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A GUIDE TO COMPUTED TOMOGRAPHY SYSTEM SPECIFICATIONS

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The sensitivity to feature and anomaly detection in industrial X-ray computed tomography (CT) systems is a function of CT system operating parameters. Established as part of the CT system specification, these operating parameters are set together with an overall envelope that strikes a balance between sensitivity, inspection time and cost. These parameter choices eventually find their way into CT system attributes: configurations, components and procedures. CT system users are concerned with sensitivity requirements for specific inspection purposes, while CT system manufacturers are concerned with their implications for the system's physical constituents, assembly and control. This report discusses the attributes and the conversion to system constituents that must occur for a useful CT system specification to be prepared. The effect of attribute specification on CT system constituent costs are addressed. Understanding these issues is critical to the successful acquisition and implementation of a new CT system. Guidelines for the preparation and evaluation of CT specifications are provided.

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ABSTRACT

The sensitivity to feature and anomaly detection in industrial X-ray computed tomography (CT) systems is a function of CT system operating parameters. Established as part of the CT system specification, these operating parameters are set together with an overall envelope that strikes a balance between sensitivity, inspection time and cost. These parameter choices eventually find their way into CT system attributes: configurations, components and procedures. CT system users are concerned with sensitivity requirements for specific inspection purposes, while CT system manufacturers are concerned with their implications for the system's physical constituents, assembly and control. This report discusses the attributes and the conversion to system constituents that must occur for a useful CT system specification to be prepared. The effect of attribute specification on CT system constituent costs are addressed. Understanding these issues is critical to the successful acquisition and implementation of a new CT system. Guidelines for the preparation and evaluation of CT specifications are provided.

Key Words

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1.0 INTRODUCTION

Computed tomography (CT) inspection provides a cross-sectional image of the inside of the inspected object. This image is a map of the X-ray attenuation coefficient of a slice of specified thickness and is usually produced on a spatial scale that corresponds with the physical specimen, as if the inspector had sliced open the specimen and were examining its interior directly. No other inspection technology provides such powerful imaging capability.

The primary selling point of CT is its ability to produce highly detailed images of the inside of a test specimen. The difficulties associated with the production of the image result in an expensive system, compared to initial capital costs of other competing technologies. For most groups involved with nondestructive inspection/evaluation (NDI/E), a CT system is the most complex piece of equipment that will ever be used, and it is crucial that the users understand what they are buying, how they will use it, and how the CT system manufacturer thinks about the system.

The physics of the CT data acquisition process and the mathematics of the image reconstruction process create constraints for the physical components, the configuration, the performance and the cost of a CT system. These constraints are sometimes stand-alone limits and they are sometimes taken together as a tradeoff between maximizing one parameter at the expense of the others.

There are really only two fundamental limits imposed by the physics and mathematics of CT. The first is the finite X-ray source size and its brightness. There is a certain maximum number of X-rays emitted from each unit area of the source, higher X-ray emission results in melting the source. One implication is that a certain minimum time is required for data acquisition on every test specimen, irrespective of how many of the other parameters one is willing to compromise. Another implication is that there is a certain maximum test specimen thickness beyond which it does not make sense to try to measure X-ray attenuation because the time required for data acquisition, even assuming a zero-noise detector, may be prohibitive.

The second limitation has to do with the accuracies with which mechanical components can be manufactured and assembled. This is far more a matter of material property characteristics and it comes into play when the spatial resolutions approach the 1 micron level. Almost all other issues of importance to the CT user involve tradeoffs in cost. These cost tradeoffs have a ripple effect on the system design and the associated ramifications on the system requirements.

The CT process is complex. Many components, procedures and processes must be made to play together in order to yield images that faithfully reproduce the interior of the test specimen. Reliable CT equipment is not easily produced; there are only a handful of CT system manufacturers. Nonetheless, the rewards of CT imaging inspection are high, particularly where anomalies are not known or expected, where nonimaging measurements of deviations from a norm defy experience or expectation, or where the test specimen is complex and the anomalies subtle. Unlike other forms of NDI/E, CT data is inherently digital and spatially well defined. These two factors make CT data naturally predisposed to analysis by computer. It is relatively easy to build databases of CT inspection data that can be examined with standard (and customized) image processing techniques to yield all manner of useful NDI/E information, ranging from types, frequencies and locations of anomalies to correlation of specific anomalies with other conditions.

The most important issue for buyers of CT equipment for NDI/E is defect sensitivity. The defect sensitivity is usually based on the imaging capability (and consequently the anomaly isolation) and on CT's two other unique advantages: (1) CT can distinguish slight changes in density from a host density, and (2) subtleties in structure can be distinguished deep within a test specimen, despite the presence of any overlying structural complex that might mask their presence with other inspection modalities.

Defect sensitivity can be viewed from the perspective of the final image, and that is what sets the primary requirements in the specification. As an idealized example, let us say that the final image of a slice is a grid consisting of 500 x 500 picture elements (pixels) that exactly correspond to 500 x 500 volume elements in the test specimen. Each volume element (voxel) is a rectangular parallelepiped having a square footprint represented by the pixel edges and a height equal to the slice thickness. The average X-ray attenuation coefficient of each voxel of the test specimen is assigned to the corresponding pixel in the image. In our idealized example, a crack (perpendicular to the slice plane) in the test specimen will meander through a number of pixels in the image and be readily detectable, as though the experimenter had sliced open the specimen and traced the crack path through it. The reality is not so simple. If the crack is narrower than the voxel width, then the image of the crack will appear with reduced contrast from a thicker one. The finer the spatial resolution of the CT system, the narrower a crack that can be resolved at full contrast. But, if the system imaging capability is in fact blurry on a scale of 2 pixels in either direction in the image, the effective spatial resolution is now 250 x 250 elements, and the ability to find that narrow crack will decrease, all other things being equal. Reduced spatial resolution limits the ability to locate a crack and reduces its contrast in the final image.

The other major issue in defect sensitivity is image noise. Because the image is made with a finite number of X-ray photons, there will be an inherent uncertainty in the value of each pixel due to statistical fluctuation. This lends a graininess to the final image, which is equivalent to a noise level from the perspective of the analysis for defect sensitivity. The grainier the image, the less certain the inspector can be about finding the crack. This graininess or noise determines the system contrast sensitivity. As resolution is improved, all other things being equal, contrast sensitivity is degraded.

These two measures, spatial resolution and contrast sensitivity, together with the slice thickness, are the primary determinants of the defect sensitivity of the system. Thicker slices provide better signal (and hence contrast sensitivity), but decrease localization and defect sensitivity to anomalies that do not extend through the slice thickness. For additional information on CT basics and defect sensitivity issues, the reader is referred to the references [1-5].

The CT system user thinks in terms of defect finding, while the CT system designer thinks in terms of resolution, contrast sensitivity and thickness. The method of relating these quantities will vary with the particular situation, and there is no easy or quick set of rules. These quantities can be derived from an analysis of required defect sensitivity, and acceptable rate of false negatives (i.e., passed defects) and false positives (normal data mistaken for an anomaly) [5]. The expected distribution of anomalies will also enter into the analysis. The CT system user should understand that the CT system manufacturer varies CT system design parameters in order to achieve the desired defect detectability.

The buyers of CT equipment should also have a basis for understanding the system initial cost, maintenance and repair, and reliability issues. This guide serves as a starting point for those contemplating the acquisition of a CT system.

2.0 CT SYSTEM ATTRIBUTES

The first task in obtaining or developing a CT system is to list the CT system specifications that must be provided. Typically, these specifications are viewed as system attributes. They include the following categories:

Specimen (size, materials, density),

Inspection parameters (spatial resolution, contrast sensitivity, slice thickness, time for inspection),

Operator interface (system control panel, image display, and processing functions),

Interaction with program flow (e.g., concurrent data acquisition and review, automatic acquisition sequencing, archiving, automatic anomaly recognition, data output for statistical process control).

These attributes are listed in Table 2-1. The major subsystems affected by the specific choice of attribute value are also shown. The subsystems are discussed in greater detail in Section 3; they are introduced here for definition purposes.

2.1 Test Specimen

The test specimen determines the scale of the mechanical handling equipment. Thus, a 40-ton rocket motor will have a different mechanical subsystem than an F-100 turbine blade. Similarly, the logistics for loading and unloading (and the associated fixturing) will be a much different problem for a high-density circuit board than for a beryllium mirror blank.

The test specimen X-ray penetrability determines the minimum energy level of the X-ray source. The rules for determination of the X-ray source energy are approximately the same as those for determining the energy level for conventional radiography (approximately 90-97 percent attenuation gives the most information per photon).

2.2 Spatial Resolution

Spatial resolution is a measure of the scale on which shapes in CT image are faithful reproductions of the test specimen. It is a measure of sharpness in the resulting CT image. While there are many CT system characteristics that affect the spatial resolution, a key factor is the accuracy of the mechanical subsystems. It is impossible to reconstruct an image to an accuracy of X unless the accuracy of the mechanical positioning is some fraction of X. This accuracy represents a root-sum-squared contribution from all random positioning errors of about X/3. In rotate-only geometries, the accuracy must be approximately X/10, as can be derived from Shepp and Stein[6].

The spatial resolution places limits on the geometric configuration (which includes the relative positions of test specimen source, and detectors), X-ray spot size and the width of any detector apertures. The width of each individual ray within a view will contribute directly to the modulation transfer function (MTF) [7].

Table 2-1 CT System Attributes and Their Major Ramifications

ATTRIBUTE	RAMIFICATION
Test specimen size, weight	Mechanical handling equipment Loading/unloading features
Test specimen X-ray penetrability	X-ray (or gamma ray) source X-ray (or gamma ray) detector type Detector/front-end electronics dynamic range
Spatial resolution	Accuracy of mechanical handling equipment Configuration Source size Detector size and aperture
Contrast sensitivity	Strength of X-ray source Energy optimization Integration time
Artifact level	Reconstruction algorithm software Accuracy of mechanical handling equipment Detector calibration
Speed of CT process	X-ray (or gamma ray) source strength Number and configuration of detectors Bus structure Speed and architecture of processors Mechanical hardware-motors/brakes,etc.
Number of pixels in image	Number and configuration of detectors Amount of data acquired Computer/hardware choices
Slice thickness range	Detector configuration/collimator System dynamic range
Operator interface	Instrument control panel Image processing system Control software Interface to remote workstation
Archival requirements	Computer/hardware choice

2.3 Contrast Sensitivity

Contrast sensitivity defines how faithfully material variations in a test specimen are reproduced in a CT image. It is a measure of how noisy the image is (i.e., quantitative graininess in the image). If the primary source of image noise is due to the X-rays that have been registered by the detection system, then anything that increases that number yields a superior contrast sensitivity. The most important factors are (1) strength of the X-ray source, usually expressed in terms of photons/cm^2/sec @ 1 meter or (more indirectly, but more often) Roentgens/minute @ 1 meter, and (2) the time allowed per individual measurement. Contrast sensitivity is also a function of the energy of the X-rays used to make the measurement; therefore, both the intensity and the spectrum are important.

The source energy spectrum is usually selected on the basis of the desirable transmission characteristic (discussed in Section 2.1) or dictated by what is available (e.g., 450 kV is the highest energy commonly available continuous wave X-ray source available). However, a requirement for achieving certain minimum contrast sensitivity in a certain maximum CT slice time may force a higher energy spectrum than would otherwise be required. This is because the flux of the conventionally determined source might be too weak to produce the desired contrast sensitivity in the required time. There is a fine balance between signal and contrast. An analogy is in making a thickness measurement of a piece of glass. If visible light is used, there is plenty of signal, but not much contrast; ultraviolet presents excellent contrast, but the glass is so absorbing that there is no exit signal to speak of. X-rays or gamma rays present the right combination of signal and contrast. If however, the measurement had to be made within 1 microsecond over a minuscule region, then we might be forced to use the visible light, because we could not generate sufficient X-rays during that time period to make a meaningful measurement. The combination of spatial resolution and contrast sensitivity requirements often leads to the infinite flux wish -- huge fluxes from minuscule sources. The tradeoff between spatial resolution and contrast sensitivity is considered in Section 4.5.

2.4 Artifact Level

Artifact level is one of the more difficult specifications to interpret. Artifacts can be viewed as correlated noise because they form fixed patterns under given conditions. Most artifacts can be classified as products of beam hardening, X-ray scatter, misalignments, inappropriate configuration, insufficient data, or an improper algorithm (improper in the sense that the algorithm is being stretched for an application for which it was not designed; this includes the CT reconstruction algorithms themselves).

Artifacts are often the limiting factor in image quality. As we try to build images that push the limits of the CT process (higher contrast sensitivity, finer spatial resolution, greater number of pixels in the image, etc.) the more likely that a new set of previously unseen artifacts (in the particular application) will be present. Artifacts are always present at some level. Mitigating their effects on the final image is best done in the place that gave rise to them. If artifacts cannot be easily fixed at their origin, the only real alternative is a software fix. Even then many artifacts are better fixed before image formation by transformations of projected data. For more detailed information about CT artifacts, see references by Shepp, et al., and Chase, et al., [6,8,9].

2.5 Speed of the CT Process

The speed of the CT process governs more subsystem choices than any other variable because everything depends on how fast the CT scans are made and displayed. For a given spatial resolution and contrast sensitivity, there must be an X-ray source capable of emitting the requisite number of photons per unit time. In order to increase the scan speed and maintain the same spatial resolution and contrast, the number and configuration of detectors may have to be changed to accommodate a large filling factor (ratio of detector area to total area) than would otherwise be required.

The bus structure -- how the various subsystems talk to each other and the speed with which data can be transferred -- depends on the overall speed requirement. Even the mechanical system, which moves a given load at a certain accuracy, must accomplish its function within the overall time envelope; thus, the motors, brakes, and control and sensing circuitry are all subject to this overall time limit. As an initial baseline, the computer and specialized processors are all picked on the basis of being able to function within the allotted time; this assumes that the digital system merely "keeps up" with the data acquisition task. Usually the subsequent CT data manipulation requirements determine the type and size of the digital system.

2.6 Reconstruction Matrix Size

Image resolution and field size govern the number of views and data samples/view that must be acquired and, thus, the number and configuration of detectors. The higher the resolution, the smaller the pixel size and the larger the pixel matrix for a given field size. The larger the matrix, the more computation power is required. The number of operations for reconstruction grows at a much greater rate than the number of pixels.

2.7 Slice Thickness Range

The slice thickness range specification affects the height of the detector and the aperture, which defines the projection of the X-ray beam onto the detectors. Slice thickness specifications extend the dynamic range over which the system must work by a factor equal to the ratio of thickest to thinnest. Slice thickness is directly related to axial resolution (axial being the direction perpendicular to the CT plane). The higher the axial spatial resolution, the thinner the slice.

2.8 Operator Interface

The operator interface determines much of the structure of the rest of the CT system. (This is covered more fully in Sections 3 and 4.) The control panel and image processing system are the two obvious subsystems, but this is just a fraction of the system that is affected by operator I/F requirements. All the control software, mechanisms, and interface to a remote data workstation are controlled by this interface. Override logic, emergency shutdown, and safety are all controlled at this point.

2.9 Archival Requirements

Archival requirements usually involve hardcopy, tape, and/or optical disk. These dictate a small subsystem choice, but can affect the software designed to keep track of the images, the parameters associated with the image, data compression algorithms, etc.

2.10 Other Requirements

Generally, other requirements are minor or affect nonstandard system configurations or uses. However, they can have serious consequences if not addressed during the initial phases of system planning. The facility requirements, while not strictly part of the CT system, affect operation and utility of the system. Facility and facility interface requirements should be established early.

3.0 CONSTITUENTS OF THE CT SYSTEM

The first task in analyzing a CT system design is to separate the CT system into its various constituents. Figure 3-1 is a block diagram for a gene..c CT system which shows this to a depth consistent with the top-level round of make-buy decisions. It is instructive to proceed through this process in a manner similar to how the CT system designer proceeds. The order in which the CT system designer looks at these constituent subsystems is different from the attribute list. The attributes is a list of what the system must do. The CT system designer's list answers the question of how the system accomplishes those things.

3.1 Operator's Console

In designing a system, the initial priority is not the geometry or configuration, or any of the instrumental pieces associated with the hardware, but the operator's console (OC) because the OC defines exactly what can and cannot be done with the system. A complex interaction demands a complex interface. A simple interaction scheme does not require much of an interface.

There are three generic types of operator interfaces:

1. A simple programming console interface, where the operator types in commands on a keyboard. This scheme is typical of standard mini- and micro-computers. This is the easiest to design and implement, but the most awkward and cumbersome from the user's perspective.

2. The dedicated console with specific function buttons and relatively rigid data and processing structures. These system OCs are usually developed explicitly for standardized, nonvarying inspection tasks. They are designed to be "functionally hardwired" for efficient throughput for that program. The price of that efficiency is a lack of flexibility or other test specimens and nonstandard programs.

3. The third type of interface uses standard workstation hardware, but employs a custom software display of the windowing type and a pointing device (e.g., a mouse) for much of the interaction.

Comparing these three alternatives we find that dedicated instrument panels and functions are expensive and difficult to change. PC-based panels are awkward unless a windowing interface is adopted. Windowing interfaces are probably the most flexible and comparable in cost to the simple programming interface in the long run.

3.2 The X-Ray Source

The energies of the X-ray photons are determined by the test specimen and by what is available in a commercial generator. The flux of the X-ray beam is determined by how many photons are needed for statistical considerations. The spot size is determined by the spatial resolution and specimen geometry requirements. A big test specimen implies a big source. The rules for source selection are almost identical for CT and conventional radiography.

The X-ray source is usually controlled and monitored by the central processing unit (CPU). For a continuous wave X-ray source of standard design, this is relatively simple. For an electron linear accelerator based source (where X-rays are made in short bursts), control, especially the timing, can be somewhat more complex.

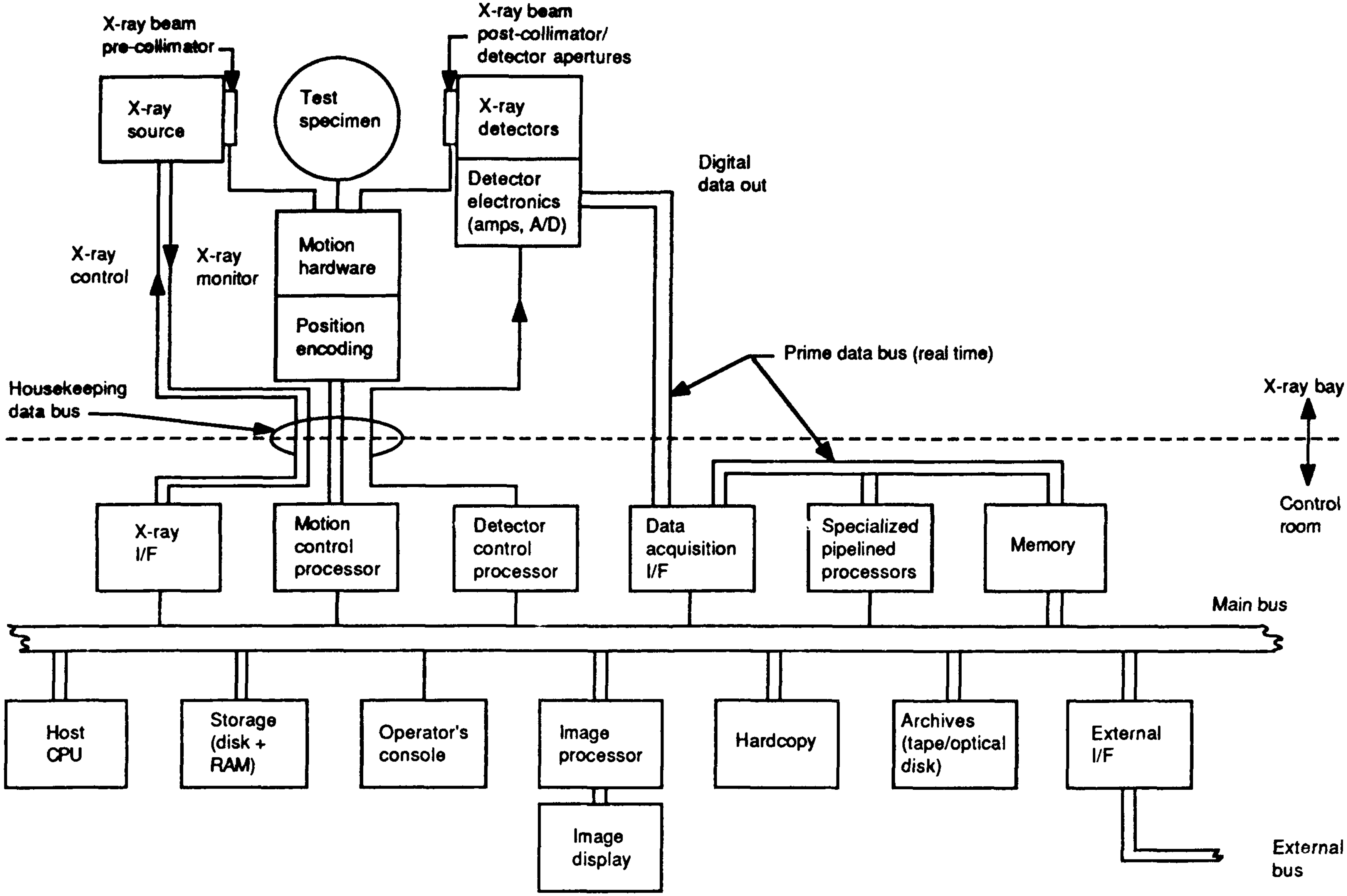

Figure 3-1. Generic CT system

3.3 The X-Ray Detectors

The detectors are usually some kind of scintillating X-ray crystal, e.g., cadmium tungstate or bismuth germanate that is optically coupled to a photoconversion device like a photodiode or photomultiplier tube. Submegavolt systems sometimes use high-pressure gas (xenon) ionization detectors. The detector width within the plane is determined by the spatial resolution requirement and is usually set by some kind of shielding aperture plates that define the detector's field of view. The required number of views is the major determinant in the configuration of the detectors. The lower limit on the number of views is determined by the combination of the number of pixels in the reconstructed image and the contrast sensitivity. There are frequently far more views and rays/view acquired than are necessary for the reconstruction algorithm to work; these extra data points are combined to improve the contrast sensitivity, and they can help reduce the level of certain kinds of artifacts.

The front-end analog electronics amplify the minuscule detector signal to a magnitude which can be digitized. Fast systems demand good fidelity of the amplified signal. What makes the task especially demanding is the fact that many signals, differing by several orders of magnitude, are frequently multiplexed on the same line in rapid succession; intersignal amplification rates are measured in microseconds.

The analog-to-digital conversion is done as close to the analog amplification chain as possible. The accuracy requirement of the A/D must be consistent with the statistical limitations of the largest X-ray fluxes and the smallest signals. There are several ways to solve this problem. Square-rooting A/Ds yields the best theoretical performance, but they must usually be customized to perform at speeds that track the high data rate. Similar performance can be achieved by the proper combination of linear A/Ds operating over several different ranges. High-speed logarithmic A/Ds are sometimes used, but the electronic "afterglow" of a very high reading can sometimes corrupt a subsequent low reading.

The data acquisition interface to the electronics and detector control usually involves the standard data-ready/data-send/reset type of logic.

3.4 Test Specimen Motion and Motion Control Systems

For this analysis we have assumed that all motion involves the test specimen. While this is not universally true, especially for large test specimens, the conclusions of the analysis are valid for all systems.

The test specimen motion systems are, collectively, the single most important feature that distinguishes one CT system from another, at least from the perspective of the CT system designer. As shown in Figure 3-1, everything below the dashed line --the hardware in the control room-- can be virtually identical for most CT NDI/E applications. The motion system, however, is almost guaranteed to change from one application to the next.

The control system for these motion systems is often based on a dedicated microcomputer configuration, e.g., a Motorola 68000, where changes between systems can be implemented in software rather than in hardware. Thus, a common selection is the 68000 operating on a VME bus, with communication between the mechanism control functions and the main bus regulated by an appropriate (microcomputer-controlled) interface. Other approaches include commercial programmable indexers directly coupled to the central processing unit. Section 3.6 discusses software in greater depth.

3.5 Computer System/Bus System

The entire digital electronics base (everything below the dashed line in Figure 3-1) can best be viewed as an assembly of blocks. The most important function, once the operator's console is defined (Section 3.1), is the selection of the bus (or buses) and the central processing unit (CPU). This selection governs how all the other blocks communicate with each other.

The best approach is to pick the best CPU and bus first, and then add the other blocks. Historically, this selection has been based on existing minicomputer CPUs (primarily DEC VAX and Data General MV series supermini-computers), their attendant buses, and operating systems. More recent CT systems use other computer systems and bus structures.

The CT application is distinguished from other real-time, data-intensive (imaging) computer system architectures by the specialized hardware processors required for image acquisition and reconstruction. The two functions of convolution and backprojection are typically performed in separate boxes that have hard-wired, dedicated circuitry operating in pipeline fashion; the number of calculations is on the order of 1×10^9 per image.

All the blocks off the main bus, including the image processing unit, the display unit, the specialized hardware processors (e.g., convolution board, backprojector), etc., can be viewed as peripherals servicing the CPU. A priority list for servicing these peripherals must be established, with the real-time operations and operator's console typically having the highest priority. They must be interfaced with the bus, and proper software encoded to control the exchange of data and command of functions.

The only other block that needs some further discussion is the external interface block. Very often, real-time applications demand an interface between the computer system attached to the CT system and an external computer or a remote data workstation. Thus, several such systems already developed for military purposes send their data over IEEE 488 or similar interfaces to a sophisticated data evaluation system.

3.6 Software

CT system designers know that, during the implementation phase of a new system, there can be wide-ranging variations from the baseline. The changes from one CT application to the next, even with the same instrument, can involve major effort. The design imperative dictates minimal change in hardware because hardware changes are very expensive. For this reason, control, measurement, and other logic functions are assigned as often as possible to computer-based systems, where changes can be accommodated in software. Almost always, the physical hardware for these systems is microcomputer chipsets (except for the CPU and the specialized hardware processors), which can be programmed and reprogrammed for various changing CT system requirements.

Generally, software-based functions minimize problems for the CT system designer. However, software control and development have demands similar to those associated with hardware. Software development is the most expensive and time-consuming activity associated with the development of CT systems; its value lies in accommodating change.

Software can be segregated into three categories: 1) logic and control, 2) algorithms and computation, and 3) movement of large quantities of data.

1) Logic and control functions reside in several places: the operating system, microprocessor-based subsystems that define the relations with the instrument in the X-ray bay, and the operator's console. (There is often a shell program,

based in the console, that lets everything else run. Sometimes the operating system itself provides the shell.)

2) Algorithms typically reside in the CPU and in the specialized hardware processors like the convolver and backprojector, whose functions are presently being done mostly by commercial array processors.

3) Data manipulation software is usually microprocessor-based. We include it as a separate software category because the problems associated with the prodigious data transfer rates often require specialized approaches, sometimes including a dedicated data bus.

Wherever possible, software is designed as part of an overall logic scheme. So-called "top-down" programming is usually how every project begins. Changing requirements and failure of certain other parts of the system to meet specification frequently drive software to compensate for those deficiencies. Unless the software designer (and all the other members of the design team) monitor the process carefully, the result is often indiscriminate software that is delicate rather than robust and follows no grand plan. Thus, a high-level language is generally chosen for the code because it is easy to understand, debug, and change. Some companies have even developed their own user languages to speed customization. When time constraints drive the hardware to the point where the compiled versions of that code do not run sufficiently quickly, the software engineer may be forced to code in assembly language. Software is often viewed as separate from hardware. This is a false view. Hardware and software must be developed together. It is impossible to separate the hardware designer from his software counterpart. Those who try such a rigid separation are doomed to a poor implementation at best; at worst, a collection of parts that do not function as a system.

With this discussion as background, the need for thorough specification and design at every stage of the user interface is clear. Insufficient definition of these interfaces and lack of organization, particularly early in the project, can result in software problems later in the development program.

4.0 TRADEOFFS: CT PERFORMANCE VS CHOICE OF COMPONENTS AND SUBSYSTEMS

The performance of a CT system will involve tradeoffs in the specification of attributes and their resulting constituents. The effects of tradeoffs in performance parameters revolve most significantly around the following constituents and attributes.

4.1 Operator's Console and Interface

The operator console and interface hardware can range from a PC interface at the low end to the dedicated instrument panel at the high end. In between is the windowing type of display. The image display and processing systems can range from an inexpensive display system without annotation capability to a highly interactive graphics-type workstation with all the capability of high-level image processing.

The software that accompanies the operator's console can function in a one-step manner, or it can follow preprogrammed sequences. The ability to construct sequences of such preprogrammed functions is a desirable capability. The ability to accomplish many tasks in parallel is desirable because this increases the system throughput. The operator does not have to wait for breaks in the data acquisition sequence to perform inspections and vice versa. The price is that the system must now be programmed in a multi-tasking mode with its attendant software overhead.

Requirements for the operator's interface can often be a significant cost driver. Thus, for instance, readouts of position of various moving assemblies or control of X-ray collimators situated on either side of the test specimen is a desirable feature, but one that requires extensive programming effort. Every new automatic feature *involves additional software development.* Unless that feature has already been developed, specifying its inclusion may be very expensive.

The tradeoff in the operator console and display is basically one of cost versus performance. High performance may mean user friendly interface, automatic sequencing, parallel tasking, high speed data handling, high resolution/high quality display, image processing options and good system diagnostics for operations and troubleshooting. Generally a higher cost operator console and interface will provide easier operation and overall time savings. Because CT is primarily an image based inspection technology, the highest quality image display and data handling capability consistent with the data quality should be maintained.

4.2 Test Specimen

The test specimen determines the X-ray source and detectors and the mechanical handling equipment. The X-ray source could be as simple as a gamma-ray source; it could be a microfocus source, a standard 160 kV constant potential source, or a linear accelerator (linac). It all depends on the test specimen. Adding test specimen range can be very expensive, especially if it pushes the designer into the next X-ray generator range or bigger mechanical components. Figure 4-1 is a plot of the energy and size of a CT system versus the component cost for the manufacture. This figure is only an approximation but provides a relative scale for assessing the tradeoff in cost as a larger test specimen is selected.

The specimen and X-ray source are the primary determinants of the dynamic range of the detectors and the front-end electronics. Simply put, the data acquisition subsystem must accommodate a signal range extending from completely unattenuated to the completely attenuated case and still provide sufficient signal resolution to be consistent with the photon statistics. Dynamic ranges on the order of 1 million are the norm.

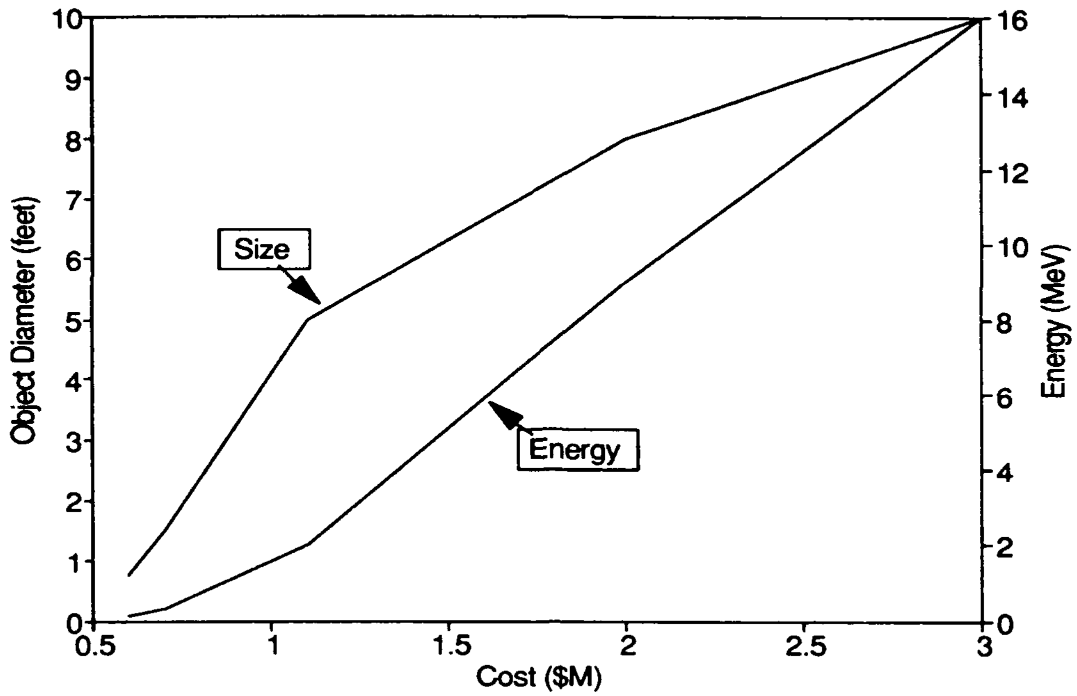

Figure 4-1 Tradeoff of CT system energy and size versus system component cost (These values are rough order of magnitude estimates based on hardware component costs for the fabrication of a CT system.)

The mechanical handling system must be built to fixture the test specimen and the source and detectors. The main structure is set by the test specimen itself; however, speed, accuracies of the equipment, etc., are functions of other variables. The motion systems can range from a simple turntable-and-vertical-linear stage of the small turbine blade, or may involve something as complex as a large 100-ton rocket-in-a-socket design. Generally, the accuracy requirements for the motion systems can be accomplished with standard-tolerance hardware, as long as the designer is innovative in his use of configuration. Super-tolerances are expensive and should be avoided.

4.3 Spatial Resolution

Spatial resolution requirements can affect an entire range of components, subsystems, and procedures. Spatial resolution places limits on reconstruction geometry errors, which are, in turn, dependent on the accuracy of the mechanical handling equipment and the equipment configuration. For extremely high spatial resolutions (e.g., 20-50 microns), the typical tolerances on parts might be 5 to 10 microns if we are to reconstruct blindly, relying on the precision of the equipment itself. This clearly would involve high-precision parts. A better solution, if possible, is the incorporation of knowledge-of-position information (which might be available with encoders and good software), which can then be fed into an appropriately configured reconstruction algorithm. Spatial resolution also limits the spot size, detector aperture width, and defines the geometry between source and detector. This defines the ray width at the test specimen [10]. Thus, a requirement for a high MTF at a certain frequency may require a microfocus source or tight detector apertures. It might require sampling at smaller spatial intervals. It might also affect the speed of the data acquisition process.

Fine spatial resolution requirements can drive mechanical designs and tolerances to extremely high costs. Typically system designs can accommodate spatial resolutions up to some limit. Beyond that limit, redesign with different, more accurate components and different assembly procedures act to drive costs to extremes. Doubling the spatial resolution (in lp/mm) could easily increase the cost of a mechanical subsystem by an order of magnitude.

4.4 Contrast Sensitivity/Speed

Contrast and speed are noted together because their primary effect is in setting the number of X-ray photons that can be detected per unit time. Contrast sensitivity determines the minimum accuracy of the X-ray attenuation measurements. The contrast sensitivity is often quoted in percent of the noise to signal ratio in the reconstructed image. Thus,

$$C = N/S$$

where C is the contrast sensitivity in percent, N is the noise which is usually the standard deviation of the image values and S is the signal which is the average of the CT numbers over a given area. The better the required contrast sensitivity, the stronger the X-ray source that is required in order to reduce the photon statistical noise in the image. For large rocket motors, it may mean the difference between a 9-MV linac and a 16-MV linac (a difference of $500K at the OEM level), and a different shielding facility.

The effective detector size and the number of detectors can be made larger to increase the capture fraction of X-ray photons, thereby satisfying a tighter contrast sensitivity requirement. Detector construction can also be affected because of the possible interference of adjacent detectors and their hardware (e.g., apertures).

Higher scan speed has effects that can ripple through the entire system. These could include heavier and more robust mechanical subsystems, a more powerful X-ray source, a faster and more powerful computer system, and a different bus architecture. Everything must work faster.

Reconstruction speeds will be influenced by the image array size, the number of views, the data per view and the computer hardware including array processors and backprojectors. If there is no requirement on reconstruction speeds, this function can actually be handled in an offline manner entirely in software resulting in tremendous cost savings.

4.5 Number of Pixels in the Image

As the number of pixels (m x m) in the image increases, the number of samples/view and the number of views must increase; otherwise, unacceptable artifacts will result. The combination of a large field size and a given spatial resolution implies a certain minimum value of m. Figure 4-2 shows the effect of resolution on the field for several common matrix sizes (m is usually selected in powers of 2). Increasing m and requiring that the same contrast sensitivity be maintained exacts a very high price.

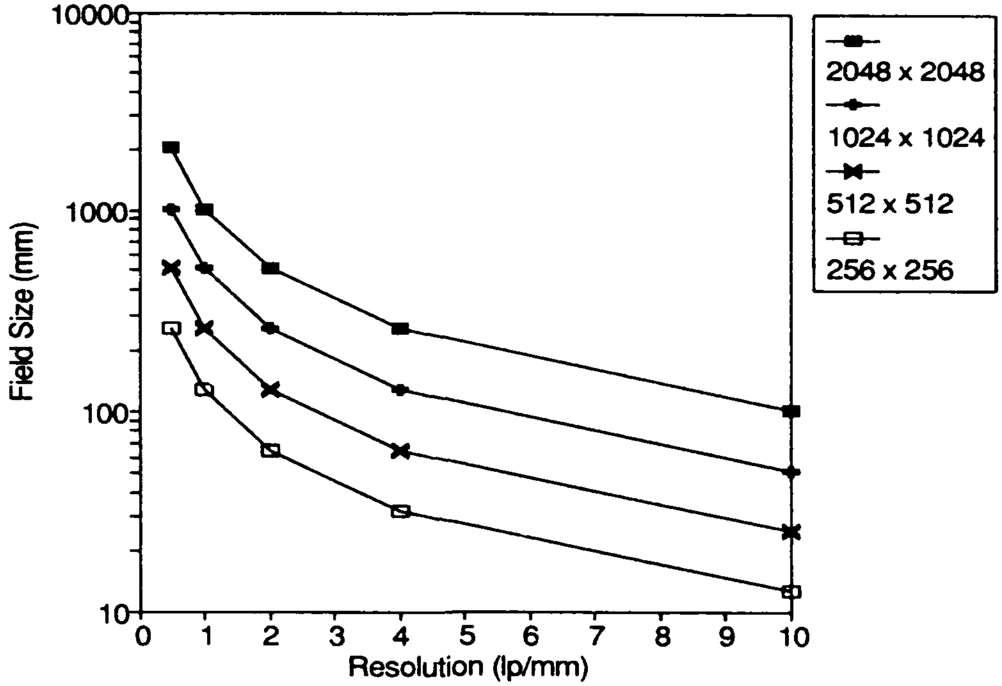

Figure 4-2 Effect of resolution on field size for several pixel matrix sizes (These are the maximum fields of view that can be imaged at full resolution with the number of pixels available.)

Consider a CT system optimized to match that the resolution and pixel size so that the spatial resolution is equal to the field size divided by m. The ray spacing for data acquisition must be at least one-half the pixel size or else aliasing will occur in the image results. The standard deviation (noise) in the image determines the contrast sensitivity: as the standard deviation increases, the contrast sensitivity degrades. The relationship of the standard deviation, resolution and number of views is given by:

$$s = k\, m\sigma/2(v)^{1/2}$$

where s is the standard deviation in the image, m is the number of pixels along one side of the reconstruction, σ is the standard deviation of the log of the data sample and v is the number of views [11]. The magnitude of constant k is a function of attenuation and the precise method of convolution but does not change for a given operating configuration. This equation shows that doubling m in order to increase the spatial resolution (of course, the effective X-ray beam width must be suitably matched) requires an increase in the number of views and a decrease in the standard deviation of the data samples in order to maintain the contrast sensitivity. If the number of views are also doubled, then the standard deviation of the sample must be decreased by a factor of $(2)^{1/2}$. This last factor is tantamount to doubling the signal. This requires 4 times as many samples taken at twice the signal strength. It is often the case that a finer spatial resolution results in a finer aperture that acts to sharpen the MTF. However, the price of that sharpening could easily be a factor of 2 loss in photons detected per unit time interval (dwell time). The dwell time for proper σ would then be higher by a factor of 4 (factor of 2 for the smaller aperture, and factor of 2 for the signal doubling necessary to improve the standard deviation). The total scan time will be increased by a factor of 16 composed of the factor of 4 for dwell time and factor of 4 for increased samples.

A reconstruction of m x m pixels requires an array processor capable of convolving 2m size lines of data (i.e., single views). The typical (and current state-of-the-art) array processor will handle a 2048 element data string, which corresponds to the number of rays in a single view. The modern array processor makes this relatively easy to extend to 4096. The number of convolution calculations approximate (m) x log(m) per line. Unless processing time constraints are severe, requirements on m should not unduly affect a state-of-the-art computer architecture and bus structure.

4.6 Detectability of Anomalies

This discussion of tradeoffs has considered resolution and contrast sensitivity effects on defect detection. These attributes quantitatively characterize CT images, but the really important question is how we predict the detectability of various anomalies. Appendix A discusses in detail the issues surrounding the probabililty of anomaly detection in CT.

Establishing detectability criteria for the CT system specification will influence the selection of the system constituents. The higher the required probability of detection, the more stringent the requirements on spatial resolution and contrast sensitivity. The CT slice thickness must also be taken into account as part of the detection criteria. The tradeoff in the probability of anomaly detection involves being able to live with false calls (accepts and/or rejects) versus spending more money on system capability.

5.0 COSTS FOR THE CT SYSTEM

5.1 Manufacturing Cost

The CT system manufacturing cost is a function of the specification for the design. The approximate cost for development of a CT system by workers who have gone through the experience previously is shown in Tables 5-1 and 5-2. This is a very subjective estimate based on discussions with representatives of several CT manufacturers. Table 5-1 shows the breakout, element by element, for a completed system. Table 5-2 shows the approximate development cost of a generic system.

Table 5-1 examines two extremes for most of the systems quoted. One is a more-or-less standard design, and the second employs inexpensive hardware where possible. The differences are almost all in the computer system and peripherals. These differences are most significant in the low-end systems where the differences can be as much as a factor of 2 in cost. The last column in Table 5-1 shows the lowest cost, but plausible, CT system that uses a very simple design and customer furnished equipment (CFE), in particular the X-ray source. Even with this system, the cost to the manufacturer is at least $50K. These costs are based on buying what is available and avoiding as many initial development costs as possible.

Table 5-2 shows the development costs associated with a typical system, based on $150K per man year. These costs are more typical for the high-end systems than for the low-end. However, even at the low-end, we would expect the costs to be a reasonable fraction, say 30-50 percent of the bottom-line cost. Table 5-2 also assumes that any of the truly high-end cost items, like a dedicated instrument panel, have already been developed, although not utilized for this application.

We have taken these costs to be typical of the late 1980's. The projected increases for inflation can be applied to the labor as necessary. Costs for digital systems and other purchased computer hardware can be expected to fall dramatically in the future. CPU's purchased in the early 1980's for hundreds of thousands of dollars can be replaced by units available at a small fraction of that original price and offering far more power.

Unnecessary widgets, options, and unnecessary speed push costs to the high end within each range in Table 5-1. Development costs shown in Table 5-2 can vary from a minimum of about 30 percent of that total to 150 percent for the more extensive set of options, including speed. The cost of a system can be increased tremendously by the changing of a single requirement.

An illustration of this effect from a real world example, with certain idealizations, is useful. A system that inspects small solid rocket motors that are 12 inches in diameter has a spatial resolution consistent with its pixel size, stretching 512 resolution elements across a 15 inch field of view. Our hypothetical solid rocket motors have a simple cylindrical construction consisting of a metal case, an insulator that lines the case and protects it from the hot gas generated during burn, and propellant that extends from the insulator inward. The requirement as given to the CT system manufacturer is that unbonds at the case/insulator and insulator/propellant interface be identifiable to a level of 0.005 inch, extending over 1/2 inch in circumference. Moreover, the CT system must be able to show which interface (i.e., on which side of the 0.040 inch thick insulator) the unbond has occurred. Contrast sensitivity requirements are driven independently. The system as conceived above with 512 elements will perform the job. Now, however, the user has decided that the system should also accommodate inspection for a design that may be changed to utilize a 0.015-inch-thick insulator. The 512 resolution element system will no longer tell which side of the interface an unbond has occurred, because the 0.029-inch pixel

Table 5-1 Costs for elements of a CT system

ELEMENT	SYSTEM					
X-RAY SOURCE						
Type	L-6000	L-3000	L-200	320 kV	160kV	CFE
Cost	$1,000K	$500K	$300K	$75K	$15K	$0
X-RAY DETECTORS*						
Channels	200	200	400	500	500	
Cost/channel	@$1K	@$1K	@$500	@$200	@$200	
Standard	$200K	$200K	$200K	$100K	$100K	
Inexpensive @$10K+$100/chnl	$30K	$30K	$50K	$60K	$60K	$10K
DETECTOR ELECTRONICS FRONT-END						
Standard @ $100/channel+$20K	$40K	$40K	$60K	$70K	$70K	
Inexpensive @$20K	$20K	$20K	$20K	$20K	$20K	$0
MOTION SYSTEM.						
Specimen weight	50-TON	20-TON	2-TON	1-TON	1-TON	SMALL
Cost**	$1,500K	$1,000K	$250K	$100K	$100K	$10K
CPU & MAIN BUS***						
Standard	$100K	$100K	$100K	$100K	$100K	
Inexpensive	$10K	$10K	$10K	$10K	$10K	$10K
IMAGE PROCESSOR AND DISPLAY SYSTEM***						
Standard	$100K	$100K	$100K	$100K	$100K	$7K
Inexpensive	$7K	$7K	$7K	$7K	$7K	
OPERATOR'S CONSOLE						
Dedicated instrument panel	$30K	$30K	$30K	$30K	$30K	
PC based	$5K	$5K	$5K	$5K	$5K	$5K
STORAGE (DISK + RAM)***						
Standard	$40K	$40K	$40K	$40K	$40K	
Inexpensive, PC-based	$7K	$7K	$7K	$7K	$7K	$7K
HARDWIRED PROCESSORS***						
Standard	$50K	$50K	$50K	$50K	$50K	
Inexpensive	$5K	$5K	$5K	$5K	$5K	$5K
HARDCOPY	$10K	$10K	$10K	$10K	$10K	$4K
TAPE UNIT	$20K	$20K	$20K	$20K	$20K	$0
TOTAL H/W COST - Standard	$3,090K	$2,090K	$1,160K	$695K	$635K	
TOTAL H/W COST - Inexpensive.	$2,614K	$1,614K	$684K	$319K	$259K	$58K

*The number of detectors and the cost per detector vary as a function of the X-ray source. We have take nominal values.

**Includes position sensing

***We expect hardware costs for digital electronics to decrease, following their history of the last three decades.

Table 5-2 Nonrecurring engineering development costs

ELEMENT	NONRECURRING ENGINEERING DEVELOPMENT COST (H/W & S/W)*
X-Ray Source	$10K
X-Ray Detectors	$75K
Detector Electronic Front End	$150K
Motion System	$200K
CPU and Main Bus	$150K
Image Processor & Display System	$75K
Operator's Console	$150K
Storage (Disk + RAM)	$30K
Hardwired Processors	$300K
Hardcopy	$5K
Tape Unit	$5K
Algorithm Development	$200K
Integration of System	$150K
TOTAL DEVELOPMENT COST	$1,500K

* BASIS: $150K/MAN-YEAR, 1989. In the future these costs can be scaled by inflation. Software costs may decline because the availability of better hardware relieves many existing constraints on software development.

cannot provide the finer spatial resolution implied by the new requirement. The inspection requirement changes bring the following system changes:

(1) A mechanical system more accurate by a factor or 2 than the previous one
(2) A slowdown in scan time by a factor of four (if we can change the detector package to compensate) or eight (if we can't) owing to the necessity for more views at increased flux
(3) A new convolver and backprojector are required for the resulting 1024 image
(4) A new display station
(5) Image storage requirements are up by a factor of 4.

The change in costs for these requirements could be as high as for the baseline system itself. The biggest cost over the long run is likely to be the operational slowdown caused by the reduction in scan time. The point of this illustration is to understand the ramification of the requirements, because the costs of overspecification (or underspecification) are enormous.

5.2 Purchase Price

There is a big difference between costs of development and hardware to the manufacturer and the selling price of a CT system. The difference can be attributed to marketing costs, inefficiencies in manufacturing, buffering risk and recouping nonrecurring engineering development costs. Actual profit counts for very little.

The primary factor in determining price is what the market will bear. The test specimen determines how expensive the CT system can be. Almost all CT systems are marketed and sold to achieve a return on investment, whether the burden is figured exactly (e.g., on turbine blade inspection systems) or figuratively, as in the studies relating to Space Shuttle CT ("we can't afford to risk life, no matter the cost"). If the market cannot support the manufacturer's perceived cost and all of the incidentals mentioned above, then there will be no CT system.

CT technology development is very expensive. The learning curve for CT is both steep and long, and companies that have tried to introduce and market CT systems, even with the best and the brightest of staffs, have not managed to succeed without very strong financial backing during the development period. General Electric, Toshiba, and the U.S. Government (via CPFF development contracts) are the primary agents involved in financing initial CT development within this country.

Marketing costs for nonmedical CT systems are extremely high. The average cost per serious bid is probably \$50K to \$100K because CT systems for NDI/E come primarily from a group of very small businesses that sell primarily one product in that marketplace, rather than a line of products. Each potential customer has a unique need that must be addressed by a CT system that almost certainly requires some modification from the manufacturing standard. Each customer requires at least several visits, including efforts by technical experts. The customer must be invited to the manufacturing facility to see that, indeed, the manufacturer is capable of building the promised system. The proposal for each CT system is a detailed analysis of the requirements of the RFP. Thus, the marketing cost for each CT system sold (dividing the business up among 4 to 5 generic manufacturers) is at least \$200K. Manufacturers who charge significantly less are not allocating their marketing costs accurately.

CT system manufacturers are usually inefficient manufacturers. For the most part they are small companies where physicists are largely the decision makers with technical people in control of the process. Most CT systems are not engineered from a manufacturing perspective but from a research and development perspective. Thus, many features that a manufacturing engineer would consider "overdevelopment" are included by technically-oriented managers. Including these features can be time-consuming and costly, but that is the nature of an R&D system. In addition, the market is so limited that production runs are not long enough to produce manufacturing efficiency comparable to medical CT.

CT system manufacturers take a risk every time a new system is built. (Even if that system is a build-to-print job that has been done before, chances are the as-built version will have to conform to slightly different requirements or will take advantage of some newer technology. That new system will be different.) The manufacturer must add a premium into the pricing to cover that risk. That is typically 15 percent to 20 percent of the cost of the system.

Most of the NDI/E CT manufacturers have not made huge profits on CT. For the most part, they have reinvested any profit by adding to their technical staffs. The investment has been in people who worked on developing these systems in the first place. The typical profit is projected at 8 percent to 10 percent on cost-plus-fixed-fee contracts (this is a typical Government figure), and at 15 percent to 20 percent on firm-fixed-price (FFP) contracts, which must include a certain contingency. The cheapest CT system, if the development is already paid for and costs are allocated properly, is on the order of $300K to $500K.

5.3 Procurement Cost

The actual cost of a CT system to the buyer includes more than the purchase price. A CT system procurement will involve time in identifying the need for the system, acquiring market information, preparing a specification, evaluating the proposals, monitoring fabrication, preparation of a facility, monitoring installation, training and maintenance. There are no set rules to the cost of each of these tasks. In some organizations these costs may appear indirectly in overhead functions which will perform them. In other cases, they must have a specific budget. If the system is to be installed in an existing facility then the facility costs may be low. If an entirely new facility must be constructed then the costs will be very high. Roughly a budget plan should allow 1 to 2 percent of the system cost for prepurchase activity, 10 to 20 percent for facility costs and 5 to 10 percent for installation and training. Maintenance costs will run roughly 5 to 10 percent per year.

6.0 SPECIFICATION PREPARATION

The specification preparation for a CT system is a critical part in the process of system procurement. This guide has discussed the system attributes and issues that surround the technical specification. This section provides some additional useful concepts to assist the buyer in assembling the specification and procuring a system.

Prior to preparing the specification, it is critical to define the purposes of the system. For example, is the CT system for research or production purposes? Is it to be a versatile system or inspect a specific part? What exactly are the part size range, anticipated quantities, required sensitivity and throughput? These issues should be quantified if possible. To assist in this definition, early discussions with CT system vendors should be held to avoid the potential problem of putting unrealistic or overly expensive requirements into the specification. Vendors are normally willing to not only make presentations on their equipment, but will often provide complimentary test scans. By discussing the various tradeoff factors from Section 4 with the vendors, a realistic specification can be developed so that the bids will fall into the allowed budget.

The specification should begin with a description of the purpose of the CT system to be procured and include the required performance in CT terminology as discussed in Section 4. The specification should not define in detail the actual hardware configuration. It is best to let the vendor suggest the optimum method to achieve the required performance. This performance may require certain compatibility issues that will define specific hardware or software. The specification should be very realistic in terms of cost, based on earlier discussions with vendors. One technique that can provide a hedge on the overall system cost is to request options. Options to a basic CT system allow the buyer to select which features provide enhancement beyond a minimum capability that will fit within budget. Options also offer the vendor the opportunity to propose innovative approaches that may overcome budgetary limitations. The specification should also require the vendor to provide references to previously delivered CT systems and examples of the CT imaging capability proposed.

The specification becomes the central portion of the procurement package to which the vendors will bid. The buyer should allow ample time for the vendor to respond to the package. Too short a time frame will result in poorly defined bids which can result in future delivery problems. The method of proposal review should be thoroughly considered prior to the package release because it will define certain responses that may be desired in the package. For example, it is a good idea to set a realistic page limit to the proposals to obtain focussed proposals and avoid wasting time reviewing unnecessary material. It may be important that the proposals respond to the specification in a line-by-line or section-by-section basis in order to be able to correlate the capability of the proposed system to the requirements of the specification. Figure 6-1 lists some useful suggestions for inclusion in the specification and bid package preparation process.

The evaluation of the returned bid packages is an extremely important function which can influence the specification. At the time of specification development, the plan for proposal review should be determined. This plan, or portions of it, may or may not be included in the proposal solicitation. The evaluation plan should define a list of criteria that proposals will be scored against. Figure 6-2 lists a number of areas that should be considered for a CT system. The specification should include specific requirements that must be met for each area. The line-by-line or section-by-section response requirement in the proposals will allow the evaluators to more easily reach a decision on the relative merits of each proposal to the area being scored. The evaluation should include a relative weighting of the various areas so that a numerical total can be calculated on the suitability of the proposals to meet the procurement goal.

Specification and Procurement Suggestions
Have vendor reviews prior to developing the specification
Be realistic about costs
Include a description of purpose in the specification
Set a page limitation for proposals
Require example scans if possible
Require references to delivered systems
Allow ample time for bidder response
Request options
Require a line-by-line response to the specification
Have a diversified evaluation team
Weight the specification criteria and have a scoring plan

Figure 6-1 Suggestions for the specification and procurement process

CT System Evaluation Criteria
Radiation Source
Detector System
Data Processing System
Software
System Resolution/Contrast Sensitivity
Artifacts
Graphics Display
Hardcopy
Mechanical Systems
Scan Time/Reconstruction Time
Data Archiving
Conformance to Other Delivered Systems
Options/Upgrades
Documentation
Facility Requirements
Spare Parts/Accessories
Maintenance and Repair
Training
Warranty
Experience
Cost

Figure 6-2 Potential areas for setting CT system evaluation criteria

The effort of the evaluation team to select the CT system that will best fulfill the project goals within budget is not an easy task. The eva'uation team and the scoring system should be carefully considered. One useful suggestion is to include individuals with varying backgrounds on the evaluation team such as NDI/E engineers, systems engineers, computer scientists and management.

The purchase of a CT system will involve a partnership between the purchaser and the vendor. By planning the specification and evaluation, with input from the vendors, the partnership should result in a successful system installation and operation.

7.0 RECOMMENDATIONS

This guide to CT system specifications has shown that a number of tradeoffs in the system design can lead to variations in cost and performance. The analysis points to some key recommendations for CT systems and system procurement.

The first and most important step that a customer can do is to write down all requirements in as much detail and as quantifiably as possible. These details should include the acceptable probability of not finding an anomaly that is present. Simply requesting the ability to detect an anomaly of a certain size abdicates the responsibility of determining an acceptable probability of detection to the CT system designer and manufacturer. Frequently the CT designer will accept the responsibility rather than educate the user to the statistical approach to detection. The difficulty arises when different CT system designers assign different levels of acceptable probability of missed anomalies. User requirements should be translated into the language of a CT system specification. They can then be discussed and trades in price and performance made. It is important that all requirements be considered and that the language be couched in CT terms. Then, the same specification can be presented to any of the manufacturers and they will respond with systems capable of doing the same things. Untranslated customer requirements are often ambiguous, and the manufacturers will respond to what they thought the customer meant.

The customer should put aside time and money for establishing and training a team of people to integrate the CT system into its intended role in the business. It makes sense to do this early. It also often makes good sense to procure independent expertise for help with the specification and the evaluation of the proposals. Small upfront efforts like these can save substantial time and money later.

Ideally, CT systems should be mature, should have undergone an evolutionary process and should incorporate no radically new technology. This is the only way that the CT system manufacturer can ensure that the system will function reliably in any kind of new application. Frequently, new subsystems in and of themselves are not the problem, but rather their integration into an old system that results in time and effort in excess of the original budget. Efforts that involve significant software development are always expensive. Standard designs should always be used if possible, parts purchased rather than designed or made, even if slight compromises in CT system performance are the price. This is not to say that new technology or new subsystems or new systems should not be procured. If the need is there, and it cannot be met by current designs, it is imperative that a system that includes that new key element be procured. There is nothing more frustrating than having a system that cannot be made to do what the user had in mind when he bought it.

The customer must ascertain that the system brackets the entire foreseeable range of test specimens and operating requirements and that the specifications reflect that anticipated range. The customer must check that the CT vendor's proposal conforms to his detailed specification. Moreover, the effects of any deviations must be noted and understood. Changes of scope can be complicated, particularly if that overall performance change forces a change in some subsystem that had been functioning at its limit. If changes must be implemented, the customer should check that neither the system architecture nor geometrical configuration suffers a major perturbation on account of that change. Otherwise, the customer is purchasing what is essentially a new and untried system. Maintenance and repair and spares contracts should be negotiated at the same time as the contract for the delivery of the system. Once the customer has contracted to buy the system, the vendor has no incentive to keep his maintenance and repair contract costs low. The customer has no other place to go - the vendor is essentially a sole source. Whenever possible, terms for these ancillary (but necessary) services should be negotiated before any CT system is procured.

Another important consideration in this precontract period is an agreement to have complete documentation for the system, including software source code. (Complete documentation is not the same as MIL SPEC class drawings, which frequently have the wrong kind of information for actually fixing things.) Complete documentation means that there is information sufficient for the expert who is technically astute in the subfield (e.g., X-ray physicist or electrical engineer) but ignorant of this particular system to fix anything that could possibly go wrong. This guarantees that no matter what happens to the manufacturer, the customer can still fix his system. It is the manufacturer's right to keep this material proprietary, but it is the customer's right to keep his system functioning.

8.0 REFERENCES

1. "Standard Guide for Computed Tomography (CT) Imaging," ASTM, (1990), to be released.

2. M. J. Dennis, "Industrial Computed Tomography," *Metals Handbook Ninth Edition, Volume 17 Nondestructive Evaluation and Quality Control*. ASM, Metals Park, OH, (1989).

3. A. C. Kak and M. Slaney, *Principles of Computerized Tomographic Imaging*, IEEE press, New York, NY, (1987).

4. T. H. Newton and D. G. Potts, eds., *Technical Aspects of Computed Tomography, Volume Five of Radiology of the Skull and Brain*, C. V. Mosby Company, St. Louis, MO, (1981).

5. H. H. Barrett and W. Swindell, *Radiological Imaging, The Theory of Image Formation, Detection, and Processing*, Volume 2, Academic Press, NY, (1981).

6. L. A. Shepp and J. A. Stein, "Simulated Reconstruction Artifacts in Computerized X-Ray Tomography," Reconstruction Tomography in Diagnostic Radiology and Diagnostic Medicine, M.M. Ter-Pogossian, et al, eds., U. Park Press, (1977), p. 33-48.

7. C. K. Mees, *Theory of the Photographic Process*, MacMillan Co., New York, (1942).

8. L. A. Shepp, S. K. Hilal and R. A. Schulz, "The Tuning Fork Artifact in Computerized Tomography," *Computer Graphics and Image Processing*, 10, (1979), p. 246-255

9. R. C. Chase and J. A. Stein, "An Improved Image Algorithm for CT Scanners," *Medical Physics*, 5, (1978), p. 497-499 .

10. S. Hughes, "Nonuniformity of Spatial Resolution in Computed Tomography Scanners," Materials Evaluation, 48, (May 1990), p. 562-565.

11. L. A. Shepp and B. F. Logan, "The Fourier Reconstruction of a Head Section," IEEE Transactions on Nuclear Science, Vol. NS-21, (June 1974), p. 21-43.

APPENDIX A - DETECTABILITY OF ANOMALIES

A1 Probability of Detection

What do we mean by detection? In its simplest form, a positive detection means something that we recognize as being different from the norm. "Positive detection" really means "statistically significant with respect to some background". How statistically significant is a matter of answering the question, how willing are we to be wrong. In other words, what probability of being wrong are we willing to live with? This is not a technical decision, but a political decision: The answers will be different for a pilot-less drone and for the ATF. Once we have answered the question, it is relatively easy to use that probability, the image size, and the number of images (sample size) as input parameters into a function whose output is the number of standard deviations above background an anomaly must exhibit in order to be considered as a "positive detection." Thus, a small sample size with small numbers of pixels will require a far smaller number of standard deviations from background to achieve the same probability of error that a much larger sample would require.

The acceptable probability of being wrong is one of the most important decisions that the CT system user can make. This concept is disconcerting to users because they are unaccustomed to thinking statistically. However, that probability is an essential starting point for the designer. From the designer's perspective, there is no such thing as a zero failure probability because this corresponds to a zero width in a measured population distribution. In practical terms, an error rate in the detection of anomalies of 1 in 1000 is far easier and much less expensive to obtain than a failure rate of 1 in 1,000,000.

A2 Types of Anomalies

CT cannot distinguish failures from non-failures; rather it distinguishes specific anomalies from a host background. The most common types of anomalies encountered in the examination of industrial components and materials can be classified into a surprisingly small number of categories: (1) Within single materials: cracks, voids, inclusions, delaminations, porosities, density variations (either relative or absolute); (2) at interfaces between different materials: unbonds; (3) dimensional analysis.

CT is primarily a volume inspection method, and from that perspective, what distinguishes CT from other NDI/E techniques is the ability to distinguish subtle density differences from a background or from what we expect to find there. For examining large regions (i.e., large compared to a resolution element size) for these subtle density variations, the spatial resolution is largely irrelevant; only the contrast sensitivity is important. Examination of features whose size is on the order of or smaller than that characteristic resolution element size requires a combined consideration of both spatial and contrast sensitivities. The spatial resolution for CT is usually considered to be poor by comparison with X-ray shadowgraph imaging. CT's excellent contrast sensitivity will usually detect these small features, albeit with reduced contrast.

Thus, detection of large-scale regions of porosity and other volumetric anomalies follows directly from contrast sensitivity measurements obtained under similar conditions of absorption. Void and crack sensitivities follow from the combination of contrast sensitivity and MTF measurements, subject to the similar absorption condition restriction. Interfaces and dimensional analysis information fall into a different category. The reason is that conclusions based on CT images are particularly sensitive to certain assumptions and models, and the presence of artifacts can badly distort the results of interface and dimensional investigations.

A3 Quantitative Estimates of Detectability

The first step in determining detectability is the determination of the probability of being wrong. Consider that we are willing to live with a probability of 1 percent of missing an anomaly of a given level for this entire lot without false rejection of a sample. The sample consists of 100 specimens, each of which utilizes 20 CT slices, leading to a total of 2000 slices. Further, let the image size be 512 x 512, leading to 250,000 pixels per image. Let us further state that this test specimen is cylindrical and examined in such a way that each CT image is a disk. (This test specimen is suspiciously like a rocket motor because the geometry is easy, but we could just as easily have selected a turbine blade or compressor disk.) There is a solid core of a substance whose density we want to measure, a thin case, and a thin liner layer between the case and the central core. There are approximately 150,000 pixels that cover the core, the case is about 10 pixels wide and runs the periphery of the slice. The liner layer is less than a pixel wide.

Finding the anomaly per se is not the big problem; it is the confusion caused by the huge sample size. (This assumes that the expected rate of anomalies is very small, and that the anomalies are therefore rare. If anomalies are common, then this analysis needs another component, which has to do with the distribution of the anomalies within the data. On the other hand, if anomalies are that common, they are no longer anomalies.) The intuitive example is looking for a 2-2T hole in a penetrameter in a conventional radiograph. If one knows where the penetrameter is located (easily found by the outline and lead letters indicating the type and thickness), finding the 2-2T hole is much easier than finding an identical hole on an identical thickness of material, but 12 inches square. Indeed, if the 2-2T hole is close to the limit of observability, as judged by an experienced radiographer, then the 2-2T hole on the large sheet will not be found.

In our example suppose that the acceptable rate of false positives for this process is 1 for the entire 2000 slices. If the density were all concentrated in one pixel (a condition clearly contrary to fact, but useful for illustrative purposes), the chance of a false positive would be 1 in 2000 x 150,000 = 1 in 300 million. This corresponds to a probability consistent with about 6 standard deviations off the norm. If the contrast sensitivity of these 2000 images were, for example, 2 percent, the density resolution for a single voxel (assuming the equivalence of voxels and resolution elements) would be 2 percent x 6 = 12 percent. In other words, the expectation would be for 1 pixel to exhibit a 12 percent deviation. If one such deviation is seen in the course of the examination of the 2000 slices, we have two choices. The first is we can say that this is consistent with our expectation, and besides, we are willing to accept a failure rate of 1 percent for the whole lot (i.e., 1 out of 100 samples) and we have met that criterion. So choice one is to stop. The second is we can say that this is consistent with our expectation for random measurement on an otherwise featureless region, and we will repeat the measurement to differentiate between chance and the true density anomaly. If the measurement is repeated, our sample size is now only 150,000 pixels, since we are concentrating on one slice. Indeed, we are looking at a certain small region of those 150,000 pixels, and the actual sample size is much smaller. If a large deviation anomaly appears again, then it is real.

While this discussion has dealt with deviation in a single pixel, the density deviation in general will cover many pixels. In the real world even the smallest of features will affect many pixels and be detected as a grouping of pixels that vary from the surroundings. Clearly the density deviation that covers n pixels can be detected at a level far smaller than the density deviation that covers only one pixel. The conservative approach leads to a reduction in intensity level by the square-root of n. Thus, if a density deviation covered 100 pixels, it would have the same probability of detection at 1.2 percent deviation as the single-pixel 12 percent deviation. (This approach tends to be followed by relatively crude, machine-based algorithms.) An approach more consistent with the way that the eye works is a reduction in intensity level by the 3/4 power of n. Under the 3/4 rule, if a density deviation covered 100 pixels, it would have the same visibility at 0.4 percent. This is quite a variation, but it shows how well the eye can do.

If the anomaly occurs very seldom, the chance of missing the anomaly is simply the probability of the occurrence being consistent with the normal probability distribution. Thus, in our example above, the chance of 1:100 of missing an anomaly which is present, the false negative rate, is tantamount to having 2.3 standard deviations above the false-positive line, or a total of 8.3 standard deviations above the background. At the 2 percent contrast sensitivity level this corresponds to a 16.6 percent deviation for a single pixel density variation and 1.7 percent deviation over 100 pixels.

In summary, the sensitivity is a function of the acceptable false positive rate, acceptable false negative rate, sample size, and dependent upon the expectation rate for the anomaly. Picking a sensitivity consistent with the consequences of failure is a nontechnical decision that must be made at the outset.

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