INTRODUCTION

There is no doubt that many of the improvements in modern medicine have been brought about by engineers. One of the most useful diagnostic tools developed by engineers has been Computed Axial Tomography, better known as the "CAT" scan. CAT machines originally allowed scanning in one direction (axial), but modern machines that allow scanning in multiple directions are simply referred to as Computed Tomography or CT; thus, the word "axial" is dropped from the moniker. The CT machine use radiography and digital image processing to image and display, layer by layer, slices of a target object.

Using this technology, it is now possible for engineers to examine objects, such as evidence from a fire scene, layer by layer without disassembling or destroying the evidence. This article outlines some of the theory behind CT scans and some of the ways in which this technology can be leveraged for the benefit of the fire investigator. We also discuss some of the considerations one may have in purchasing a CT system.

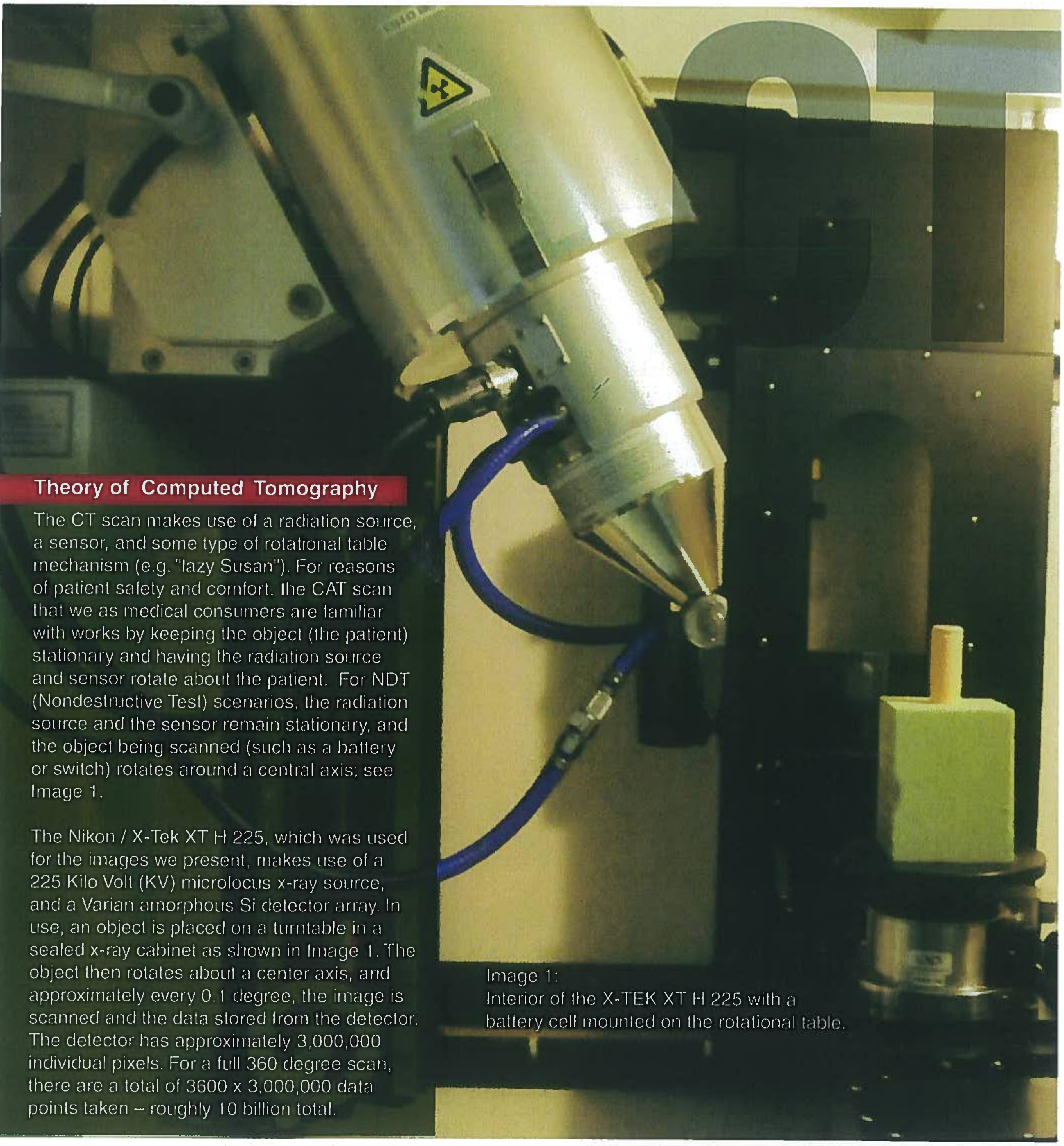

Image 1:
Interior of the X-TEK XT H 225 with a battery cell mounted on the rotational table.

Theory of Computed Tomography

The CT scan makes use of a radiation source, a sensor, and some type of rotational table mechanism (e.g. "lazy Susan"). For reasons of patient safety and comfort, the CAT scan that we as medical consumers are familiar with works by keeping the object (the patient) stationary and having the radiation source and sensor rotate about the patient. For NDT (Nondestructive Test) scenarios, the radiation source and the sensor remain stationary, and the object being scanned (such as a battery or switch) rotates around a central axis; see Image 1.

The Nikon / X-Tek XT H 225, which was used for the images we present, makes use of a 225 Kilo Volt (KV) microfocus x-ray source, and a Varian amorphous Si detector array. In use, an object is placed on a turntable in a sealed x-ray cabinet as shown in Image 1. The object then rotates about a center axis, and approximately every 0.1 degree, the image is scanned and the data stored from the detector. The detector has approximately 3,000,000 individual pixels. For a full 360 degree scan, there are a total of 3600 x 3,000,000 data points taken – roughly 10 billion total.

Forensic Usage of Computed Tomography

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All objects have some *radio-opacity* (or x-ray density) to them. Items such as plastics are not very dense and are passed through easily with x-ray energy. Likewise, elements such as a lead (Pb) block almost all x-ray energy. The DuPont manual, published jointly by DuPont and the US Government, outlines some of the basics of x-ray science. (1)

For purposes of discussion, we will assume that we are imaging a jellyroll capacitor, as shown in Image 2. The jellyroll has alternating layers of metallized film (aluminum) and polypropylene. Depending upon where one takes an imaginary 'slice' of the capacitor there can be as few as one layer of aluminum, or 10 or 20 layers of aluminum or more. The layers of polypropylene are similarly distributed. The differences in x-ray energy that pass through the capacitor are dependent upon how many layers of aluminum and how many layers of polypropylene the energy must pass through. Each material will have its own coefficient of attenuation μ, with actual attenuation being determined by both density and by thickness τ. In imaging the capacitor, we have measured the capacitor's numerous VOlume ELements, or *voxels*. Voxels are essentially three dimensional pixels.

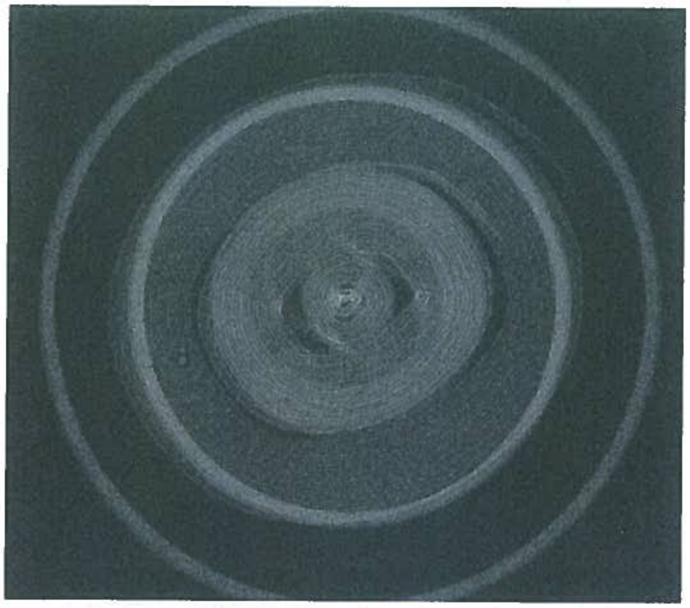

Image 2: Capacitor jellyroll

The CT voxels measure *X-ray linear attenuation*. This is how much one unit of length of material reduces the X-ray intensity. It is usually measured as a logarithmic value, μ, and is in units of inverse length (e.g. mm^{-1}). The basic equation is

$$I=Io\,(e^{\mu\tau})$$

where I is the intensity after passing through a thickness of a material with attenuation μ, and where Io is the initial intensity.

$$I\text{measured} = I\text{black} + (I\text{white} - I\text{black})\exp(-\mu\tau)$$

$$\text{So, } \mu = \ln\{(I\text{white} - I\text{black}) / (I\text{measured} - I\text{black})\} /$$

We have 'black' (no x-ray energy) and white (x-ray power at its highest) reference images (so we can then calculate μ and τ for all projection image pixels) – this is done for all 3 million pixels on the Si detector array. When we reconstruct the volumes, we show the values of μ for all voxels. Think of μ as the *X-ray density* of the material.

Mathematically, there is no difference between imaging a brain or a battery. However, the designs of medical and NDT CT systems are quite different. The typical 'spot size' of a medical x-ray is about 1 mm, while the NDT spot size is about 5 uM – a difference of about 200 x. The NDT machine clearly provides greater detail, as shown in Image 3. Medical CT systems use low energy x-rays to avoid radiation burns, while the NDT CT systems can have energies of up to 450,000 volts. For NDT, there is no concern about tissue damage. Since there is no 'burning' of an inanimate object, we can take longer on an NDT CT scan. As we take longer to scan and gather more data points, our image quality improves. The human body scan is certainly affected by blurring – caused by both biological functions and the difficulty of a patient being completely still.

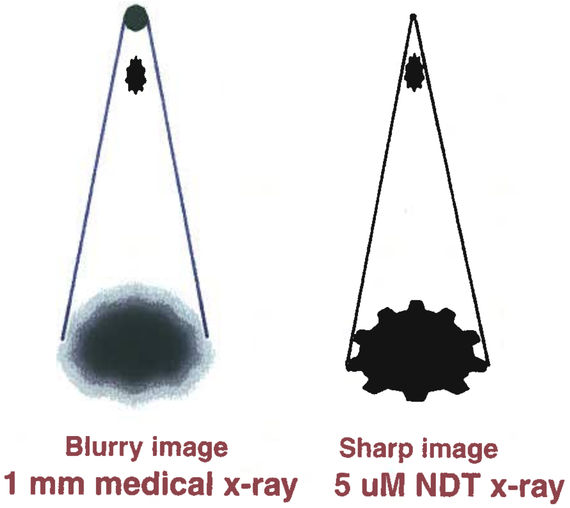

Image 3: Differences in spot sizes (Courtesy Nikon)

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The CT Machine

Image 4 shows a picture of a CT imaging machine. It is essentially a steel cabinet that is lead lined. It contains a 225 KV x-ray source, a 5 axis manipulator, and an arrayed sensor or detector. The unit is driven by a PC which controls the x-ray gun, moves the object of interest (positions it and then rotates it), and gathers the digital data from the detector array. The detector data is processed off-board by a second PC. This second PC is equipped with graphics processor cards, and works in a background mode. The entire CT system weighs approximately 2500 kgs (5500 pounds). A water chiller is used to provide cooled water to the x-ray gun so that it does not overheat.

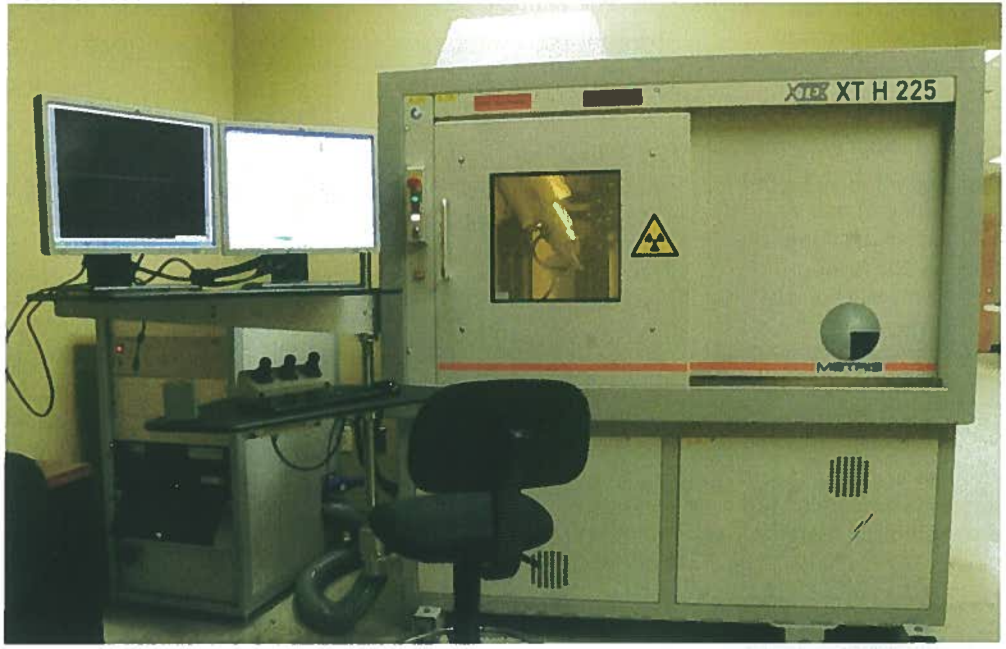


Image 4: View of entire CT machine

Signal Levels

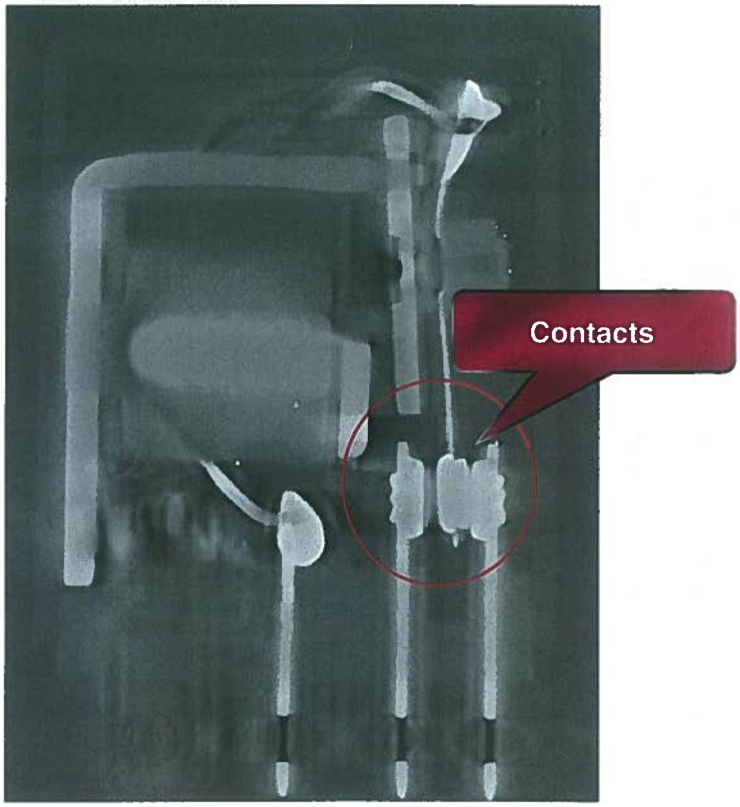
CT images differ from ‘normal’ x-ray images in terms of signal levels. With conventional NDT x-rays, we adjust currents and voltages (power to the x-ray tube) for a quality image. With CT, we instead try and ‘push’ the tube by using the maximum power as is practical. The numerous calculations carried out in the reconstruction demand multiplication is carried out to many digits. For this reason, we want the greatest Signal to Noise Ratio (SNR). The noise level (N) is somewhat fixed, so we increase our SNR by increasing the X-ray power (and thus the signal S) that is emitted into the object.

Use of Computed Tomography

Some engineering labs now have the ability to X-ray objects taken as evidence from a fire scene. X-ray, particularly real time X-ray, is a useful tool given the right circumstances as it allows viewing of the interior of an object without disassembly. However, X-ray also has its limitations. If the object of the X-ray has multiple components and depth, the X-ray does not provide one with a very good depth of field of the interior of the object. In other words one cannot discern spacing between one component and the next. The X-ray essentially takes a two dimensional image of the object. It may show components deeper in the object, but without depth of field they are still seen as two dimensional. Additionally, if one component is behind another in the line of vision, the component may go completely unnoticed. Certainly, the object may be rotated and tilted for various views in an attempt to view the interior in its entirety, but still the image can be lacking depending on the object being investigated.

Computed Tomography allows the user to view the interior of an object in its entirety by stepping through the object such that any slice of the object can be viewed. For example, suppose the object was a relay with three sets of contacts. Suppose the contacts were on the same plane in line with one another. X-ray imaging would need to be aligned such that a direct shot of the contacts would show whether the contacts were open or closed. If the other two sets of contacts were behind the first set in a direct X-ray shot, one could not see these contacts behind the first set. The object could be turned to an oblique view or 90 degrees to see all three, but those views would not allow visibility of the contacts directly to determine if they were open or closed. Computed Tomography allows us to view the first set of contacts, move through the first set onto the second set for viewing, then through the second set onto the third set. (See Image 5.) A few more examples of how CT may be used follow.

Image 5: CT image of a set of relay contacts.



We created a short in a two cell lithium polymer (Li-Po) battery by penetrating the pouch with a needle. An X-ray of this pack allows us to see the interior of the pack, but we are limited to the following images. Image 6 is an X-ray of the broad side of the pack and also shows an X-ray of the side. Both sides would look similar. The broadside image shows the hole where the needle penetrated. In Image 6, the side views shows that something is happening near the center of the cells, but we really can't see much else.

Image 6: X-rays of Lithium Poly Cell

A CT scan of the same pack allows us to go through the pack to its center to obtain the following image (Image 7) showing where the needle penetrated the pack and the resulting molten material left by the event. Image 7 is a slice looking through the side of the pack and Image 8 the view is looking through the top of the pack.

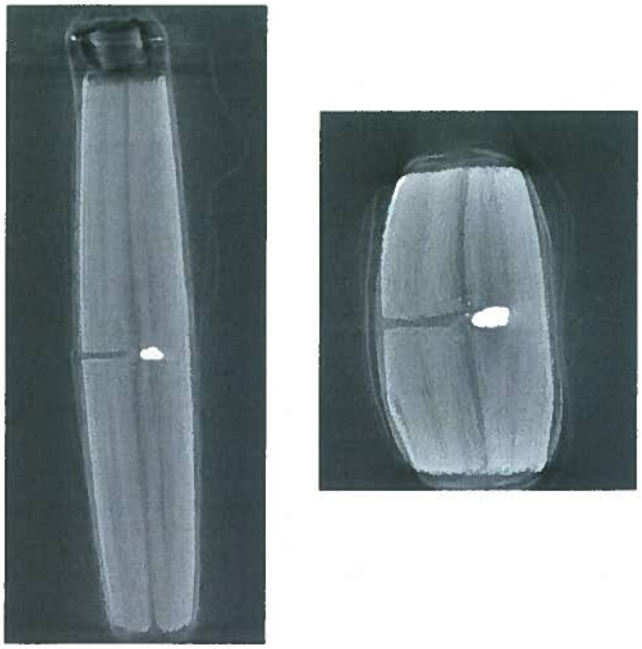


Image 7 & 8: CT images of the Same Lithium Poly Cell, side and top view respectively.

It should be noted that a battery cell can be examined via CT or by disassembly. The latter is a cheaper technique (in terms of capital equipment) but sometimes any cause of failure such as a debris particle can only be found by CT. This is because many times the size of said particles may be about 20um and disassembly may result in loss of such small yet vitally important particles.

Research is currently being performed that examines the internal pore structure of molten copper as a means to distinguish an arc from melted copper. (2) How does one view the pore structure of an arc bead? One can pot or mount, grind and polish the bead for viewing under an inverted metallographic microscope or use CT. One limitation of preparing metallographic mounts is that it may be considered 'destructive'. Sequential or consecutive grinding and polishing operations allows the pore structure to be viewed through the cross section of the bead. One advantage of microscopy and etching is the ability to examine sub-features at up to 500 time magnification including the internal line of demarcation between the melt region and adjacent wire microstructure. However, a CT scan can show the entire pore structure throughout the molten area. Image 9 shows the arc produced in our laboratory followed by a CT scan of this bead in Image 10. Image 10 gives us a great view into the pore structure of the bead, but if we need to see how the pore structure changed at different points throughout the bead we could view them as well. The dimensional element and detail of CT can be used to preserve the bead if metallographic examination is desirable.

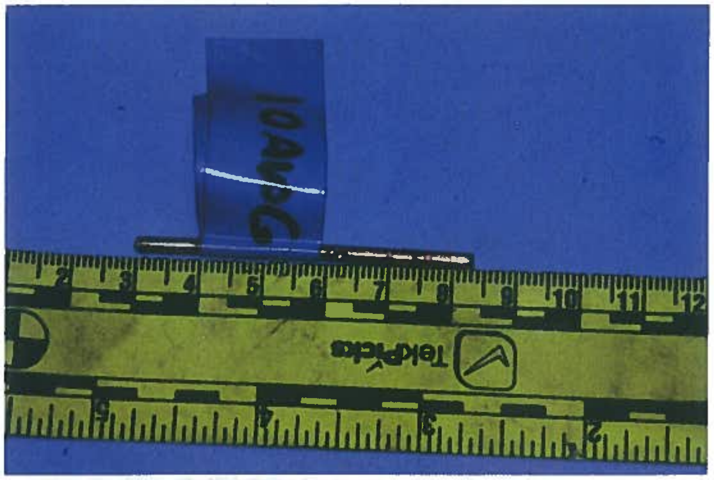


Image 9: Photo of laboratory produced arc bead

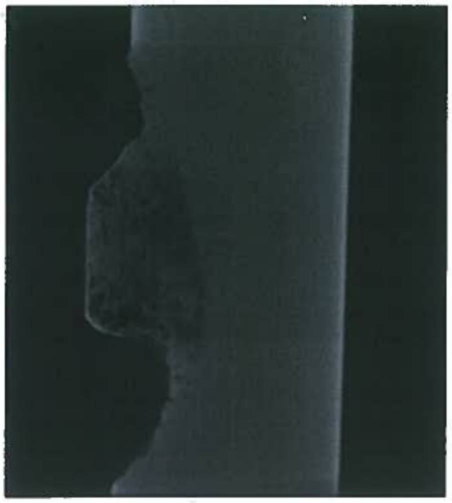


Image 10: CT Scan of Arc Bead in Image 9

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Computed Tomography is a useful tool for battery analysis as it shows the entire volume of the battery slice by slice allowing engineers to view the entire structure. For example, Image 11 shows a slice down the Z axis of an 18650 lithium ion battery cell. In this slice we see a spot in the copper electrode that has begun to dissolve – an indication of overcharge. Only a CT scan can show this level of detail to find and identify such a spot.

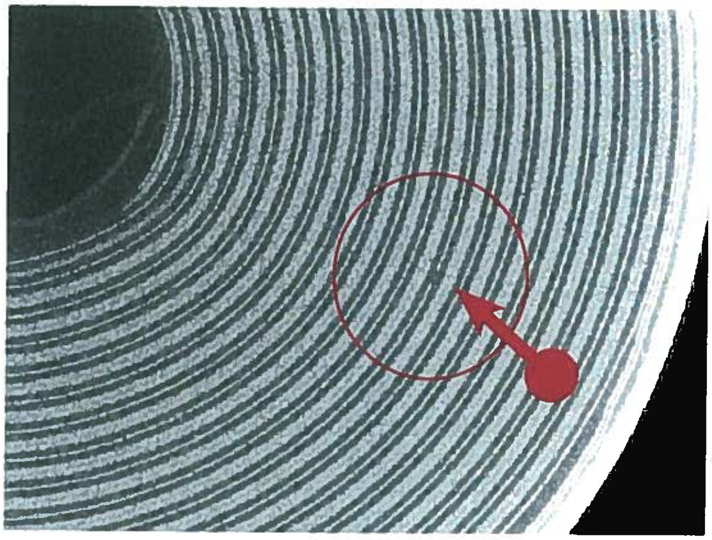

Image 11: Slice of 18650 cell

Another use of CT instruments is in failure analysis of mechanical objects. As previously mentioned, CT technology allows investigators to nondestructively examine objects. There are many types of mechanical items encountered in failure analysis in which Computed Tomography is preferable as x-ray imaging is limited. An example of this is in materials analysis. CT imaging allows one to search for voids and cracks in materials without actually sectioning the object. Image 12 shows a brass nut that has a fracture. Although the crack is visible on the exterior, the extent of the crack is better understood from a CT scan.

Image 13 is a slice of a gas regulator. Voids in the material are visible from the manufacturing process. Obviously, CT scans help to answer the question as to whether the casting was porous or not.

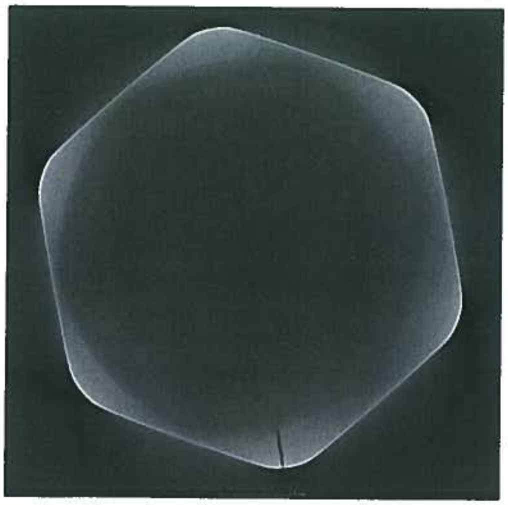

Image 12: Fracture of a brass nut (total thickness 45mm, approximately 7.5mm from top of the nut)

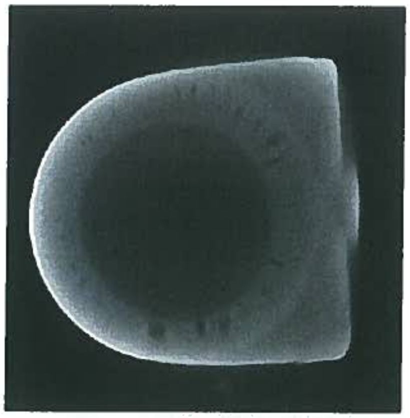

Image 13: Gas regulator, voids in a material

Image 14 shows a propane bottle type gas regulator. X-ray reveals internal components, but the precise orientation of the components is unclear because the series of components lie atop each other. Computed Tomography allows us to move beyond the items blocking the view of what we want to see and view the object or component desired.

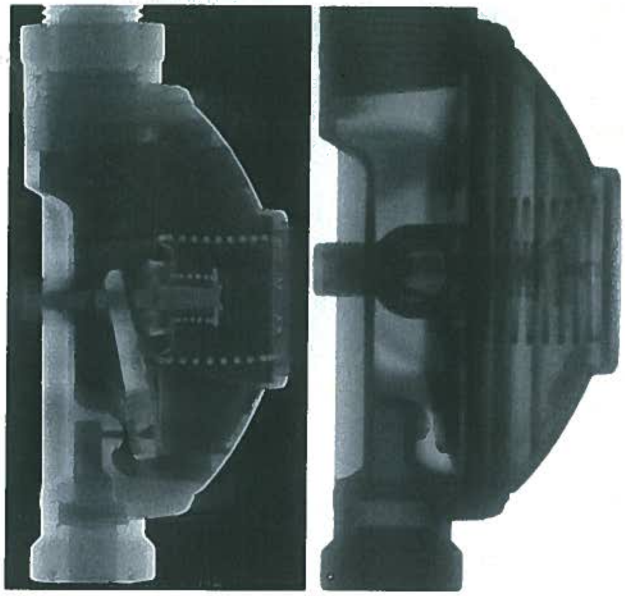

Image 14: CT of the internal components of a gas regulator (left), X-ray of regulator (right)

Another Use for CT (ANIMATION)

Those readers who were engineering students recall two of the more difficult tasks in engineering drawing classes. These tasks were drafting the hidden view and the isometric drawing. These two drafting techniques allow a user to better understand how a device is assembled or how it functions. If one is reverse engineering an assembly, many tens of hours can be saved in developing these additional images.

Images 15 and 16 show several views of a gas regulator assembly that was imaged with computed tomography. If desired, reconstruction software can be used with CT data to not only visualize, but also dimension the image.

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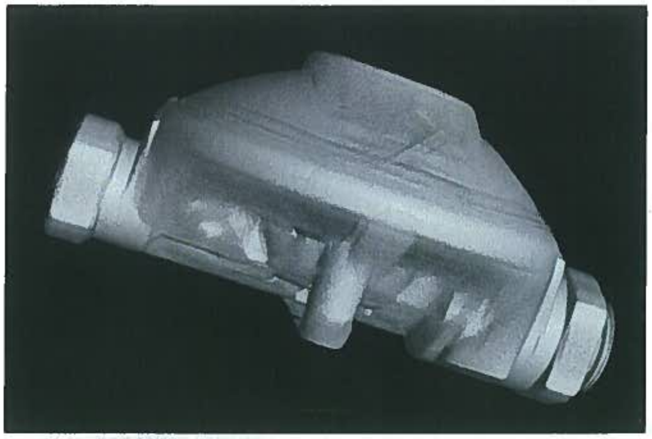

Image 15: Regulator

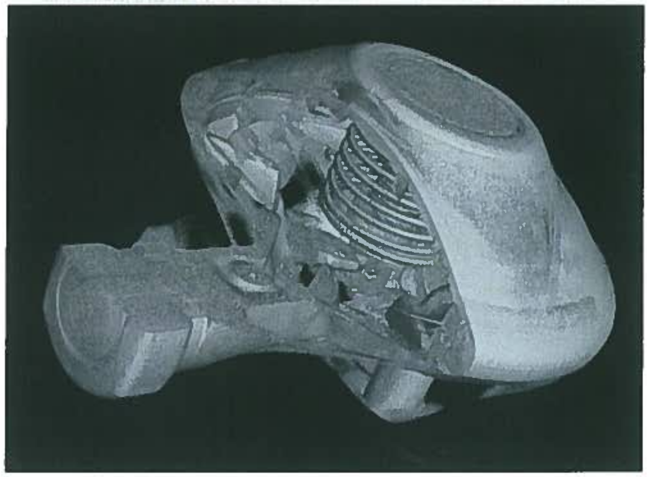

Image 16: Regulator cut-away view

Artifacts

In computed tomography, the term artifact is a uniform 'error' that occurs between the CT numbers in the reconstructed image and the actual attenuation coefficients of the object. CT images are much more apt to having such defects, given that a voxel can contain data resulting from millions of calculations. The reconstruction technique assumes that the measurements taken by the Si detector are consistent – thus, an error in measurement will result as an error in the reconstructed image.

In electronic measurements, as an example, a Digital Multi Meter (DMM) may have an error of less than .01% when reading resistance. With radiography, a 5% error among adjacent pixels on the Si detector is not uncommon. Fortunately, the logarithmic manner in which the eye senses differences in contrast and brightness tends to compress the error.

There are several kinds of artifacts, with the chief being that related to *beam hardening.* Beam hardening artifacts occur because x-ray energy is a continuous spectrum of photons. As the x-ray energy passes through objects, its mean energy level becomes higher, as lower level photons are absorbed – IE, the beam becomes harder. The result can be that some CT images the outer edges of an object appear brighter than the center and have streaks in them. The way to avoid the streaking is to 'pre filter' the beam (harden the beam) by placing (as an example) a 1 or 2 mm thick copper plate over the output of the x-ray gun. The copper plate helps to harden the beam, and causes much of the streaking to disappear.

A second artifact is that of *photon starvation.* This phenomenon occurs when densities are such that few photons reach the detector. The resultant SNR decreases and this makes the image look blurry. Increasing power will decrease photon starvation, but the user needs to remember the laws of nature. If one wants to image a lead acid battery, the results will be poor. X-ray cabinets are designed with Pb liners, and the Pb will not easily allow passage of radiation energy.

Other artifacts also exist, including cupping, partial volumes, *ring-effect* and *under sampling.* The user of a CT system is urged to become familiar with these artifacts, such that quality scans can be obtained.

Caveats

There is one huge difference between medical CAT scans and CT as used by engineers. The biggest difference lies in training and how that manifests itself. A radiologist spends about 8 years in training studying one object, if you will – the human body. When an anomaly such as a berry aneurysm is spotted, it will look similar among all humans.

The engineer is called upon to read and interpret a number of objects, and even variations of the same object. As an example, there are easily 1000 different manufacturers of small transformers (5 to 30 watt) in the world. And while all transformers function equivalently, each one can have subtle nuances. The *trick* is to insure that one is properly interpreting an *anomaly* (which would be of interest) and not a *nuance* caused by a different design.

On some objects, there are not a lot of variations. After all, how many ways are there to build a metallized polypropylene capacitor? But other objects do have nuances that can be misinterpreted. It is for this reason that it is desirable to have exemplars available for comparison purposes. However, it must be stated that there are situations which arise when an *exact* exemplar cannot be located. By way of example, we can assume that the both the O&C and the engineering work show that a fire started due to the failure of a defective circuit breaker on a power strip, while CT imaging shows the nature of the defect. Unless we know what brand breaker (or power strip) was involved, we will probably not find an exact exemplar.

An additional observation is that the CT technique is still limited (as are other investigative techniques) by fire damage. If we assume that a Li-ion battery fire is caused by a fragment of iron that has pierced the separator film, the energy released in the fire (as the battery conflagrates) will likely alter or dislodge the particle. The CT cannot resurrect evidence that has been destroyed or changed.

Finally, we must understand that vast differences in opacity (density) on the same object are still problematic. If we have a brass bodied gas regulator and we are looking for a defect in the BUNA rubber diaphragm, best of luck. The opaque brass body will often mask the imperfections in the rubber.

Conventional Usage

This article has been devoted to CT scans. However, there is nothing to prevent the CT machine from also being used for conventional real-time x-rays. The 5 axis manipulator allows the user to view in real time devices that are being imaged as they are rotated and translated. The amorphous Si detector, when used with software that can average readings for increasing SNR, provides images that are extremely clear. For example, examine Image 17, an x-ray of a 4x4" steel j-box taken with a real time X-ray machine (using an image intensifier). Image 18 is an x-ray taken of the same j-box with an amorphous Si detector that is part of a CT scanner. One can easily see the difference in quality. It is also noticeable that the unit using an image intensifier is non-linear in nature. This could cause significant errors and artifacts if used in conjunction with a CT instrument.

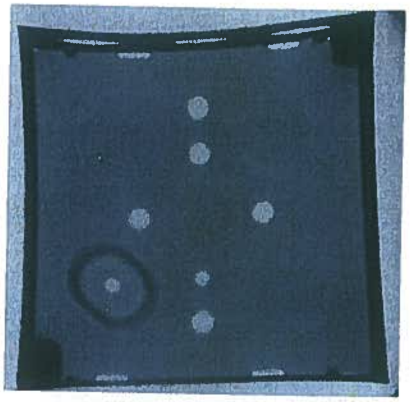

Image 17: X-ray using Image Intensifier

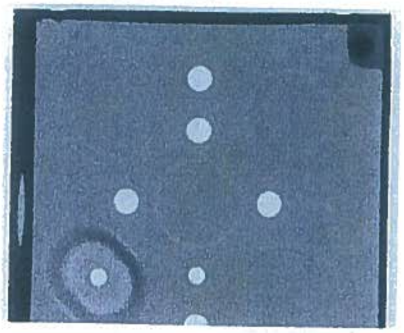

Image 18: X-ay using Amorpous Si sensor

Licensing

Laws regarding radiation differ by jurisdiction. However, the CT scanner is a sealed cabinet, and is considered a minimal threat device by the Federal Government. That often means that pocket dosimeters will not have to be worn or monitored. A check of radiation leakage, as well as verification of interlock operation on the door, is required annually. This device falls in the same category as luggage screening devices at airports.

Utilities

Required power will vary by manufacturer. Chilled water is required by every CT machine that we are aware of. In that the X-ray cabinet does generate a substantive amount of heat, it is recommended that the water chiller be placed in a separate room. Similarly, reduced lighting in the CT room and added air circulation all work to properly manage heat.

Phantoms

One of the desirable accessories to build for a CT machine is called a *phantom.* A phantom is a test target, and they are available for the medical profession. If one is a radiologist working with brains, a skull phantom can be purchased; it has features in it that radiographically mimic brain structures. The phantom is used for test purposes – to insure that the system is working. By storing slices, it is possible to periodically image the phantom and insure that the image quality has not changed over time.

We have not found a suitable phantom for use in fire research. For that reason, we made our own. The phantom consists of polypropylene capacitor, a 9 volt battery, a wire wound resistor in a sand body, a section of type NM stranded #6 x 2 cabling (copper), a 30 ampere 250 volt cartridge fuse, and a relay; these are all mounted on a round base and are cast into place. The base can be scanned, and the various features of the components seen. The different materials and their different densities are representative of the types of materials we see in our lab. Image 19 shows a CT slice of the phantom we use in our lab.

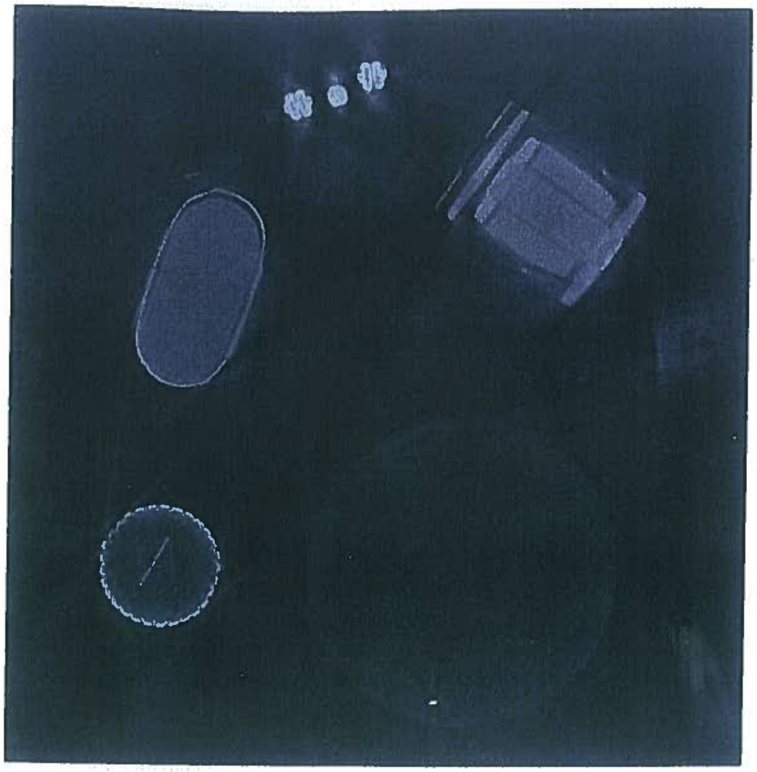

Image 19: Phantom

Image Storage

CT machines are expensive - $400 to $500K and more. For that reason, there is a market for CT services, whereby a fire investigator pays to have a third party scan an object. But unlike lab exams where data is shared with all parties on a jump drive or flash card, CT data is quite bulky. Typical CT data sets are on the order of 15GB to 20GB per complete scan. CT scans may be converted to jpeg format reducing their size to a more manageable file size to allow sharing. However, the data set is still quite large and will likely need to be shared via removable media. The removable media will contain numerous slices, and they can be viewed sequentially. Moreover, the data will contain projections in 3 planes – front, top, and side. The specific software we use has recently released a viewer that can be distributed to clients for image viewing.

SUMMATION

The use of CT scans for examination of fire damaged remains allows an investigator to view an object internally in multiple dimensions without disassembling, damaging, or destroying the evidence further. There are also many scenarios in which disassembly of the evidentiary item would destroy evidence, rendering it useless. The CT makes such analysis possible so items of evidentiary value are not lost.

The best advice that we can offer the CT user is to have exemplars available for comparison purposes. In this way, one can determine what images depict anomalies, and what images depict just nuances.

REFERENCES

1 DuPont, NDT Radiography Manual, March 1968.

2 Buc, E PhD, Sing, T, Reiter, D. 2011, NFPA 1033, The Forgotten Standard – Fire Investigation Technology, Schertz, TX, Central Texas Fire Investigators Association Annual Conference.

BIOGRAPHIES

Mark Goodson is licensed in both electrical and mechanical engineering. He holds a BSEE from Texas A&M, received in 1979, and is licensed as a PE in 13 states. He is the principal of Goodson Engineering of Denton, Texas. His specialties include fires caused by electrical and mechanical failures, electrical design, and CO and electrical deaths. After engineering school, he was in training at UT SW Medical School in the forensic medicine track.

Mr. Goodson holds three patents related to fire safety, and has 3 more pending. He also consults with public sector agencies to include Medical Examiner (ME) offices. He was the first PE appointed to the State of Texas Electrical Board. From 1989 to 1991, he served as a Court Special Master. He has published over 20 peer-reviewed papers on fire investigation. He serves on the Fire and Arson Investigator Editorial Review Board. He recently was appointed by the Texas State Fire Marshal as a member of the Scientific Advisory Group, which is charged with reviewing possible wrongful convictions and also training the state's fire investigators.

Michael Shuttlesworth received his BSME from Oklahoma Christian University in 1997 He is a consulting mechanical engineer / EIT with Goodson Engineering and laboratory manager. Mr. Shuttlesworth operate the laboratory equipment, such as SEM/EDX, Computed Tomography, FTIR (Fourier Transform Infrared Spectroscopy), Real time X-ray, and also designs and implements various testing regimes.

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