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Paper Session III-B - Computerized Tomography (CT) Inspection of Mechanics of Granular Materials (MGM) Modules for the Study and Analysis of Phenomena such as Earthquakes

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Computerized Tomography (CT) Inspection of Mechanics of Granular Materials (MGM) Modules

A Study and Analysis for Phenomena Such as Earth Quakes

Introduction

Suppose someone sawed through a thick log, gathered up all the saw dust in a bag, and gave it to you requesting that you put the saw dust particles back together just as they were in the tree. And, no fair looking at the sawed ends of the log; not that would help! If you could re-assemble the particles exactly as they were in the tree, you would have a tomo- (slice) gram (picture) of just that thin section of the log. This of course would be impossible, but in the late 1960s, a fellow (G. Hounsfield) at EMI, Ltd. In England used an established mathematical theory by J. Radon (Radon's theorem) to do that task (Reference 1). Hounsfield's "saw" was x-radiation, and the saw dust grains, gathered with a powerful computer and re-assembled exactly, are called pixels. Each "saw dust grain," (pixel) is a computerized picture element representing a small (e.g. 1mm by 1mm) density region of the original object (the log). Correctly placed together, the pixels represent a density "map" of the object sliced. Now Hounsfield did not slice a log, but applied his Nobel Prize winning invention to the imaging of tissue, and the diagnosis of disease, in the human body. In the early days, the slices were all performed across the axis of the specimen (body) and thus was born the CAT scan acronym meaning Computed (computerized) Axial Tomography. Improvements in the way objects can be x-ray sliced (any plane) and subsequently reproduced into images have resulted in dropping the axial term, and the favored acronym is just "CT."

In the case of CT, the industrial world made use of the technology some time after its acceptance in the medical arena. Early CT of industrial objects to get a non-invasive look inside made use of medical scanners. Requirements for greater penetration by x-ray sources, and faster and more detailed results in objects much denser and larger than humans, provided the need to produce CT scanners specifically for industrial purposes. Industrial scanners began being developed in the 1970s. In 1985, NASA at The Kennedy Space Center, put into operation NASA's first industrial CT system (Figure 1).

Figure 1

A view of the NASA/KSC CT system. The CT has been in continual operation since 1985, and can scan objects up to 2000 pounds, five feet wide and 6 feet tall. It uses 420kVp (420,000 volt peak) x-rays or Co-60 isotope gamma rays (average 1.25 million electron volts, MeV) as the penetrating source for data acquisition. 125 scintillation detectors (seen in the back) convert object attenuated x or gamma beam into light pulses which are further changed to electrical pulses, digitized and convolved to form a CT image.

The NASA/KSC CT

The NASA/KSC Computerized Industrial Tomographic Analyzer (CITA) (Figure 1) (Reference 2), one of only a few dozen industrial CT systems now in operation in the World, is designed to examine the internal structure and material integrity of a wide variety of aerospace related objects. In particular is the subject of this paper, the Mechanics of Granular Materials (MGM) units, flown in the micro-gravity of space in the space shuttle. More about MGMs shortly.

The NASA/KSC CT uses a 420 kVp x-ray, or for very thick and dense objects, a cobalt 60 isotope source which produces 1.17 and 1.33 MeV gamma rays for penetrating materials with equivalent paths up to eight inches of steel. The CITA can scan objects as small as a wristwatch or as large as a 5 x 6 ft (1.5 x 1.8 m), 2000 lb (910 kg) cylinder. CT systems are now in place at other industrial facilities which can scan much larger objects (e.g. entire rockets) using linear accelerator sources producing x-rays of energies of 10 or more MeV.

The CT system is used daily for the research and development of the capabilities of this unique inspection system, as well as for inspections performed on aerospace components where no other non-invasive inspection technique will provide more useful diagnostic results. The CT can produce digital radiograms of dynamic density ranges that far exceed radiographic film; special kinds of "near" slice type pictures called laminograms of very thin objects such as circuit boards; and, its primary function, tomographic images anywhere in an abject. The CT is not tasked so much as a nondestructive testing device to find flaws, as it is a diagnostic tool for the visual, dimensional, and actual density evaluation of materials and objects. CT excels in dimensional and density analysis because the acquired data can be analyzed with near distortion free accuracy. The CT slice images are basically two-dimensional attenuation (density) maps of a cross section of the specimen. The data is acquired and processed by a powerful computer, and viewed on a high resolution (RGB) monitor. The most significant use of the viewed image is to locate specific regions of interest where the data can be accessed for further processing and quantitative analysis.

The NASA/KSC CT has for years used a Micro-VAX II computer for data acquisition, and a SUN Sparc-10 workstation for data processing, viewing, and analysis. As mentioned, the system has been in operation since 1985, and with very little "off" time. It is now scheduled for upgrades to more powerful computers, and x-ray detection systems. Over the past nearly fifteen years of operation, the CT has processed and archived many billions of bytes of digital data, representing images of shuttle components such as valves, elevon (wing) leading edges, shuttle "chin" panels (under the nose), space lab switches, Delta, Atlas, and Titan rocket motor components, and even containers of ripe and unripened wheat! Typically, raw CT data exceeds several megabytes in file size, with the resulting processed images up to one or two megabytes. This is not a "real time," fast system, and some single CT images require an hour or more from start to finish. Improvements in the detector and computer systems of newer CTs allow much faster data acquisition of an entire object's volume (instead of a slice at a time). CT systems of this capability are being tasked to provide computer aided design and modeling (CAD) and reverse engineering where the accurate internal and external dimensions of an object, obtained by CT, can be used to "clone" the part in lieu of engineering drawings.

The following discussion about the MGM module inspection is an important example of how the NASA/KSC CT system is tasked to solve an otherwise nearly impossible problem: how is it possible to examine in detail the internal structure of something as frail as a column of sand?

Mechanics of Granular Materials (MGM)

It is not the intent of this paper to describe in detail the MGM module or its function in the NASA Space Shuttle micro-gravity program. Rather, a discussion of how the NASA CT is tasked as an important part of the program will be presented. One is encouraged to view the NASA Marshall Space Flight Center's web site: http://science.msfc.gov/newhome/headlines/ for details about the MGM project.

Briefly, the MGM project involves the study of how any number of materials of granular structure (sand, salt, coffee, etc.) behave under stress. To quote the referenced web site: "What do a brick of vacuum-packed coffee, land under houses in San Francisco, powdered makeup, and tire tracks on Mars have in common?

"They all behave according to laws of granular materials which we don't yet fully understand. To get a better grip on what happens when the ground shifts - under a house during an earthquake, or under the wheels of a rover exploring Mars - NASA (is flying) the Mechanics of Granular Materials (MGM) experiment to expand investigations started on STS-79 in 1996."

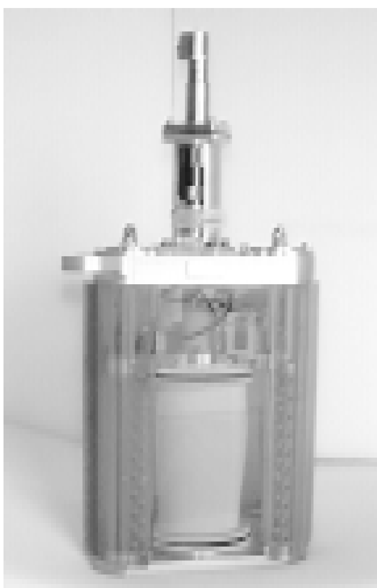


Figure 2

Mechanics of Granular Materials (MGM) module. The light colored column inside is a membrane filled sand column surrounded by water. The unit is about two feet tall.

Figure 3

A close up view of the sand column inside an MGM module. The light colored membrane is semi-permeable, and allows the sand to stay wet, but does not allow the sand to leak out. Density features impressed in the sand in the micro-gravity of the space shuttle are maintained, and CT scanned back on earth for analysis.

An MGM module, which is about two feet tall, is shown by Figure 2. The modules are composed of aluminum and steel frames surrounding special plastic housings. Inside the plastic container is a semi-permeable membrane cylinder full of sand (Figure 3). The membrane of sand is surrounded by water in the plastic housing. The membrane allows water to pass into the sand column, but does not allow the sand to come out. Above and below the sand cylinder ends are special pistons that can be actuated (in the micro-gravity of a flying space shuttle) in order to impress controlled and measurable pressures on the sand column. The micro-gravity environment of the shuttle in space eliminates influences from external gravitational effects. The impressed forces send minute force shock waves through the sand column producing subtle, but distinct density gradient patterns in the wet sand. These patterns are then preserved in the wet sand, and studied back on earth in order for scientists to better understand the laws of granular materials, and thus better understand the nature of phenomena such as earth quakes. Much of this analysis is performed at The University of Colorado at Boulder for NASA MSFC.

Roll of NASA CT for MGM Analysis

It would be very difficult to inspect the density gradients in the sand columns by any other means except CT. The reason for this is quite obvious as the slightest disturbance of the MGM unit after flight would no doubt alter the density pattern produced in flight. Taking the sand column apart, filling it with epoxy and “slicing” it physically, or any other means of looking at the internal patterns of the sand column would disturb the delicate features that are indicative of the mechanics of the MGM device. Here is where the CT analysis excels.

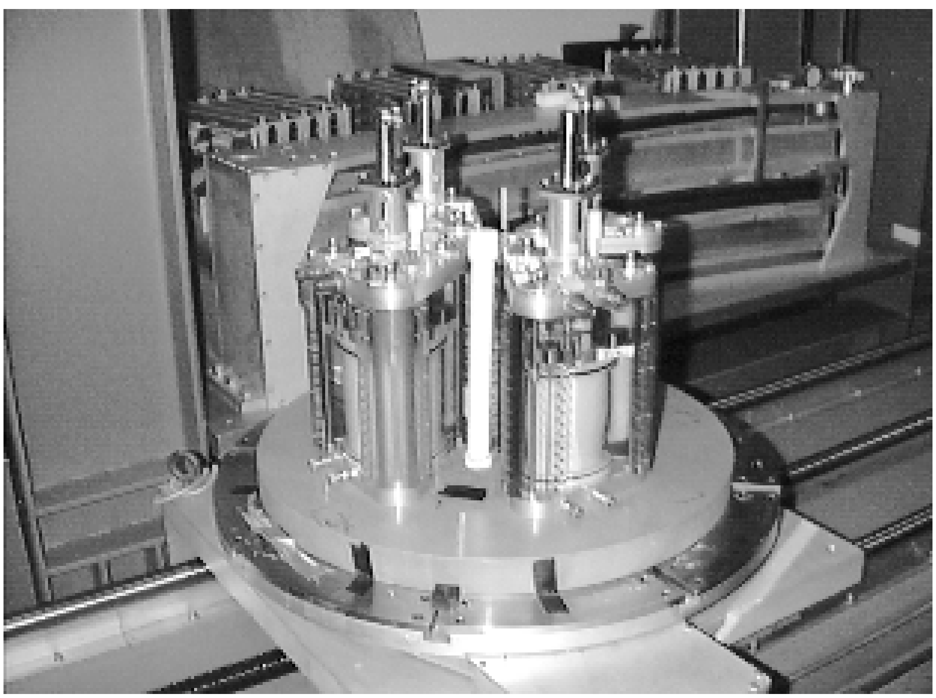


Figure 4

Four MGM modules mounted on the CT scanner table ready for obtaining 155 slices every 1mm down the sand column. The white pvc tube contains water as a calibration device for density analysis.

An MGM module or up to four modules are placed on the CT scanner table (Figure 4). The CT system is then programmed to automatically obtain tomographic images every millimeter down and across the sand column. In the present example, 155 CT image slices were obtained from the upper

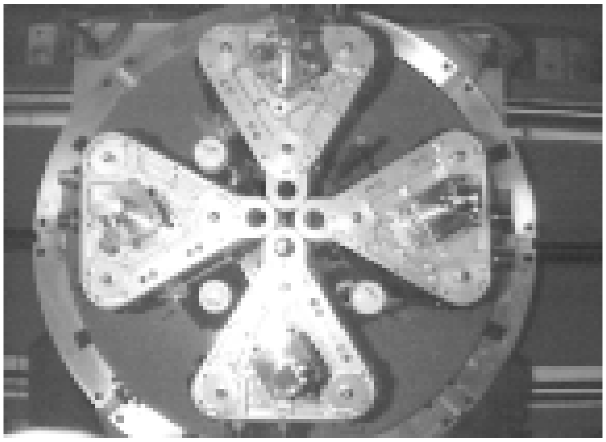


Figure 5

A top view of four MGM modules on the CT scanner table. This is the view that each of 155 slices will be obtained through the MGMs. Only the sand columns inside are of interest, however the entire unit(s) must be scanned in order to preclude masking data from outside the acquisition circle. The data circle is 600 mm (24 inches).

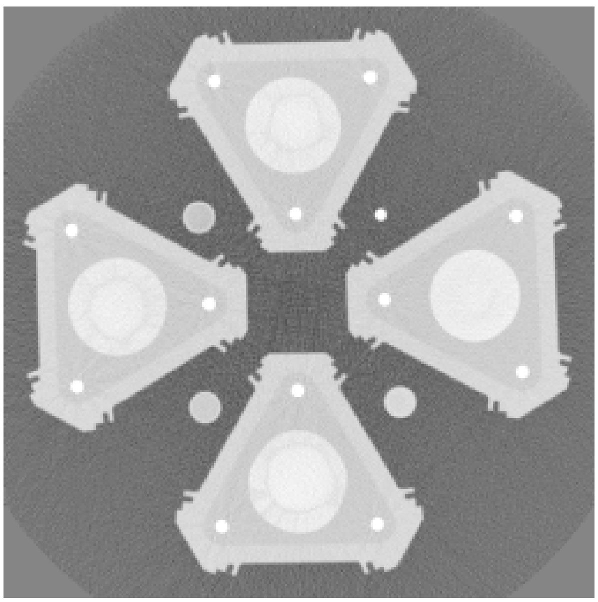


Figure 6

A full view of one CT slice through the four MGM modules. Note the darker (lower density) features in the cross sections of the sand columns (center circles in each triangle). It is these features which tell MGM scientists about the nature of the mechanics of granular materials.

piston, down through the sand column, and into the lower mechanism. The orientation of the MGM units, and their subsequent CT slices are in the plane shown looking down on the CT scanner table (Figure 5). One example of a full four unit CT image is shown by Figure 6. When analyzing each MGM's slice image, the data is reconstructed one unit at a time. This reduces the amount of data processed, and affords a reasonable file set to work with, without having the MGM structure in the field of view. Only the sand column patterns are reconstructed in the planes of interest. You may note in Figure 6 four additional round features not attached to the MGMs. These are density calibration standards of PVC tubing filled with water, sugar, and salt, and the smaller circle is aluminum. These standards are being investigated to see if true density data may be inferred from them. This is, typically, how density analysis is performed with the CT. Space grown micro-gravity industrial-use crystals are analyzed by the NASA/KSC CT in much the same way. Using CT data for density analysis requires developing a functional relationship between the CT data and attenuation coefficients of the standards and unknowns. The CT computer has an imbedded programming ability for producing complex utility programs. Nearly all CT inspections performed with the NASA CT require some uniquely developed software in order to specifically analyze data to which it can be tasked.

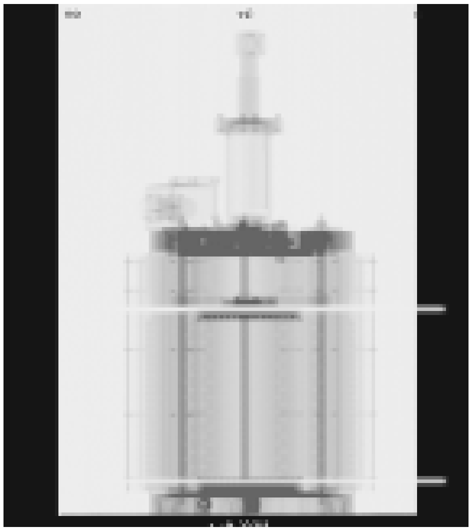
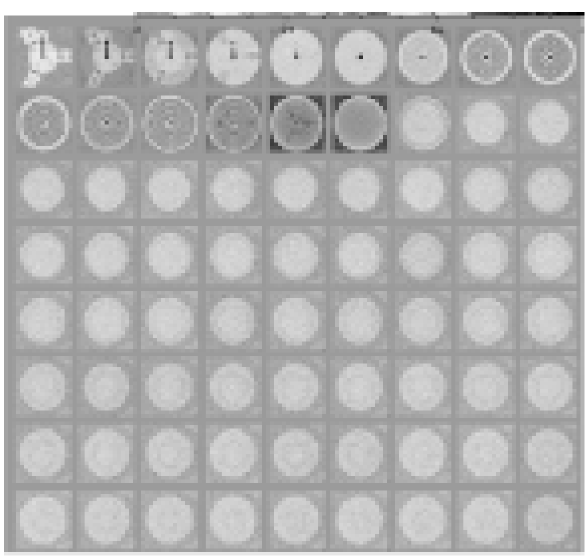
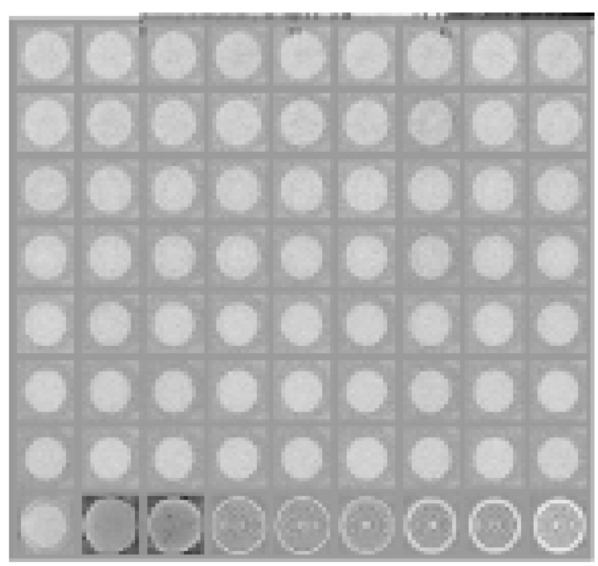


Figure 7

A digital radiogram (similar to a conventional file radiograph, but made by the CT computer) shows the operator where to start and stop collecting CT slice plane data; the two white lines.

Figure 7 is a digital radiogram of an MGM unit made by the CT system. Digital radiograms are used to initially set up a CT program which automatically locates the CT slice planes for the experiment. Figure 7 shows two lines above and below the sand column, and once located, the computer is programmed to obtain CT data every millimeter between the two lines. Figures 8 and 9 show the results of reconstructing (most) of the 155 CT slices from one of the four MGM units scanned. The upper and lower mechanisms are scanned in order to insure that the entire column's data is obtained, as well as providing an orientation of the column relative to its housing.





Figures 8 and 9

A near complete set of CT images from one MGM module sand column. The first and last structures are CT images that insure that a complete set of sand data has been collected, as well as providing orientation benchmarks for the sand columns inside the units.

CT Scanning Protocol used for MGM

In order to present a flavor of the amount of data that is processed (the amount of CT "saw dust") the following is typical of most CT inspections, the present MGM study in particular. The CT obtains data by defining an object circle size whose diameter will more than encompass the four MGM units. This was 600 mm (24 inches). The scanner table in this particular mode of CT data acquisition is then passed at a constant speed through the radiation beam. The radiation beam is apertured so as to "slice" (saw) through the object at about one millimeter thickness. The speed of the object is synchronized to acquiring a ray of data every 0.2 seconds for each of 125 detectors placed about 10 mm apart, and about two meters from the cobalt-60 radiation source. Each data ray (called a ray sum) is obtained every 0.5 millimeter as the object traverses through the beam. In order to obtain enough data rays (attenuated by the object) to produce a suitably high spatial and contrast (density) resolution image map, the object is moved through the beam for a travel of approximately 1475 mm. The object passes through the beam at six angles relative to the beam (0, 30, 60, 90, 120, and 150 degrees). This protocol satisfies an optimum Nyquist sampling rate. So, for the 1475 millimeter travel, sampling data every 0.5 mm by each of the 125 detectors at six angles, the raysums collected total 1475 x 2 x 125 x 6 = 2,212,500. With 4 bytes of computer data for each CT datum, and several thousand bytes for headers and associated scanning data, this amounts to raw data files of 9,080,000 bytes…9.08 megabytes! Multiply this by the 155 slices and the total unprocessed CT data for this one study is more than 1.4 gigabytes.

The CT image of Figure 6 has been reconstructed with image pixels the same size as the data pixels for, essentially, a 1:1 reproduction. This particular reconstruction, in CT parlance, was Fourier filtered and back projected to 4.024 megabytes. A slight enlargement of the image is performed by reconstructing the 0.5mm by 0.5mm data pixels to 0.387mm by 0.387mm image pixels over a specified grid for each individual sand column. Each of the individual cell CT images is now 312,000 bytes, but this amounts to a grand total of 193,440,000 bytes of CT "saw dust" left for the University of Colorado Scientists to analyze! The time required for the CT to acquire just the raw data was about an hour per slice, so data acquisition time alone took over 155 hours. The reconstruction process, however, flies in comparison taking only a few minutes to reconstruct each CT image. Image reconstruction is performed coincidentally with data acquisition so that when the scanning is completed, the images have been made (except for the last one) and, including the raw data, archived to some digital storage media such as a CD disc. Figure 10 is one of the 155 CT images processed, and shows the density gradient details that are examined by the project scientists.

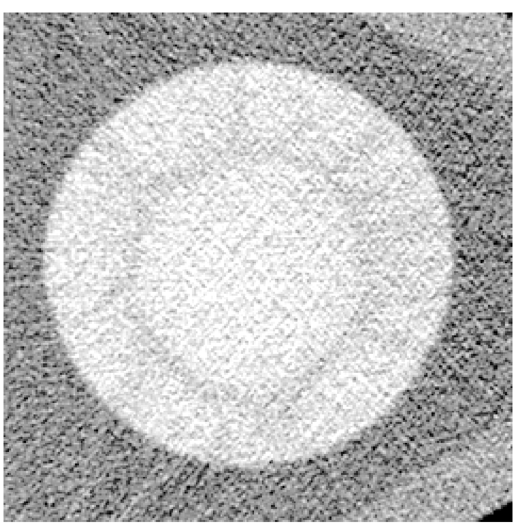


Figure 10

A detailed view of just one of the 155 CT slices obtained from each of the four MGM modules under test. Here, the dark, lower density features are clearly seen. It is these features that are analyzed for the mechanics of the results of stresses applied to the sand, and ultimately any granular materials.

Once processed, the MGM CT image data is transmitted from Kennedy Space Center to the University of Colorado at Boulder via inter-net by a fast data transmission protocol called ftp (file transfer protocol). Some of the interesting data manipulations that can be performed are shown in the remaining figures.

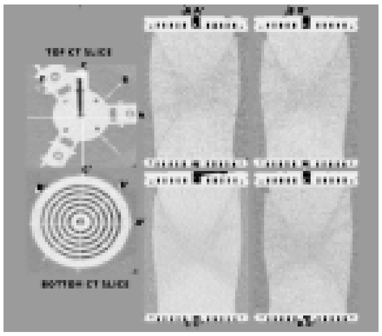
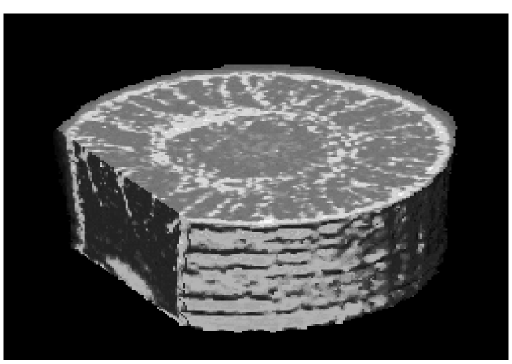


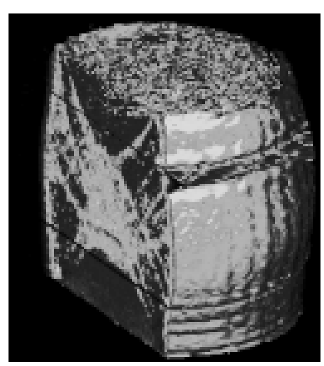
Figure 11

This figure shows four axial slices produced by interpolating (synthesizing) the planer CT data along the axis of the sand columns. Four slices are produced by defining starting and ending lines at top and bottom of the sand column. Any number of slices can be made at any oblique set of angles (here 0, 45, 90, and 135 degrees). A twist plane CT can also be made by starting at one angle and ending at another. All this data processing is done by the CT computer in a matter of seconds.

In order to obtain the most information about the stresses that produce the density features in the MGM sand columns, the 155 CT slices may be reconstructed in any plane, oblique or twisted, through the stack (column). Four such reconstructions of the 155 slices of one of the modules are shown by figure 11. Here, four line locations are identified at 0, 45, 90, and 135 degrees across the top and bottom of the image stack. The computer then produces a synthesized CT image axially down the column as shown in Figure 11. Notice the interesting pattern in the sand that was produced by the MGM device. The darker streak patterns are lower density than the surrounding material, indicating stress patterns developed that are not, it is theorized, unlike those that are produced during earth quake activity. Study and analysis of these patterns yield granular material mechanics information not easily obtained by means other than computed tomography.

Two other CT data images obtained from the referenced MSFC web site are shown in Figures 12 and 13. Here, special computer algorithms and software make a three dimensional cut away view of the entire sand column, giving an unparalleled view of the sand features, and their relative locations inside.





Figures 12 and 13

These are images from CT data produced early in the MGM project at the Los Alamos Laboratory (see referenced MSFC NASA web site). By producing complex three dimensional views of the CT data, the MGM scientists obtain valuable information about the mechanisms involved.

Conclusion

This paper has introduced you to the exciting technology of computed tomography, and how it is being used industrially, especially at NASA. It is interesting to note that many technologies, especially those presented at the NASA Space Congress are, or have been, the off-spring of developments in the NASA aerospace program. In the case of CT the opposite is true, as the development of industrial CT was an off-shoot of the medical profession "CAT" scanner.

Industrial computed tomography is truly a 3-D volume, non-invasive, internal structure inspection and analysis tool, excelling in Diagnosis, Dimensions, and Density. As new and challenging problems are encountered for collecting those saw dust particles to see inside the "log," CT will be tasked as the modality of choice.

References

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2. H. P. Engel, NASA's Computed Tomography System, Aerospace applications of industrial computed tomography (CT) at the Kennedy Space Center, Standardization News, American Society for Testing and Materials, .March 1989