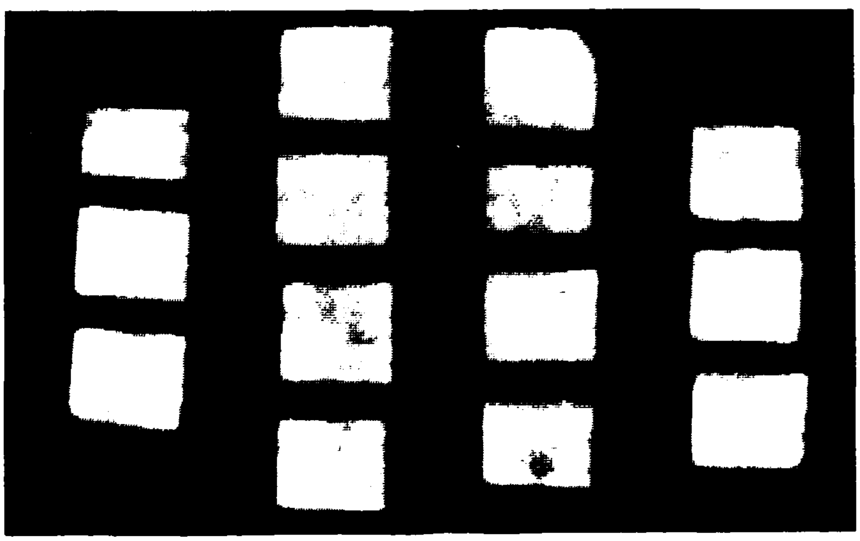


Figure 4.1-3 CT image of tensile test samples.

Table 4.1-1 Measurements from the Casting Tensile Specimens

Specimen	CT Mean	CT STDEV	YS (ksi)	UTS (ksi)	Elongation (%)
G-36-3	691.33	4.66	43.5	44.0	2
G-18-3	689.66	5.19	30.1	39.6	5
G-23-3	689.34	4.92	31.5	42.2	8
G-24-3	689.44	4.67	30.7	41.8	8
G-29-3	687.99	5.39	36.1	41.8	2
G-34-3	688.45	5.01	38.7	45.3	4
G-17-3	690.61	4.58	29.7	39.3	3

Figure 4.1-4 is a graph of strength versus the average standard deviation of the CT numbers across the neck region for each specimen. The standard deviation is a measure of the uniformity of the specimen material density. A high standard deviation would be an indication of porosity or other defects. The figure shows no obvious correlation between the CT standard deviation and the strength. A similar result was found for the elongation values. Because none of these specimens were out-of-family, i.e. none failed at a significantly lower stress than the others, this result is entirely consistent.

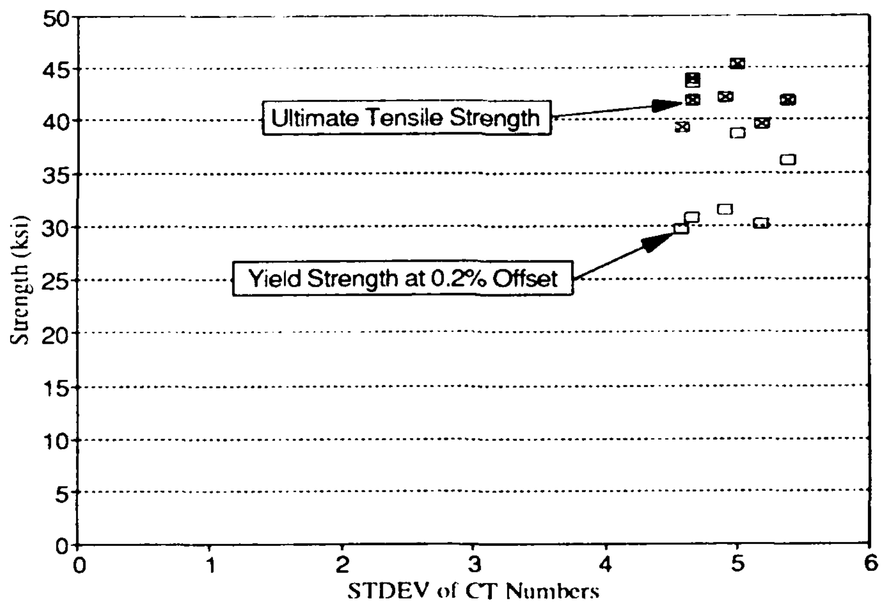


Figure 4.1-4 Graph of strength versus standard deviation of CT value for the tensile specimens.

4.1.2 Boeing Materials Technology Tensile Test Specimens

A second experiment to evaluate the correlation of material property to nondestructive evaluation methods was performed by Boeing Materials Technology. One hundred and fifty-five test specimens were selected from regions of various castings of aluminum alloys 356-T6, A356-T6, and A357-T6, which showed rejectable dye penetrant indications. After machining of the tensile specimens from the castings, reinspection with penetrant showed only 53 of the tensile specimens still showed penetrant indications. Of the original 155 tensile specimens, only 16 were identified by film radiography of having an ASTM quality level less than grade A. Of these 16, 15 of the specimens were a subset of the 53 specimens that showed penetrant indications. The other specimen contained an inclusions identified by film radiography. The 15 specimens that were identified with film radiography as having defects were combined with an additional 15 specimens (for a totoal of 30 specimens for CT evaluation), 12 that were considered good radiographically and with penetrant, and 3 that were considered good radiographically but had penetrant indications. Figure 4.1-5 shows the specimens and how they were stacked together for scanning purposes.

(a) (b)

Figure 4.1-5 Photographs of the tensile specimens a) several individual specimens and b) the 30 specimens assembled for CT examination.

The center 25 mm (1 in) of the specimens were scanned on a CT system, with a slice taken every 1 mm. Figure 4.1-6 is a CT image of one of the scans showing the variation in density across the various specimens at that location. Measurements of the CT mean value and standard deviation were made in a ROI in each specimen on the CT system. Graphs of the mean and standard deviation of the CT values across the test section of three of the specimens are shown in Figures 4.1-7 and 4.1-8. These graphs show that within each specimen the values will vary depending on the presence of voids or porosity. In Figure 4.1-7 there is a correlation between the position of drops in the mean CT value and visual observation of voids in the corresponding CT image. The failure locations of these sample are indicated and usually occur at local minimum, were the cross section is reduced because of the voids. The same voids cause the standard deviation of the CT value to increase as shown in Figure 4.1-8. The variability between samples is also clearly observed.

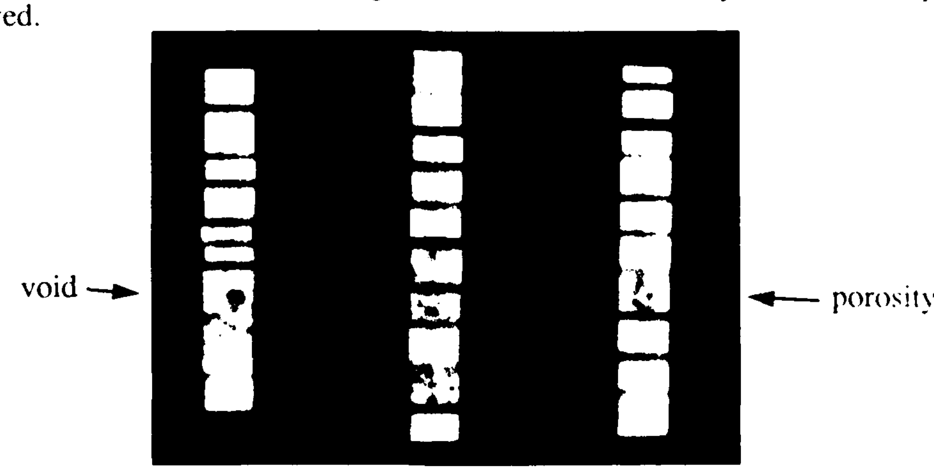


Figure 4.1-6 CT image of tensile test samples.

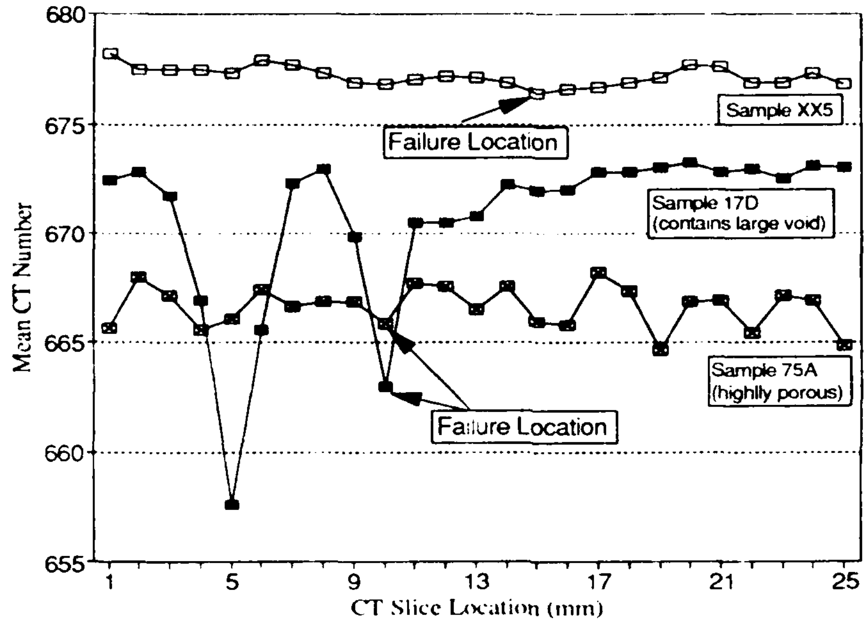


Figure 4.1-7 Mean CT value versus position across 3 tensile specimens.

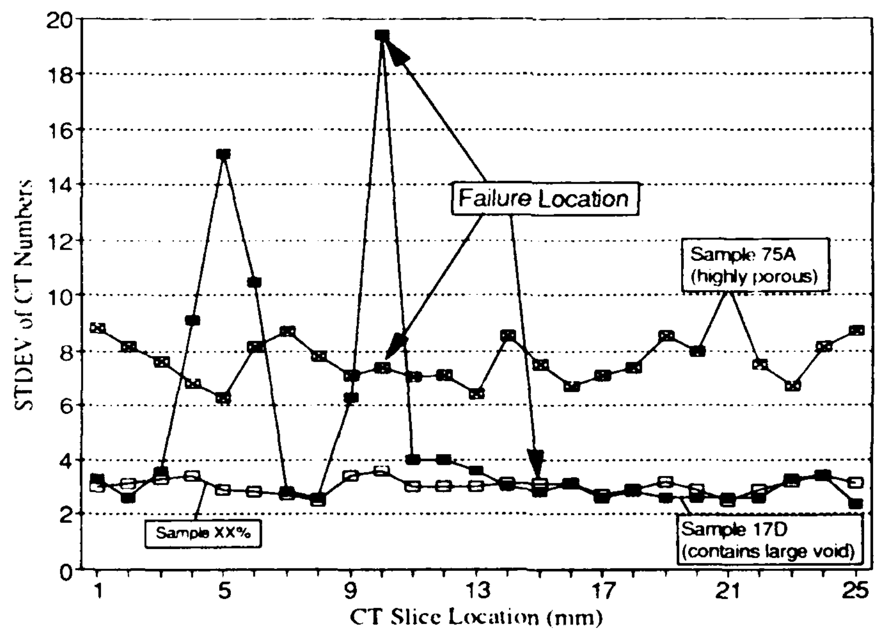


Figure 4.1-8 Standard deviation of CT value versus position across 3 tensile specimens.

All the specimens were pulled to failure in tension while measuring the yield strength, ultimate strength, and percent elongation. Table 4.1-2 lists the 30 specimens along with the measurement results from the three NDE methods and the material properties. Graphs of the results, plotting standard deviation of the CT values against mechanical properties, are shown in Figure 4.1-9, 4.1-10 and 4.1-11. The three specimens which are out of family show low strength and high CT standard deviation. Although CT may not correlate directly with strength in these castings, the most porous specimens show a clear reduction in strength and were clearly identified as different from the other castings by CT.

Table 4.1-2 Measurements from the Casting Tensile Specimens

Specimen	NDE Method				Material Properties		
	Dye Penetrant	Film Radiography	CT Mean	CT STDEV	TYS (.2%)	UTS	Elong.
		Grade			(ksi)	(ksi)	(%)
356-T6							
75A	All Rejectable	D	666.6	7.69	26.7	32.0	1.60
75B		D	663.9	7.98	29.4	32.4	0.99
75C		D	660.1	9.05	28.3	32.5	1.42
65-B		A	674.6	3.22	32.3	42.8	5.71
21C		C	671.1	3.65	29.4	35.4	1.70
2A-1		A	674.7	3.50	32.1	37.4	1.47
2E		A	687.3	2.74	30.8	38.5	3.43
4S		A	678.6	3.40	32.1	38.2	1.84
4E2		A	683.0	2.48	33.7	42.0	4.40
4G		C	677.9	3.98	32.8	38.1	1.32
9H		A	669.0	3.21	31.1	38.8	3.50
17C		B	677.0	4.22	32.8	38.2	1.46
17D		B	670.8	4.83	31.0	34.8	0.76
3B		B	674.3	3.42	30.4	37.0	2.17
3C		B	670.2	4.29	31.2	37.6	2.28
5D		B	670.3	3.28	31.6	43.3	15.0
A356-T6							
XX-1		A	668.8	4.26	32.0	43.1	7.65
XX-5		A	677.2	3.03	30.9	41.0	4.72
ZZ-5		A	671.3	3.60	31.1	43.4	11.0
A357-T6							
7N		A	678.0	3.32	41.5	48.9	4.50
7P		C	661.2	5.37	39.2	44.8	1.65
7S		A	680.3	3.41	38.5	44.2	1.74
7W		A	685.7	4.89	42.5	45.0	3.93
22N		A	682.0	5.60	42.1	45.9	1.00
22P		C	676.8	4.47	42.3	48.2	2.37
22Q-1		A	677.4	3.93	41.9	45.9	1.35
15W		B	664.4	3.90	42.0	44.5	0.69
15X		B	672.2	3.66	42.9	47.4	1.11
15AB		B	673.2	4.74	41.8	45.6	0.93
15F		A	681.7	4.42	40.8	45.9	2.06

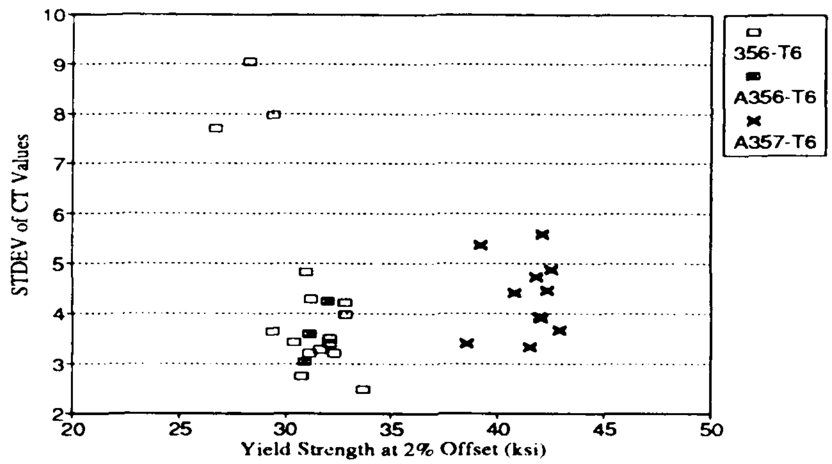


Figure 4.1-9 CT standard deviation versus yield strength at 2 percent offset.

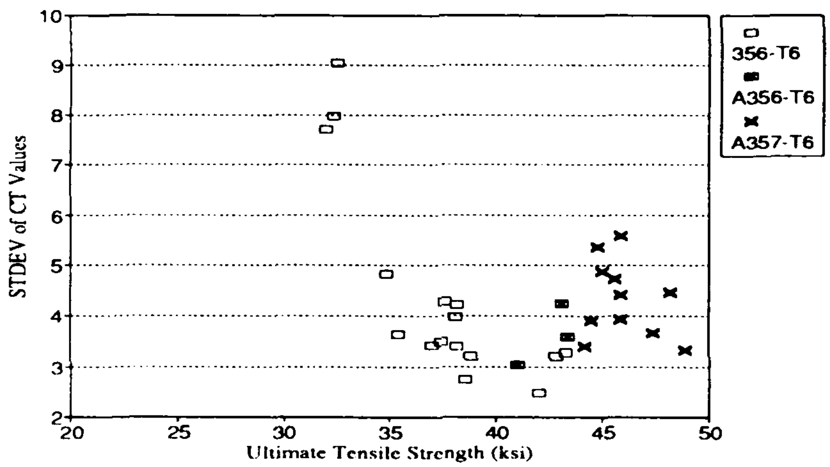


Figure 4.1-10 CT standard deviation versus ultimate strength.

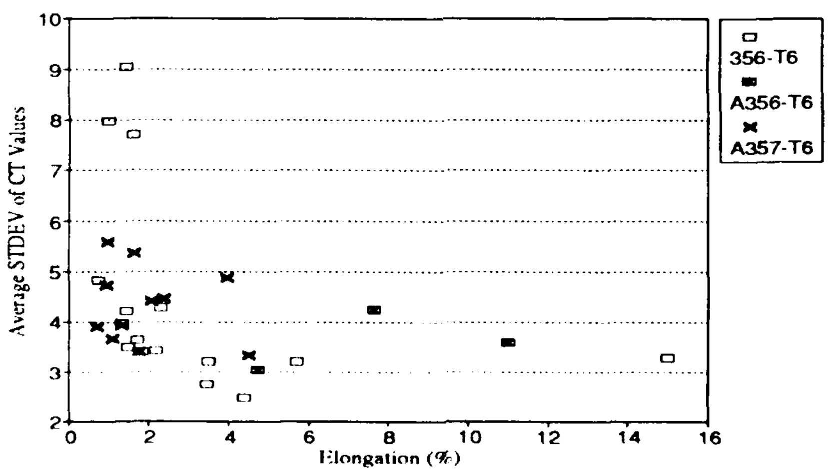


Figure 4.1-11 CT standard deviation versus percent elongation.

The mechanical testing results indicate that there is considerable room for modification of the approach for the rejection of castings based on nondestructive evaluation data. All of the originals samples were taken from castings that were rejected by penetrant examination. However, the performance of the tensile specimens indicates that the mechanical properties were not necessarily compromised in the total number of samples that had penetrant indications. In an associated study [14], a correlation between all the specimens that showed penetrant indications and a reduction in mechanical properties was found and depended on the alloy and treatment. This correlation was not evident in the smaller 30 sample set employed in the CT study.

Film radiography showed a range of grades with three of the 30 samples listed as grade D. These same three specimens were clearly out of family from the rest of the specimens in terms of strength. Figure 4.1-12 is a graph of the ASTM E-155 Numbers for radiographic inspection for the porosity versus the standard deviation of the CT values for the specimens containing indications. The CT data clearly correlates with the radiographic evaluation of the specimens, but provides a quantitative measurement of the porosity in each one.

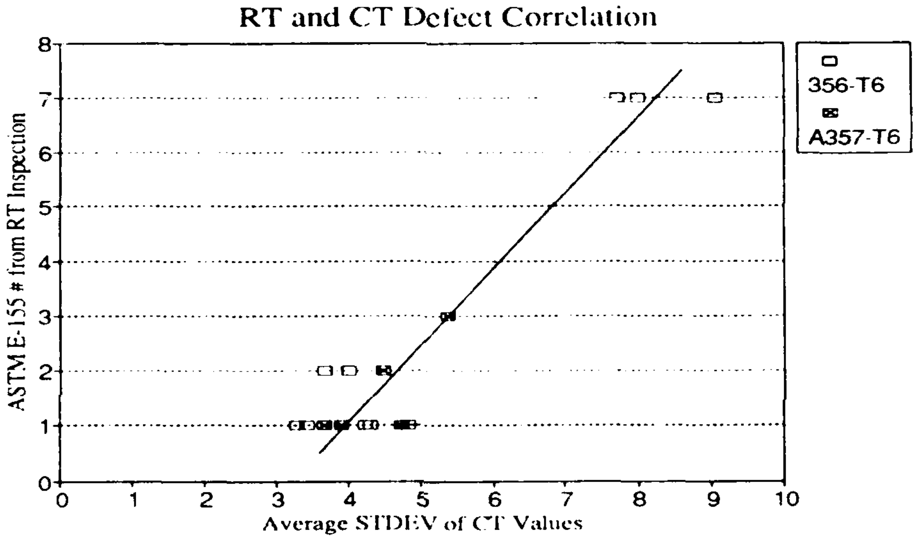


Figure 4.1-12 CT standard deviation versus ASTM Number.

These results indicate that a quantitative method of nondestructive analysis, such as CT, could be used to dramatically reduce the amount of rejected castings. This same type of analysis needs to be done with fatigue specimens, so that a correlation with fatigue strength in castings can be explored.

These results indicate that current NDE methods of inspection do not correlate to static strength properties in aluminum castings. The vast majority of tensile specimens excised at dye penetrant indications on the surface of the castings were defect free (no penetrant or radiographic indications) once they were machined to shape and showed no degradation in tensile properties. Those specimens which did show penetrant or radiographic indications did not demonstrate any statistically significant reduction in tensile properties either. Therefore, current and traditional NDE methods for castings appear to be extremely ineffective for predicting actual strengths this material. The need to obtain quantitative NDE data that correlates to actual mechanical properties is obvious. CT has shown the ability to measure voids which reduce area and result in a loss of strength. CT analysis as part of a nondestructive evaluation program for castings is expected to be beneficial.

4.2 CT for Design Geometry Acquisition

There are many instances in which the geometry of a cast part can not be adequately determined beforehand or completely measured afterward by conventional means. This is especially true for both aerodynamic and ergonomic surfaces. These surfaces tend to be complex in nature and difficult to define on paper or digitally in a computer. Attempts to use coordinate measuring machines or optical (visual) scanners to provide the digital coordinate data have often proven to be expensive and time consuming, except for relatively simple exterior surfaces. In addition, they have either under-defined or are unable to define all the required geometry in complex parts, especially if interior contours are required. The data that has been received from these other methods can also be difficult and costly to deal with because they are discrete points measured on a surface in 3 dimensional coordinates. Often, only reasonable approximations for the actual surfaces are used, and/or the part is never properly defined in the documentation.

CT provides an ideal tool for defining exterior and interior geometry of castings. An example is the geometric acquisition of an ergonomically designed magnesium control wheel casting shown in Figure 4.2-1. The master drawings of the control wheel that were provided to a foundry that was being qualified as a new source, resulted in a part that was acceptable per the drawing, but unacceptable when compared to the master model. The problem is that original drawings will not necessarily reflect the final master mold for components that are shaped to final ergonomic criteria. CT provides a method to retrieve the correct as-fabricated geometry is needed. Other components such aerodynamic surfaces have been equally successful in using CT for reducing the schedule and cost of geometry acquisition and improving the quality of the design process.

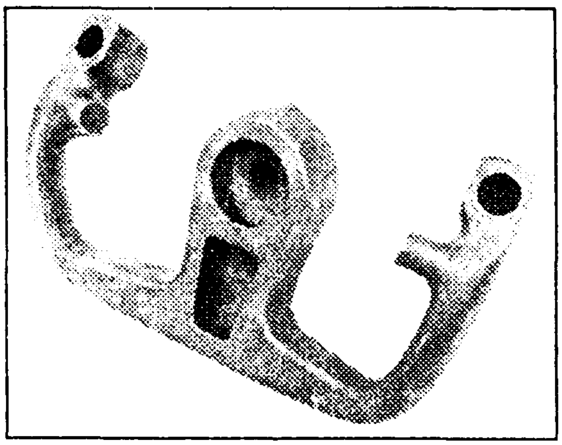


Figure 4.2-1 Photograph of an aircraft control wheel.

4.2.1 Technique

Although in principle, one could use CT to acquire digital geometry for any casting, there are constraints of available hardware, software and accuracy requirement which influence the actual approach. For hardware, medical CT scanners or industrial scanners can be used depending on the size and material of the casting. Medical scanner provide a much faster throughput than industrial scanners. Industrial scanners can provide much greater penetration and can handle large objects or provide finer resolution for very small objects. The dimensional accuracy requirement from the castings examined to date has been 0.5 mm (0.020 inch) tolerance, which is readily achievable with medical or industrial CT systems.

The software methods of determining where the part edge position in the CT slice frame of reference currently being used are either, thresholding directly on the density (i.e. 50 percent), or using a gradient magnitude approach. The part or model to be evaluated with CT for geometry acquisition will work best if it is composed of a single material on the surfaces to be defined. Although the gradient magnitude approach will accommodate multiple density materials they must still be of reasonable homogeneity and relatively void free.*

The process of CT for geometry acquisition requires the selection of a test or scan plan, which involves the definition of the surfaces that must be defined, how they will be obtained from the CT scanning and how the data must be reduced on the CAD workstation. One approach is to transfer piecewise linear string contour data of each CT slice to the CAD workstation and then to form idealized contours (splines and straight lines) using the CAD capability. Finally, spines are added in the CAD model, which tie the contours together. The number of CT slices and their orientation should be defined by the designer who will use the data to create the final CAD model.

4.2.1 Control Wheel Example

In the case of the aircraft control wheel, the scan plan called for 100 percent coverage of the part. To obtain this data in a reasonable time, a medical CT system was used. One hundred ninety-six CT slices were taken, which formed approximately 800 contours that described the flight control wheel. Figure 4.2-2 shows the contours obtained from CT after they were converted to Initial Graphics Exchange Specification (IGES) format and transmitted into a CAD workstation.

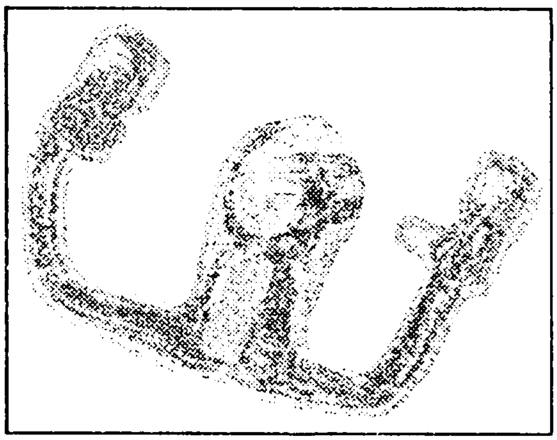


Figure 4.2-2 CT contours of the control wheel after IGES transfer to a CAD workstation.

The data was reduced on the CAD workstation by defining planes that cut through the contours, in the orientation where frames for the wireframe model were required. This process is the same whether the input data is from CT or other geometry acquisition methods. The new contours

* It was found with a model which had wood (0.2-0.5 g/cm^3), aluminum (2.7 g/cm^3), auto body putty (4.0-4.5 g/cm^3) and steel (8.7 g/cm^3) that the gradient magnitude approach would not work. Significant development of the algorithms to handle such a varied group of materials including a porous, low density material such as wood is needed.

were reduced into points and idealized into straight lines, radii and splines to redefine the closed contour in a reduced data format. Approximately 80 to 120 wireframes were needed for the flight control wheel, which required approximately 0.5 to 1.0 hours each to build. Once a wireframe model was produced, it could be skinned and shaded as shown in Figure 4.2-3.

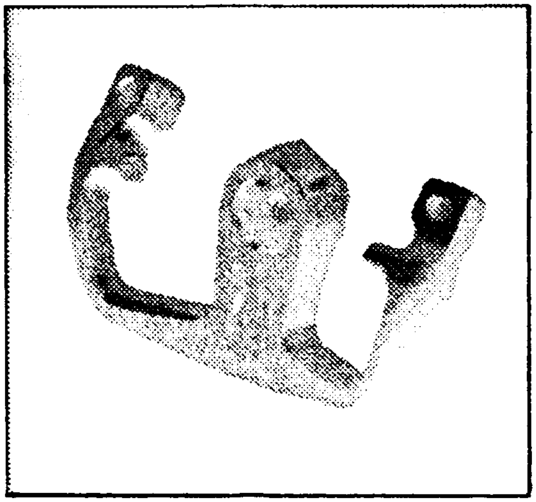


Figure 4.2-3 CT shaded model in a CAD workstation.

4.2.3 Dimensional Measurement

The general approach of CT internal dimensional measurement addressed in Section 3.1 of this report can be enhanced by importing CT slices of a part into a CAD workstation and using CAD software to make the measurements. A CT slice of the first discharge fitting was converted into IGES format and input into a CAD machine. Once it was modelled on the computer, the section of the fitting could easily be measured for thickness at any location. Figure 4.2-4 is a CAD drawing of the part showing the dimensions at the locations specified. In general, if one has an existing CAD system, one can make important dimensional measurements on a part from a model of it produced by CT slice data.

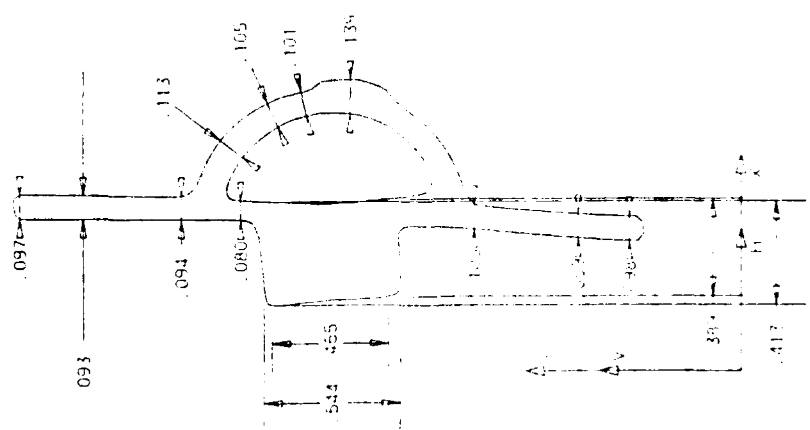


Figure 4.2-4 CAD model of a CT slice through the discharge fitting.

5.0 COST BENEFIT ANALYSIS

CT can serve as a cost effective evaluation tool for the development of new castings. The areas in which CT can be of technical and economic value are internal dimensional measurement, flaw characterization, performance prediction, and geometry acquisition for engineering and design. Although any one of these areas may provide a specific cost benefit for a particular foundry condition, it is the overall cumulative impact of CT that provides the best payback. This is also the most difficult to quantify.

5.1 Internal Dimensional Measurement

The discharge fittings of Section 3.1 can serve as a baseline example for the cost benefits of CT for dimensional measurements. The fittings are estimated to cost approximately $450 a piece to manufacture in small (<20 piece) lots, once the engineering and patterning have been established. For a component of this complexity, the development costs of casting engineering, patterning and first article evaluation can exceed $10K. The cost of CT examination of the first article on the high resolution industrial CT system was over $2000, which is a large fraction of the component's development expense. The medical CT costs were less than $500 for a single fitting. This is a significant cost, but not prohibitive. The destructive sectioning and measurement of the first article performed in this study actually cost $240. Although CT is twice the cost, if the first article had been acceptable, and could be used, then CT would save the $450 value of the part and be the most cost effective approach. The use of CT will depend the foundry operation and whether "good" parts are actually scrapped for internal dimensional measurements.

Costs of CT analysis can often be greatly reduced through simultaneous scanning. The results of a test described in Section 3.1 demonstrate that simultaneous scanning can reduce evaluation costs and provide sufficient measurement accuracy. Such cost effective use of CT can compete with the costs of destructive sectioning. Figure 5.1-1 shows a graph of the projected costs of measurement for the destructive sectioning and CT examination when more than one fitting can be examined at a time. This data was calculated and extrapolated from actual costs of examining the first discharge fitting. If a fitting is measured by CT, but is out of tolerance and must be rejected, the cost of scrapping the fitting ($450) is added to the scanning cost. This possibility is shown by a separate curve. If all the fittings measured by CT are "good" the cost per fitting would follow the lower curve. There can be an economic incentive to use CT over destructive sectioning depending on the requirements for and number of units that are sectioned. Qualitatively, the CT scanning will ensure a quality product delivered to the customer. The economic use of CT for dimensional measurements by a foundry will depend on a number of particular factors in the value of the part, the first article development costs and the difficulty of obtaining the number of required measurements destructively.

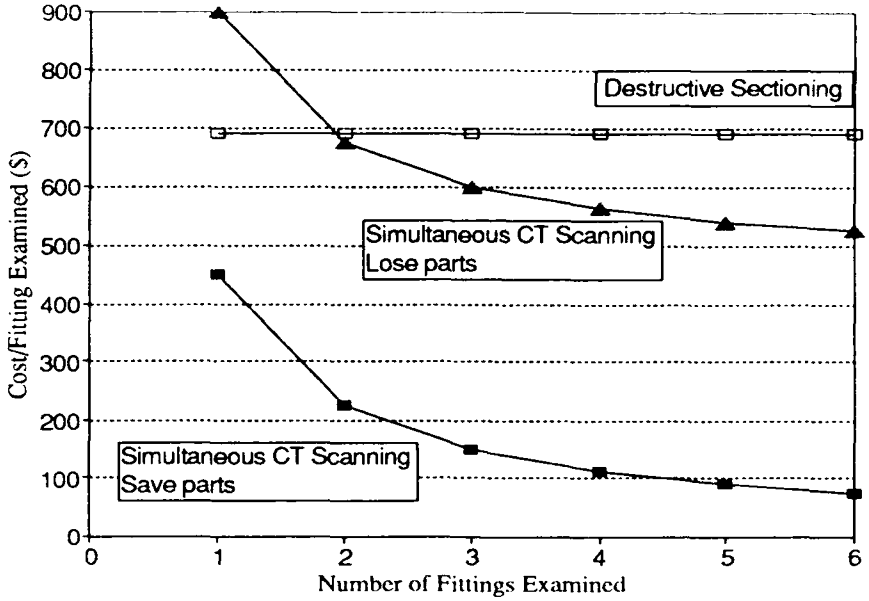


Figure 5.1-1 Graph of the economic benefit CT when multiple castings must be examined for dimensional measurements.

5.2 Flaw Characterization

The wall thickness in the small tube in casting (030184C) was shown to be out of tolerance. The evaluation was performed when the casting had just been poured and saved the additional costs (approximately $100) associated the manufacture of this casting, grounding, sand blasting, and HIPping. The "dead end" costs associated with completing the manufacturing steps on castings that will ultimately be rejected by another method can be reduced or eliminated. If CT evaluation (for example, for internal dimensional measurements) is performed on every casting, the cost of CT will need to be a fraction of the value of each of the castings, that is less than the scrap rate, for CT evaluation to be cost effective. The use of CT in "early screening" would probably provide a relatively small amount of savings in a few special cases.

In many cases, a casting containing a flaw can be repaired, or even passed, if the flaw size can be quantified and the wall thickness is shown meet specification. CT provides three-dimensional density data that allows one to determine the size, shape, and location of the defect. This information enables flaw assessment and intelligent repair. If every casting is CT scanned for flaws, the effect on casting costs can be estimated from Figure 5.2-1. The figure is based on CT scanning costing a fraction of the casting manufacturing. For example, if CT scanning of the casting were to cost only 10 percent of the original manufacturing cost of the casting itself, a benefit will be realized when 13 percent or more of the castings in the lot are saved through acceptance or repair. This would most likely be applicable for new processes that are not yet under control. The curves assume that CT costs can be obtained at 10 or 20 percent of the casting value. This would be true for very high cost castings or for a very low cost CT system. An average 10 percent of the casting value cost to allow for repair if required.

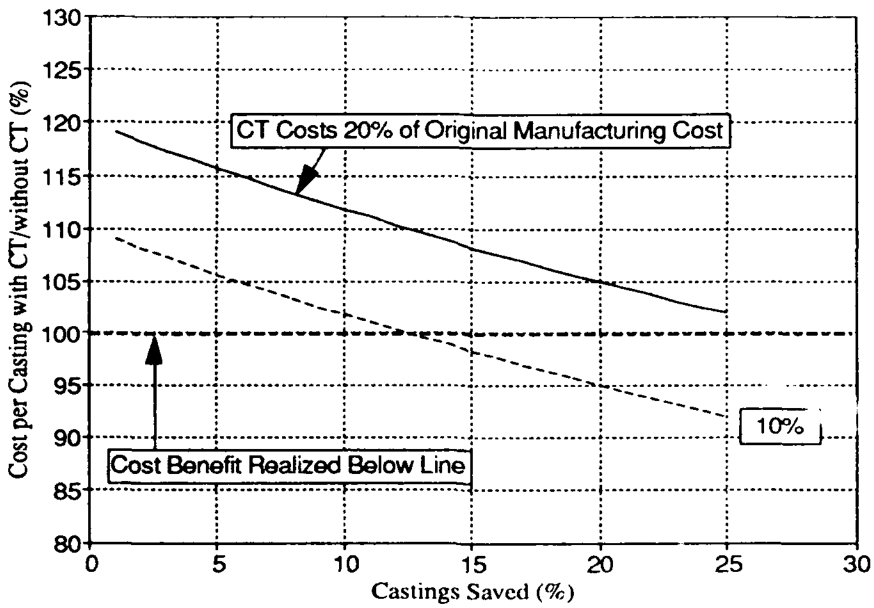


Figure 5.2-1 Graph of the economic benefit CT for repair or passing of castings with flaws.

The savings that are due to the reduction or elimination of other NDE methods is not included in Figure 5.2-1. This savings amount could be substantial, depending on the inspection requirements for the particular casting. Casting inspection with film radiography is normal for castings used in the aerospace industry. The radiographic inspection costs can vary widely depending on the casting and contract requirements. In some cases, all castings require radiographic inspection, in others only a small percentage require inspection. Assuming a radiographic cost of 10 percent of the total manufacturing costs (a conservative estimate in some cases and too large in others), could be eliminated by using CT, Figure 5.2-2 represents the new cost curves, which are shifted down 10 percent from Figure 5.2-1. In this case, CT could be 20 percent of the original manufacturing cost, and begin to show a cost benefit if 13 percent or more of the castings are saved. In general, the cost of casting manufacturing could actually go down if CT evaluation could be performed within the cost of present radiographic evaluation because CT provides superior information for decision making on the casting process and control than radiography.

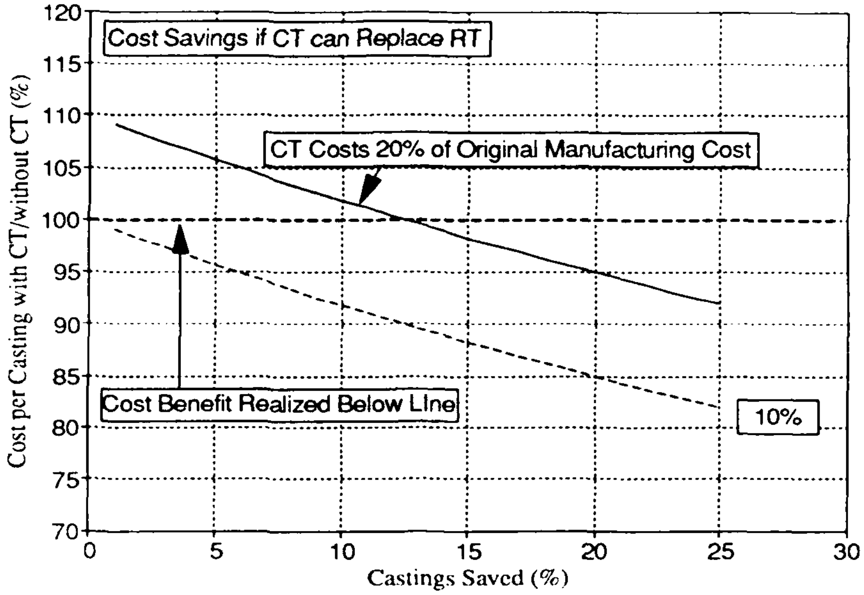


Figure 5.2-2 Graph of the economic benefit CT for repair or passing of castings with flaws when RT is eliminated.

The economics for flaw characterization are different if only initially rejected castings are CT scanned rather than all of them. Figure 5.2-3 shows how rapidly the average cost per casting decreases when all rejected castings that are scanned can be repaired or accepted. An average 10 percent of the casting value is assumed as the cost for repair. This curve shows an immediate payback with CT evaluation for this scenario. There is a payback whenever the cost of CT evaluation plus repair, as a fraction of the value of each casting, is less than the fraction of the castings that are saved.

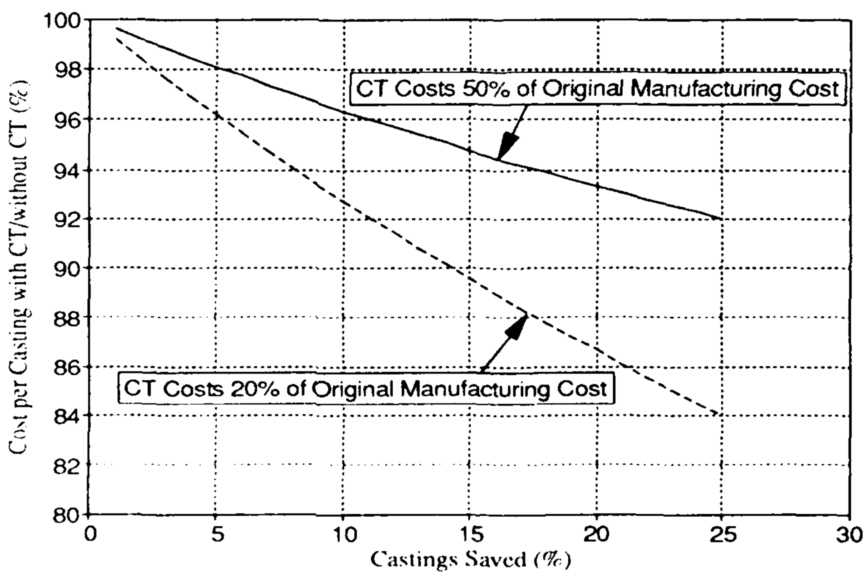


Figure 5.2-3 Graph of the economic benefit CT for repair or passing of rejected castings.

The use of CT for flaw characterization is most applicable in critically stressed regions. In such cases or in regions which tend to have defects it may be possible to use CT for only a portion of the entire casting. CT can be used in conjunction with the digital radiography (DR) available as part of the CT system; full coverage of the part is possible with a DR, and critical regions or anomalous indications can be fully evaluated with CT. In this case, CT can be more economical than film radiography, providing characterization of any flaws. This approach has been demonstrated by General Electric in the development of the X-ray Inspection Module (XIM) system for cast turbine blade examination. The XIM has both CT and DR capability; DR is used routinely, and CT when needed in particular regions.

5.3 Performance Prediction with Mechanical Testing

CT allows an engineering evaluation of castings based upon performance, and can reduce the number of "good" castings which are rejected based upon a qualitative assessment. In this report CT data correlated with tensile strength in samples that contained very high levels of porosity. In the example given in Section 4.1.2, CT might have allowed acceptance of 90 percent of the specimens, while rejecting the 10 percent which actually showed a reduction in strength. The other methods, dye penetrant (before removal of the coupons) and film radiography, would have rejected 100 percent and 50 percent respectively.

Normal rejection rates for radiographic and penetrant evaluation of castings during manufacturing are often in the range of 5 to 20 percent or more. However the evidence from the mechanical studies indicate that these rejections do not necessarily correlate to a reduction in the mechanical strength. The quantitative evaluation of internal condition of the castings should create a superior criteria for acceptance or rejection, with subsequent economic benefit. Figure 5.3-1 shows the curves for the cost affect of using CT on casting production when CT is used to replace radiography, if quantitative criteria for performance is considered. If CT costs were 20 percent of the casting value and twice the cost of radiography, then CT would show a savings if 11 percent in a lot could be saved from rejection based on an improved CT based evaluation criteria.

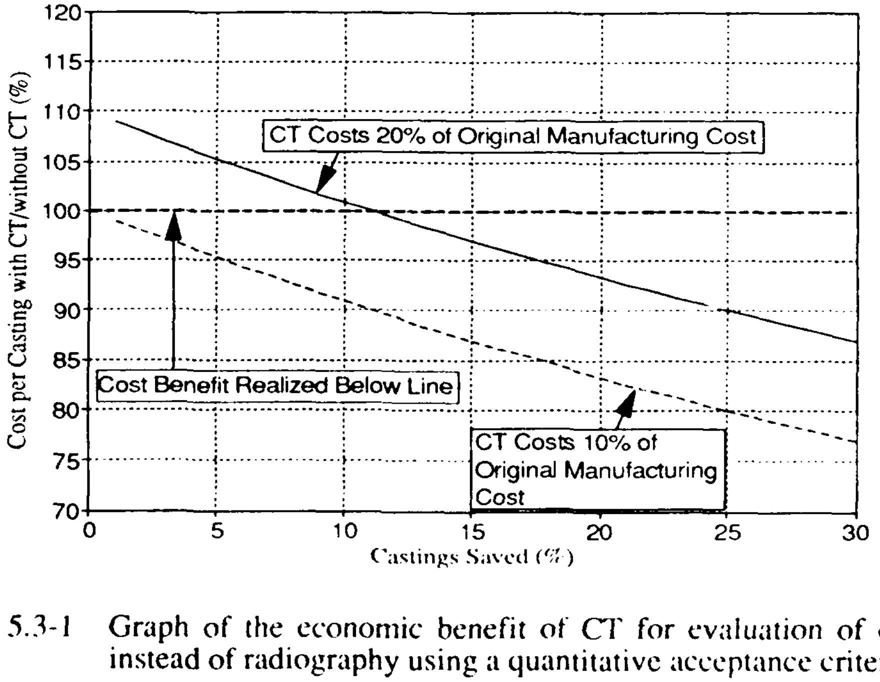


Figure 5.3-1 Graph of the economic benefit of CT for evaluation of castings instead of radiography using a quantitative acceptance criteria.

The curve in Figure 5.3-1 is very similar to Figure 5.2-2 but does not include the cost of repair. In fact, the actual application of CT would hopefully involve both a new criteria for acceptance of castings and also provide information to allow better repair. If the CT cost is less than or equal to the RT cost to inspect a casting, a manufacturer would see the greatest savings by using CT instead of RT for all castings.

The cost benefit of using CT to replace RT versus evaluating RT rejected castings will primarily depend upon the cost of CT relative to RT. For example, if CT is significantly greater than the cost of RT, it would be most economical for a manufacturer to purchase CT scanning services only for RT rejected castings. However, if CT costs (using a CT system with DR capability) could be implemented in an evaluation scheme at nearly equal to the cost of RT, the manufacturer would save by replacing RT with CT. This is shown graphically in Figure 5.3-2.

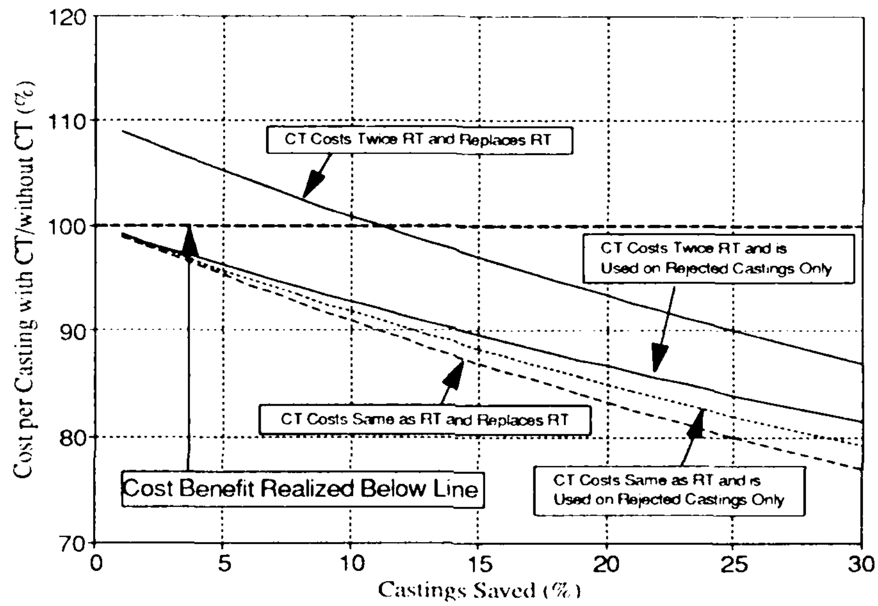


Figure 5.3-2 Graph of the economic benefit CT for evaluation of castings using a quantitative acceptance criteria.

The casting factors and high scrap rates associated with subjective inspection methods for castings can be reduced through the implementation of CT. Casting weight and scrap savings which could come from a performance based criteria should be substantial. This however will remain speculative until specifications are modified to actually allow the implementation of CT in this type of analysis.

5.4 Geometry Acquisition

Defining ergonomically designed or 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. This was demonstrated with the example of the flight control wheel in Section 4.2.

The cost of defining a control wheel using an optical surface measurement approach can be quite high compared to using CT. In one case, 450 labor hours of engineering (estimated to be comprised of 200 hours dealing with the type and sparseness of the measuring machine data, and 250 hours to fully develop the surfaces of the wheel) and 120 shop hours (for measuring of the surface at approximately 200 discrete pre-selected points) were required for a symmetric (right/left mirror image) control wheel. CT geometry acquisition provided a 200 engineering hour and a 100 shop hour savings. (The 250 hours to fully develop the surfaces of the wheel are still required with the CT data set.) Additionally, the conventional method only provided definition of the external surfaces of a hollow cast part (where the hollow portion is used for routing control wiring), while CT could define interior surfaces as well. CT geometric acquisition represents a 300 out of 570 hours (53 percent) savings.

For the non-symmetric wheel, there would be a potential 600-hour savings for the total process by using CT for the geometry acquisition because both of the horns would be obtained directly by the CT data acquisition but each would require significant engineering effort in the optical acquisition case. Although a 600 hour savings is significant in cost, the 7 to 14 calendar week schedule required to do the work is often of more concern. The turnaround time for the CT geometry acquisition process was one calendar day after receipt of the model (the availability of the CT facility scheduled in advance). This included the time required to have the data reduced and ready to load into the CAD workstation.

CT shows tremendous cost savings potential as a tool for geometry acquisition for a variety of ergonomically designed or complex shaped components.

5.5 Overall Benefit

The above sections have broken down the use of CT into various areas and attempted to assess an economic payback. In some cases, the payback is more obvious than others. And, depending on the particulars of the casting and foundry, the economics may in many cases be marginal at best. The curves of the previous sections indicate that higher value castings are most likely to benefit from CT evaluation. The fixed costs of CT operation will determine to a first approximation the minimum costs that CT can be performed; the casting program will need to be worth at least five times that amount. The CT system costs for foundry acquisition were discussed in an earlier report [7].

However, the example of the development of the discharge fitting demonstrated a significant economic potential that cannot be directly quantified. The casting engineer, who manufactured the fitting commented that had CT been required in the original specification for the casting purchase, the risk in the product development would actually have been reduced. A result of this could have affected a lower original bid for the discharge fitting program.

A key incentive for moving CT into broader foundry applications will be the development of low cost CT systems. The low cost CT may come in terms of higher throughput of existing designs or entirely new designs. For casting evaluation, a system with volumetric data acquisition (see Appendix) would have considerable value. The ability of CT to reduce or eliminate radiographic film by virtue of digital radiography and/or CT slices is an important economic factor. Although there are certainly cases where CT could provide a benefit on its own evaluation merit, the overall economic benefit of CT in the casting industry will require specification changes. The implementation of these changes will have a positive effect on the bottom line costs in the casting industry.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Computed tomography provides significant technical input to casting processes that can be economically viable. Presently, the economic incentive is as an engineering aid on difficult, high cost casting evaluation and as a tool for geometry acquisition. 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. Lower cost CT data acquisition will need to be available as well.

CT evaluation provides internal dimensional measurements in castings that are as good or better than destructive sectioning. 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.

CT provides flaw characterization capability in critical regions that is not available with nominal casting NDE methods. This capability allows the evaluation of regions which tend to have defects in the developmental stages of a casting process, or 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, as in the example of the flap drive control unit housing. 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 non-critical, and to provide exact locations for repair when required, therefore saving an otherwise scrapped part. This is particularly advantageous on high value parts where CT costs are small fraction of the casting value.

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 can be cost effectively used for geometry acquisition on ergonomically designed or complex shaped components for input into CAD models for engineering design and assessment. Because it can generally be done at a lower cost, in less time and include interior features, CT is an improvement over optical or physical dimensioning. This application of CT is considered to be useful by designers for even relatively simple components. As the geometric complexity increases, the value of CT for geometric acquisition can be very significant.

6.2 Recommendations

For many foundries, the present cost of CT systems or services is too great for the technology to be cost effectively implemented. The development of a low cost CT system, as an add-on to existing radiographic equipment, or as a new foundry X-ray evaluation facility need to be explored.

CT evaluation needs to be established in the government and industrial community as an acceptable tool for casting evaluation. Casting designers need to be educated on CT capabilities so they can call for CT evaluation as part of the drawing, particularly for critical regions and internal dimensions. Criteria for acceptance of castings based on CT evaluation should take into consideration the location of features. With CT, a new set of acceptance criteria should be established which relates anomalies to the mechanical loading that the casting will experience in service. This activity can be initiated by the development of specifications and handbook standards.

More research needs to be done to establish what correlations may exist between CT measurements of castings and material properties. Although there are material variables in castings which are independent of CT measurement (such as grain size or dendritic arm spacing, for example), the effort to quantify correlations with CT density where they exist would be an important part of establishing a performance based assessment for castings. In order to do this, it is important to study the process of failure in cast specimens under load. CT should be used during mechanical loading of tensile specimens. The goal of this effort needs to be an understanding of the mechanisms involved.

CT should be used as the method of choice for digital geometry acquisition, particularly when internal measurements are required. The development of additional tools for evaluation of CT contours in multiple material samples and software for transferral of CT data from various CT systems to various CAD workstations should be developed.

Because of the ability of CT to provide a superior evaluation of castings than present methods, Purchasing agencies should consider the requirement of CT evaluation as part of the contract.

7.0 REFERENCES

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APPENDIX - 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.

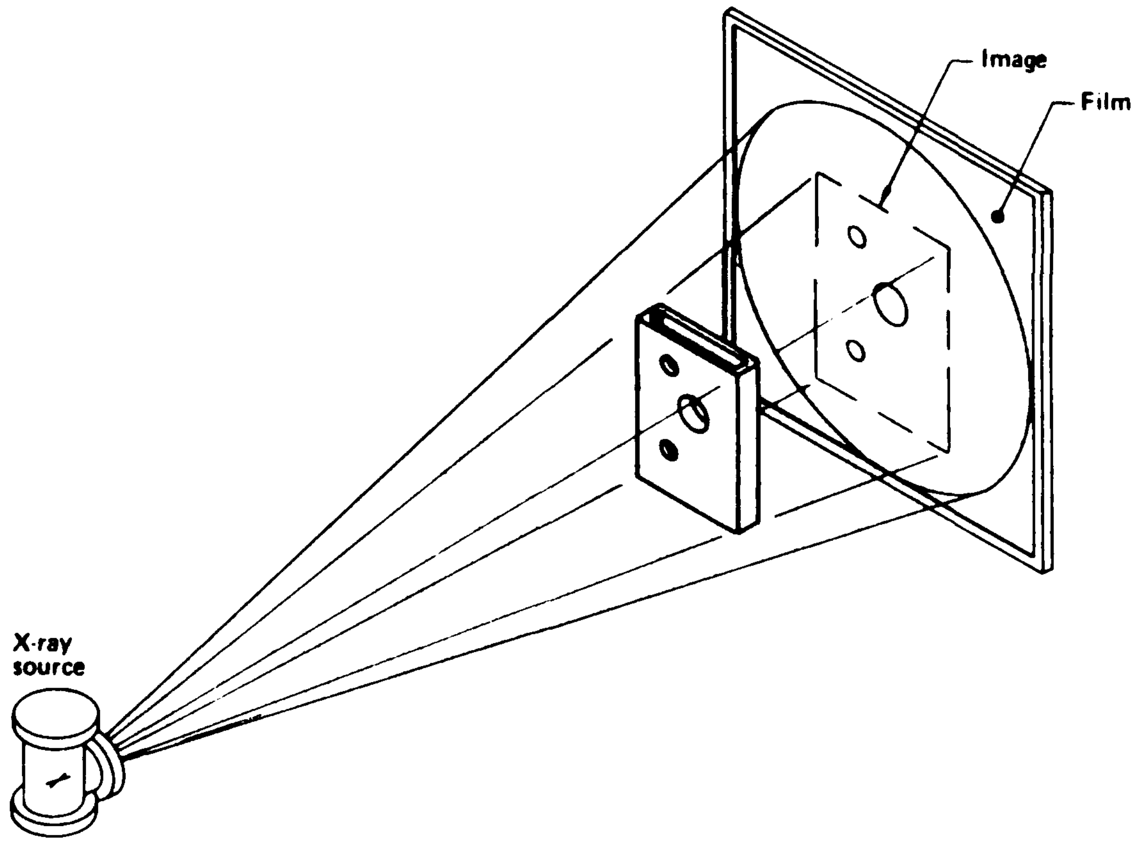

Figure A1-1 Film radiography.

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.

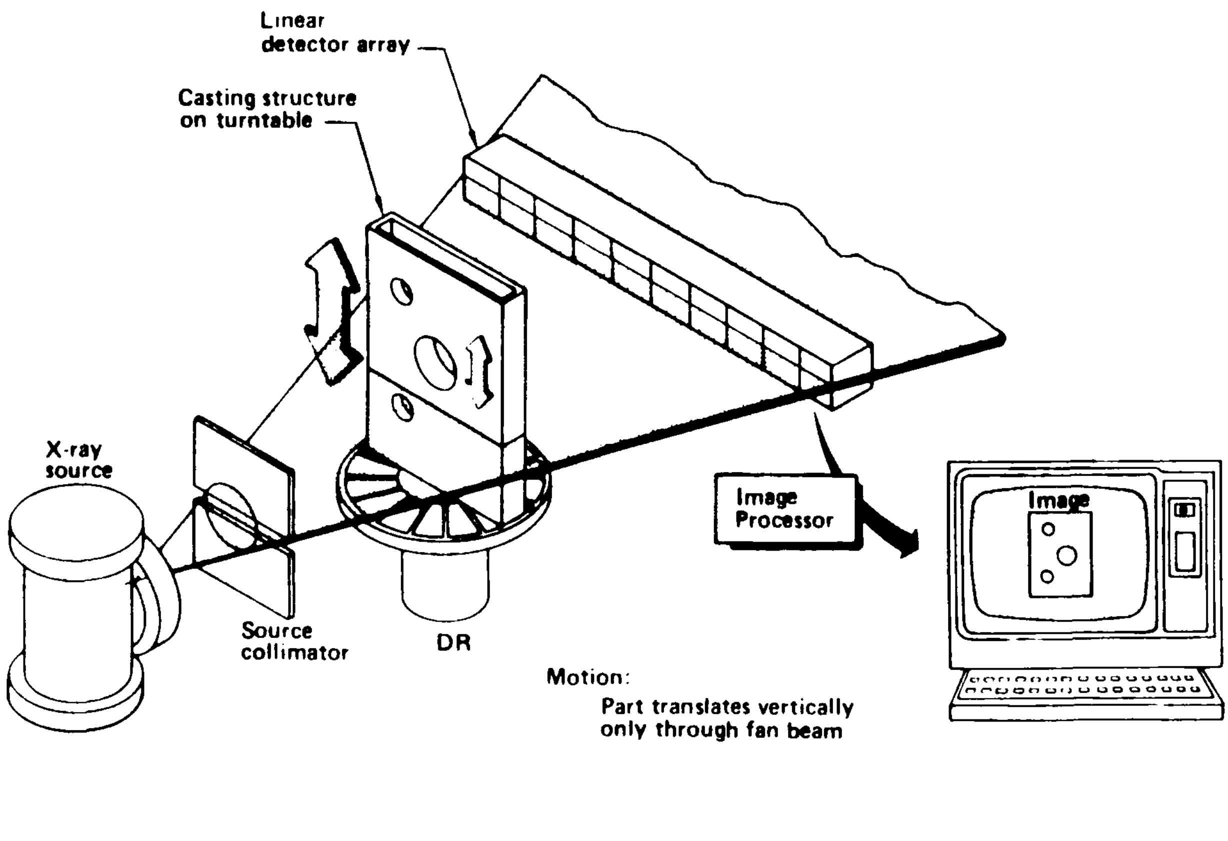

Figure A2-1 Digital radiography.

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, 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.

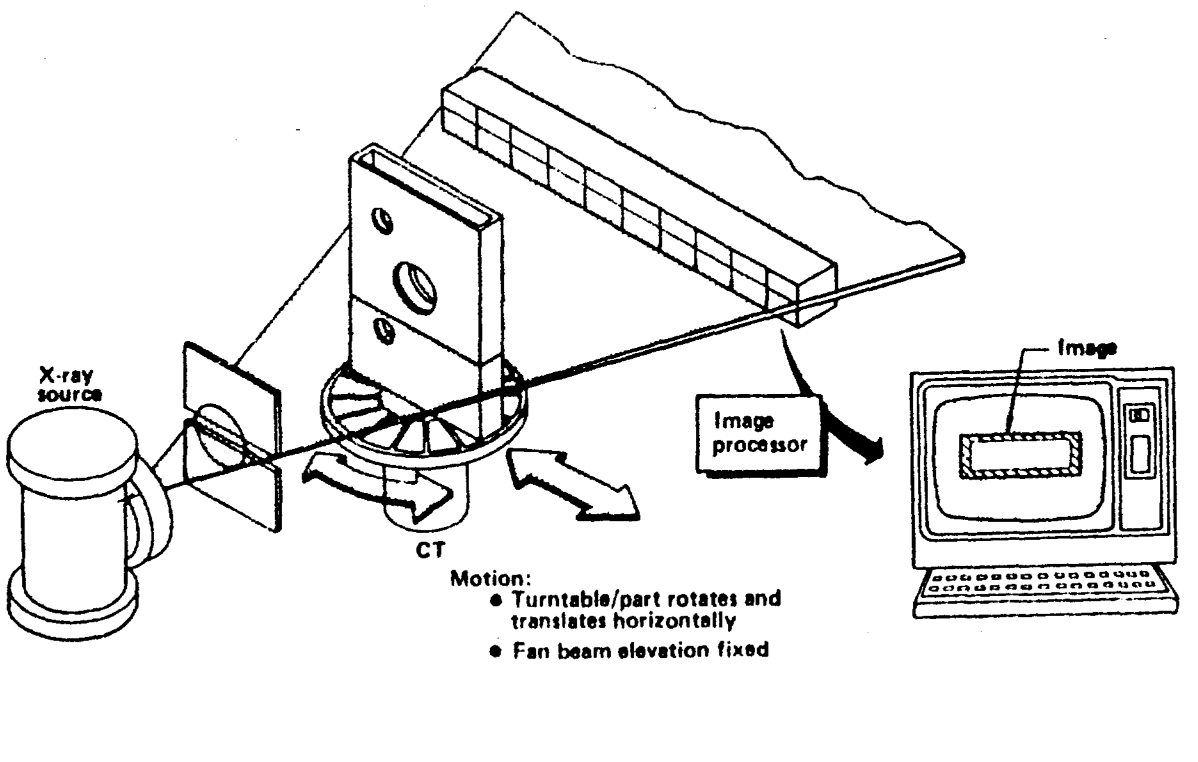

Figure A3-1 Computed tomography.