AN INTRODUCTION TO COMPUTERIZED X-RAY TOMOGRAPHY FOR PETROLEUM RESEARCH

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By

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May 1989

Work Performed Energy Under Contract No. DE-FG19-87BC14126

Prepared for
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ACKNOWLEDGEMENTS

I wish to acknowledge financial support provided by the Department of Energy through the Stanford Petroleum Research Institute, Contract Number DE-FG19-87BC14126. I also acknowledge the partial financial support provided by the SUPRIA Industrial Advisory Committee.

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Executive Summary

This report summarizes the state of the art in the application of medical tomography (CT) to petroleum recovery problems. A brief review of the basic principles of x-ray computerized tomography is followed by a discussion of the governing equations of the method. Calculation techniques and appropriate correlations for continued testing are described and discussed. A review of existing medical software is done. Consideration of the specific software needed for petroleum engineering as well as applications of new technologies such as image processing and computer networking are described.

Criteria for the choice of a machine suitable for most petroleum-related applications are given. Emphasis is placed on flexibility, reliability, accuracy and price of the scanner. Two separate sections discuss positioning of the core and design of the core holders. Examples of possible applications of CT scanning to problems of geology, core analysis, EOR as well as operational process problems are discussed. An appendix presents the status of the CT research at the Stanford University Petroleum Research Institute.

The basic conclusion of this work is that computerized x-ray tomography is a powerful tool for petroleum industry researchers. Present technology allows its use by major research centers in an effective manner providing that some simple criteria are met. Existing hardware is adequate and adaptation of existing medical software in combination with other sources is possible. No new technology is needed.

Basic Principles of Computerized Tomography

CT measures linear attenuation coefficients μ, which are defined by Beer's law $I/I_s = e^{-\mu x}$, where I_s is the source x-ray intensity, I is the intensity measured by the detectors, and μ is the attenuation coefficient. In computerized tomography, a series **of** one-dimensional projections of the attenuation through **an** object is obtained by moving an x-ray source and an array of detectors at various angles. These projections are then processed by the system computer to create a cross-sectional image (or matrix) of attenuation coefficients $\mu(xy)$. CT can measure attenuation differences as low as 0.1 % with a cross-sectional resolution of less than $1\,mm^2$.

a) Equations

The equation describing x-ray adsorption on one path **is** given by Beer's law which can be written for a homogeneous medium as follows:

$$I/I_s = e^{-(\mu/\rho)\rho x}$$

where μ / ρ is the mass attenuation coefficient, ρ is the density of the medium, and x is the thickness of the material.

If several materials are in the path of the x-rays, Beer's law can be generalized as:

$$I/I_s = e^{-\sum(\mu_i/\rho_i)\rho_i x_i} \qquad (1)$$

where i is the material considered.

If the object contains a mixture of components, the overall mass attenuation coefficient of the mixture will be:

$$\mu_{mix} = \sum_{1} P_i S_i \qquad (2)$$

b) Effect of various parameters

If the components are not miscible, S_i is the saturation of the phase i, i.e. S_i is the volume fraction of component i such as water, oil or gas. If the components are miscible, this

formula can still be applied with the understanding that S_i is the pore volume fraction occupied by component i which is distributed among all phases. For example, in C02 miscible flooding, CO_2 is present with oil, brine, and free gas. CO_2 as interpreted by the cat-scan measurement will not be the amount of CO_2 as free gas, but rather the volume fraction occupied by C02 distributed among all the phases. This assumes that the volumes are additive (i.e. $1cc$ of C02 mixed with $1cc$ of oil $= 2\ cc$ of mixture). If the bulk volumes are not additive, CT measures the weight of each component in the pore volume. The linear attenuation coefficient of each component as measured before mixing must be scaled after mixing by the ratio in component density to the pre-mixed density.

Different mechanisms are involved in the adsorption of x-rays. The relative importance of these mechanisms depends of the energy level of the incident x-rays. In general, μ depends on both the density and the chemical composition. If the energy is above 100 keV, μ depends mostly on the electron density (Compton scattering). If the energy is below 100 keV, photo-electric adsorption becomes the main mechanism, depending mostly on the atomic number Z of the material studied. So, one can express the linear attenuation coefficient μ as:

$$\mu \approx \rho\ \sigma(E) + (bZ/E^{3/2})\rho \qquad (3)$$

where $\sigma(E)$ is the Klein-Nishira coefficient, ρ is the electron density, E is the energy level in keV, Z is the atomic number, and $b = 9.8 \times 10^{-24}$.

Some comments about Eq. 3:

- The heavier elements will attenuate more than the lighter ones.
- The coefficient of adsorption μ for a given material changes with the energy level of the source. This change depends mostly on the atomic number of the element considered.
- In addition to this change, heavy elements exhibit a jump (k adsorption edge) in the adsorption coefficient in the photo-electric region. This phenomena can be used as

described by Vinegar and Wellington (1) to design systems with dopants.

- By measuring adsorption at two or more energy levels, one can obtain two independent measurements (for example, measurements when $E_1 < 100$ keV and $E_2 > 100$ keV). This allows for the solution of problems when three phases are present.

c) Subtraction Techniques

As described before, the linear adsorption coefficients are additive. The subtraction technique performed on the mamx of adsorption coefficients allows the elimination of extraneous objects, such as core holders, for better interpretation of the quantities needed by the researcher.

1). Subtraction Technique applied to one pixel

Let us consider one pixel (volume element of the slice considered). Rigorous application of Beer's law (Eq. 1) to this element can be written as:

$$I = I_s\, e^{-\rho\mu x} \qquad \textit{where} \qquad \rho\mu x = \sum_i \rho_i \mu_i x_i$$

with i representing each component in the system.

For example, let us take an element containing rock and fluids, and suppose that one wants to measure only the fluid saturations. Eq. 1 for this case can be written and arranged as:

$$\log I = \log I_s[\mu_R \rho_R (1 - \Phi)x + \rho_f \mu_f \Phi]$$

where μ_R is the adsorption of the rock, ρ_R is the density of the rock, μ_f is the adsorption of the fluids, ρ_f is the density of the fluids, and Φ is the porosity.

The quantity $\rho_f \mu_f \Phi$ can easily be obtained by taking two adsorption measurements:

- First, measure the slice at reservoir conditions. The equation is:

$$\log I_1 = \log I_s[\mu_R \rho_R (1 - \Phi)x + \rho_f \mu_f \Phi]$$

- Second, measure the same slice at the same energy level of the extracted core.

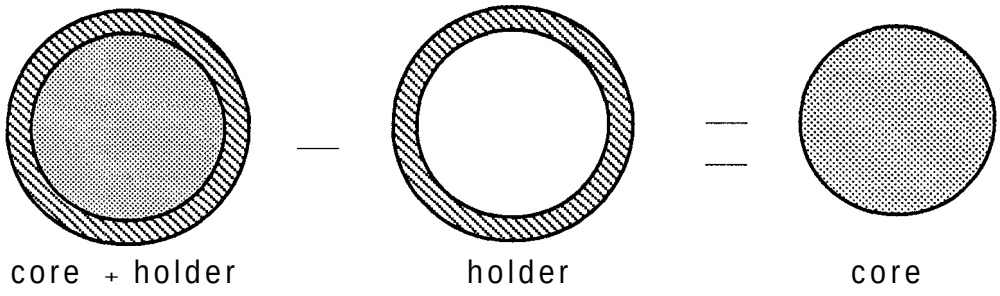
$$\log I_2 = \log I_s[\mu_R \rho_R (1 - \Phi) x]$$

- By taking the difference one obtains $\rho_f \mu_f \Phi$

In fact, the procedure is simplified by using a CT because μ and ρ are measured directly, and x is a constant. Direct arithmetic subtraction **is** consequently possible.

2). Spatial subtraction

For clarity, it is often desirable to remove extraneous objects from the image. Lets, for example, consider the following system:



Measurement 1 - measurement of empty holder

If one desires an image of only the core, the system can be decomposed into two parts by using spatial subtraction.

Most computers attached to modern scanners can perform this type of operation. It is sometimes possible to do a subtraction with only one measurement using edge detection techniques, i.e. telling the computer to remove every pixel with a CT number (or $\mu\rho$) over or under a certain threshold. Subtraction techniques are useful not only for removing core holders or the rock matrix; their use can be expanded for a variety of purposes such as numerical

analysis or fracture or void space detection.

d) Example Calculation

1). Two-phase saturation:

For simplicity let us consider **a** core containing only two phases, having subtracted the core holder as shown above. The governing equation is:

$$\rho_B \mu = \mu_R \rho_R (1 - \Phi) + \Phi(\mu_1 \rho_1 + \mu_2 \rho_2)$$

where ρ_B is the bulk density of the system.

Measuring the evacuated core gives $\mu_R \rho_R (1 - \Phi)$ and, we are left with the following system of two equations with two unknowns:

- $\mu = \mu_1 S_1 + \mu_2 S_2$ where 1 and 2 are phase 1 and 2 respectively,
- $S_1 + S_2 = 1$

2). Three-phase saturation:

The above analysis can be expanded to three-phase saturation. The additional unknown requires an additional, independent measurement. This is done by scanning at a different energy level. Supposing the phases are water (w), oil (o), and gas (g), the system of equations will then become:

$$S_0 + S_w + S_g = 1$$

$$\mu_1 = \mu_{01} S_0 + \mu_{w1} S_w + \mu_{g1} S_{g1}$$

at E_1 energy level 1

$$\mu_2 = \mu_{o2} S_0 + \mu_{w2} S_w + \mu_{g2} S_{g1}$$

at E_2 energy level 2

By calibration with phantoms (or values from tables), μ_o, μ_w and μ_g are known for each of the phases. The system can then be easily solved.

Calibration Techniques

Medical scanners are usually calibrated for values close to the value of water. For petroleum research applications, calibration with the materials generally encountered in reservoirs is needed.

a). Use of phantoms

Phantoms are simply homogeneous samples with known values. A scan is made of these samples, and their adsorption coefficients are noted at various energy levels. This information can be stored in the computer, which then allows subtractions or comparisons to be made automatically. Examples of phantoms used for petroleum applications are:

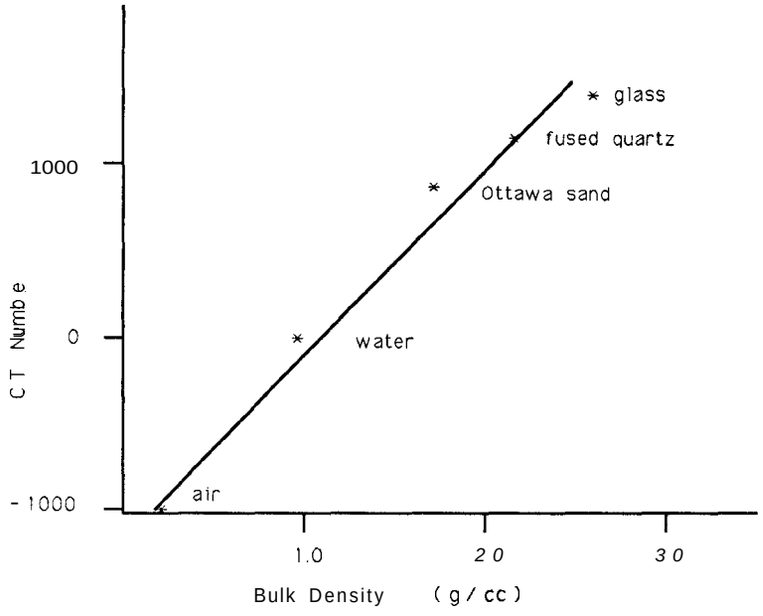
- Distilled water and brines of various salinities
- Oils of various compositions
- Rocks, clean sand, and clays
- Metal or plastic (as used for core holders)

Phantoms can also be used to define the spatial resolution of the scanner. Holes or slots of various dimensions as well as different shapes are cut into a piece of material and a scan is made. Various techniques of analysis of the resulting images can be applied to determine the resolution in space of the scanner under these conditions. Phenomena such as beam hardening (interferences caused by shapes or presence of materials of different characteristics) can also be studied on phantoms.

b). Correlations

CT data output is not the classic linear attenuation coefficient μ (cm^{-1}). Instead, the output is read on an international standard scale in units of Hounsfields (**H** or CT numbers). This scale is usually defined by two points water = 0 and air **is** -1000. Hence, each CT unit represents about a 0.1% change in the attenuation coefficient. Medical systems are usually calibrated near the water end of the scale. For petroleum applications, we must use other phantoms as well.

It is possible to simplify the calibration in the case of rock samples with the following precautions. **As** rocks have higher atomic numbers than water, the linear relationship observed between CT number (H) and bulk density as observed near water must be recalibrated. For example, sandstones are mostly silica, while carbonates have an entirely different chemical composition, ***so*** a correlation derived for sandstones will not be valid for carbonates, and vice versa. **As** the adsorption also depends on the energy level, it **is** necessary to derive **a** correlation for each energy level studied.



(figure adapted from reference 1)

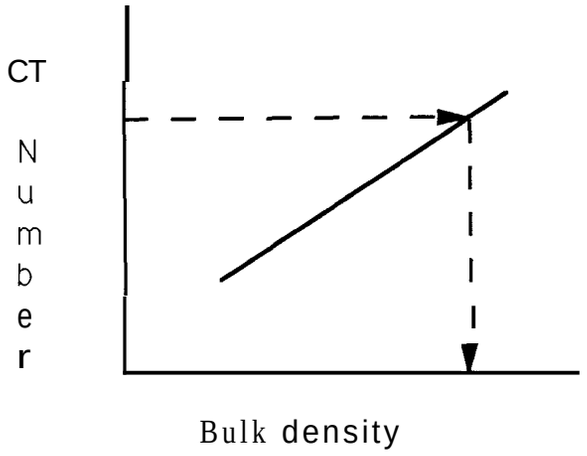
The figure shows a possible calibration for sandstones based on measurements of fused quartz, Ottawa sand, and glass. It is also possible to curve-fit results from samples of known bulk density.

c). Quick Analysis Techniques

Once correlations of the type described above are obtained, determination of parameters such as density and porosity is possible. Although these methods are not exact, they are usually accurate enough for most applications.

Examples of Density and Porosity **Logs**

Assume that for a given type of rock, you have calibrated the scanner as described above.



Scanning an unknown sample with the same or similar chemical composition will give you a CT number. It is possible to obtain its bulk density by reading the value directly from the correlation. Porosity can then be determined by using the formula $\rho_B = (1 - \Phi)\rho_R$, assuming that the core is saturated with gas only. ρ_R is the grain density of the rock and must be obtained independently. These techniques are valid for analysis of large numbers of samples on a routine basis. **A** practical application of the above example could be verification of density logs, or study of drilling mud-invaded zones.

Software

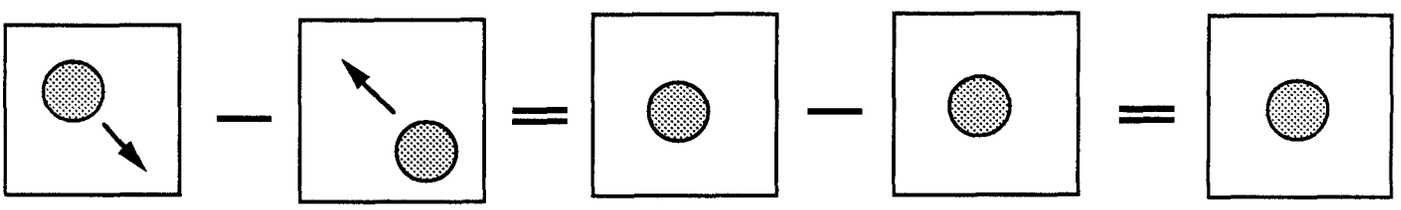
a). Existing Medical Software

All medical CT scanners are provided with a computer that performs the following functions:

- Determination of a matrix of CT numbers (or μ).
- Visualization (usually on a TV screen but also possibly on film using cameras).
- Zoom (allows study of details of an image).
- Statistics calculations such as the value of the mean and standard deviation in all or part of an image.
- Selection of one part of an image (region of interest) for statistical processing or zooming.
- Adjustments via subtraction algorithms.

Some additional options which may or may not be provided include:

- Edge detection (selection of specific areas of the image based on changes in CT numbers).
- Automatic shifting of images before subtraction.



This requires edge detection algorithms.

b). Image Processing

A variety of image enhancement or graphic programs can be adapted for use in combination with a CT scanner, depending on the capacities of the computer and software being used. Some examples are:

- Colorization of images
- Contouring of various areas
- Video or slide display
- Reconstruction of linear cores by superposition of consecutive slices.

Most of this software is already available or can either be found in-house, or obtained from specialized software companies. At Stanford, for example, we use in-house mapping programs from the geology and geophysics department.

Development of such sophisticated software is not recommended because of the effort and high level of computer expertise required. This is a computer science programming problem that should not, in my opinion, be attempted by petroleum company scientists.

c). Petroleum-related Software

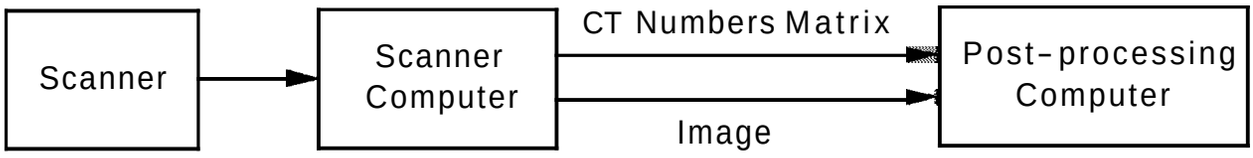
In order to process data for petroleum applications, software can be added to the existing medical and image processing software. Unlike the two previously described categories, petroleum-related software is not readily available, except from Shell. This software is, however, relatively simple to develop, and can be done in-house or by a good computer science student, providing that both medical and image-processing programs are already available. Software needed for petroleum application includes:

- Most importantly, reference libraries for calibration. Included should be phantoms of fluids commonly found in the oil reservoir of interest, as well as of rocks of various chemical compositions. This library should also cover at least two energy levels, allowing independent measurements for solution of multi-phase problems.

- Correlation data files of the type described for sandstones, along with programs which automatically interpolate for geological or petro-physical data.
- Calculation routines for saturation determinations like the ones presented above.
- Special subtraction algorithms for core holders and/or rocks.
- Some statistical packages.
- Finally, possibly a program which automatically controls the scanner, especially for positioning it, such as the program used by Shell.

d). Computer Networking

The medical system computers usually work as block bases. As such, they are difficult to program for the non-technician. For image enhancement and petroleum software special applications, it is consequently useful to network a second (post processing) computer with the medical scanner in the following manner:



The transfer can be accomplished using either the matrix of CT numbers, or the image files provided by the medical computer. The main difficulty in this transfer is to obtain data files which are compatible with both the medical and the post-processing computer. Several techniques of networking are possible:

1). Direct data transfer through cables

The data stored in the disk or tape drive on the scanner computer can be transferred to the processing computer through the use of an interface cable (at Stanford, an RS232 interface and cable are being used). This requires writing a data transfer program or protocol that will allow correct formating of the CT number mamx. Unfortunately no such program is readily available for medical systems.

2). Transfer through video output.

CT images are usually projected onto a screen in the diagnostic console. One can use this video output as an easily formatted input into a video digitizer for direct transfer to the processing computer. Video digitizers are readily available, very accurate, and require no extra software.

Because computer networking is heavily dependent on the existing support system in a company, efforts should be made to utilize the predominantly used operating system and computer language.

Hardware

In this section we will detail the requirements for using a scanner for petroleum applications and review some of the existing models.

a). Scanner Generations

Medical scanners are usually classified by generations. This term refers primarily to the type of movement used by the source and detectors to send the x-rays through the objects.

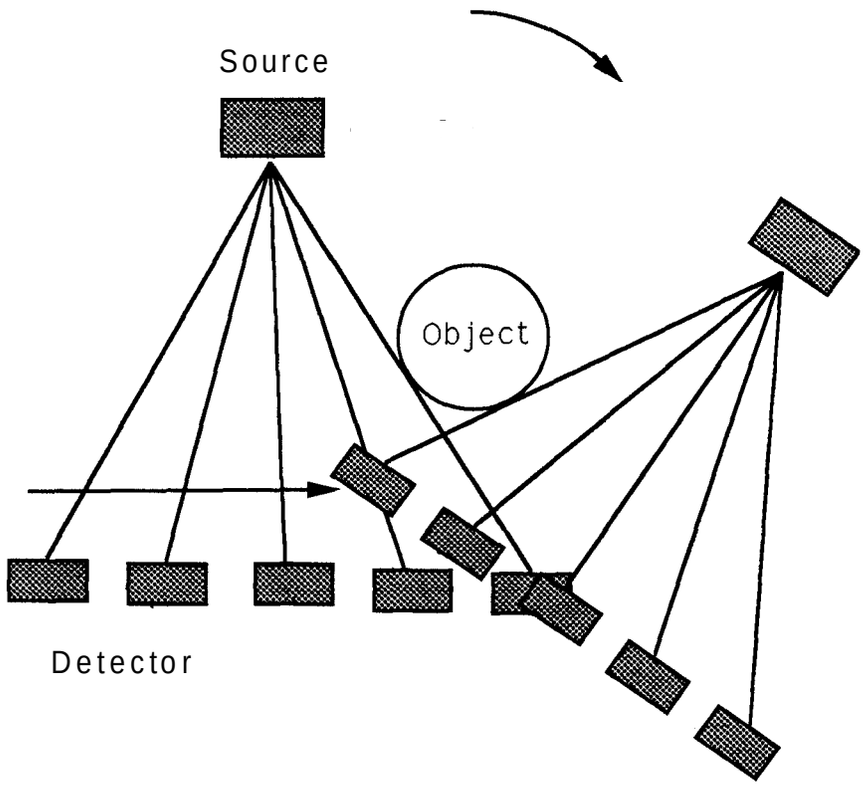
First generation

These scanners are now obsolete and are not recommended for use. They operate only in a translation mode, and the computers are not adequate. They have been abandoned for medical use.

Second generation

This is the most extensively used type of scanner. In this system the source and detectors travel together in a translation, then rotate to start another translation. It is called a translate-rotate scanner. Although relatively old, these scanners have some characteristics that make them very suitable for petroleum applications:

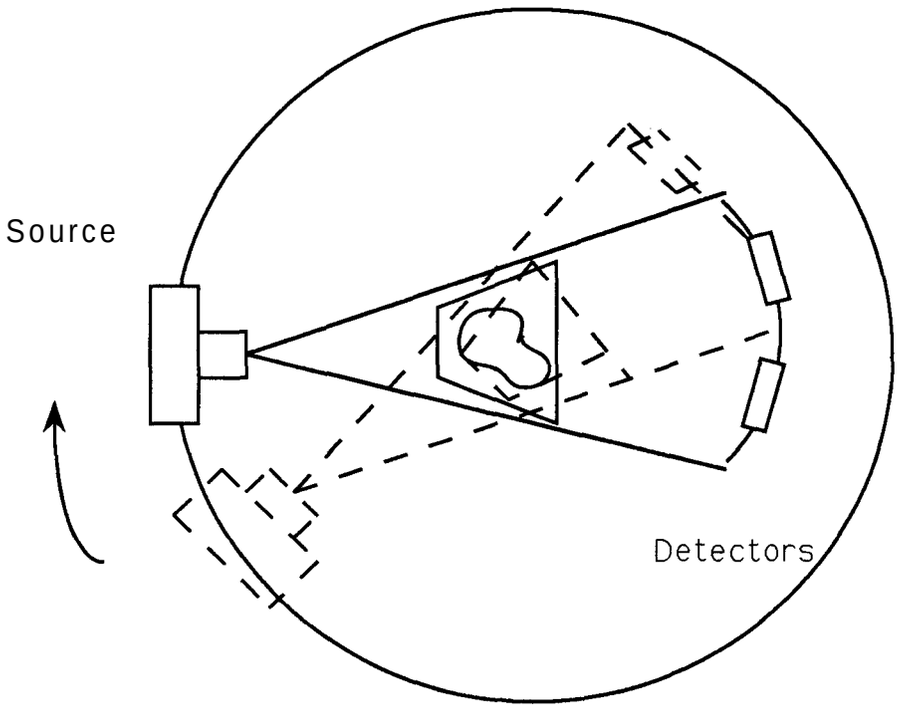
- adjustable energy levels
- easy calibration
- reasonable price and easy maintenance (see **later)**



The main limitation for medical use is that the speed of each scan is slow (between 18 and 80 seconds per slice). This poses no problem for our application.

Third generation

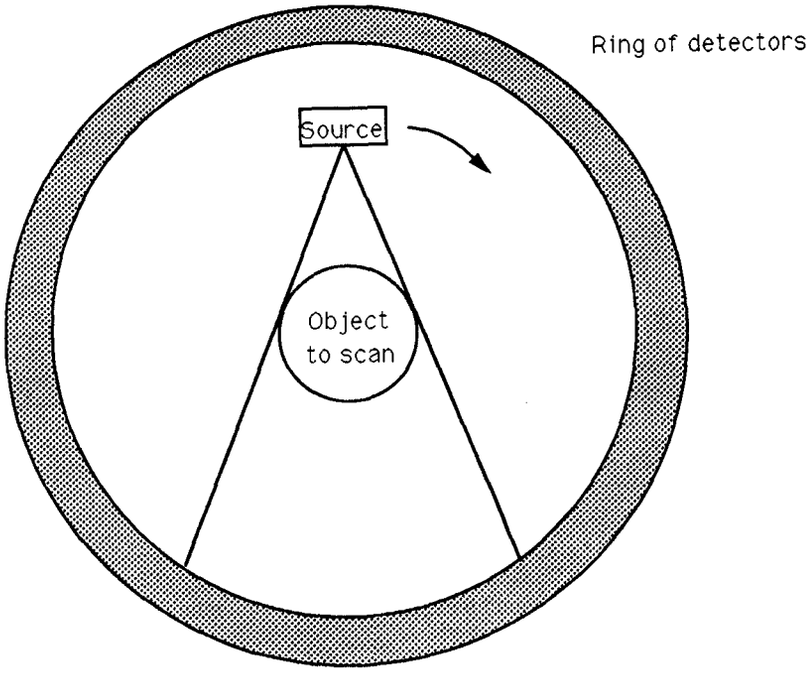
In order to improve the scan speed, some scanners have a design where the source and detector assembly rotates in concentric circles. This improves the speed of scan, but may increase costs and raise the level of required maintenance.



The computers associated with the third generation scanner usually offer more elaborate software compared to second generation computers. This is reflected in a much higher price.

Fourth generation and above

The most modern scanners are referred to as fourth generation (GE also has a 5th generation). In these designs only the source rotates inside a circle of detectors. This allows very rapid scanning, which lowers x-ray exposure. This is an important consideration for patients, but not for our application.



These scanners are equipped with very good computers, but several problems must be solved before they can be adapted to petroleum applications. Of particular importance is the fact that they often do not allow dual energy scanning.

b). Review of equipment being used for petroleum applications

A survey of companies having experience in the application of cat-scanning to petroleum-related problems was taken. The following table summarizes the results:

TABLE I

Existing Cat-Scan Systems For Petroleum Applications

Company	Scanner	Experience	Effort	Comments
Shell	2 Deltascan 100's (2nd generation) bought used $5k each	7 years	3 engineers 2 programmers 5 technicians	used routinely, very successful, heavy manpower investment (> 50 man*yrs) geology, core analysis, flow EOR
Mobil	1 ELSINT (2nd generation) bought new $1 million	3 years	1 manager 3,4 engineers programmers	maintenance problems expensive scanner geology, core analysis
University of Houston	4th generation expensive $400K	1 year	1 manager 3,4 technicians students	not yet fully operational; maintenance problems
SUPRI	1 EMI 5005 (2nd generation) bought used $25k	1 year	1 technician students	inexpensive, simple, fast results very good geology, core analysis, flow EOR
ARCO	1 GE 8800 (4th generation) bought new $1.5 million	2 years	about same as Mobil	good results, but very expensive, no flow experiments no EOR studies
University of Texas	1 industrial scanner (BIO-imaging) bought new $400k	2 years	same as U of H	no results yet
Alberta Resource Council	1 used scanner (2nd generation)	6 months	?	reported good results past experience with hospitals
University of Calgary (Canada)	none			preliminary studies only will buy a scanner
IFP (France)	none			preliminary studies only will buy a scanner
INTEVEP	2 Deltascan 100's	none	?	just bought the scanners will use one for parts use Shell's experience

Also worth mentioning is the research being done in Norway, England (Winfrith), and France (Toulouse) using gamma rays. In addition, the use of Nuclear Magnetic Resonance

(NMR) is being looked at by Shell, Mobil and Stanford's Electrical Engineering Department.

c). Criteria for choosing a Scanner:

Technical criteria, economic considerations, and requirements specific to the company must be considered. Some of the main factors to consider are:

1). Spacial Resolution

It is desirable for the elements to be as small as possible. The resolution will depend mostly on the size of the matrix of CT numbers provided by the scanner.

A minimum of 320 x 320 pixels is needed to obtain suitably sized elements for our application. A pixel size of $1mm^2$ or less is desirable. The thickness of each slice should be as small as possible in order to minimize errors. Typical thicknesses are in the range of 0.5 to 1.5cm. Use of subtraction techniques can allow interpretation of slices less than lmm thick.

2). Field of Scan

Medically, the design of a scanner is intended for head or whole-body scans. The field of scan is a circle with approx. a 25cm diameter for the head, and about 40cm diameter for the body. For our application, a smaller field of scan will result in better spatial resolution because the number of pixels available remains constant. Hence, the head scanner is more appropriate. Some scanners, such as the EMI 5005, allow both body and head-scan positions. This capability is useful if cores of various sizes are investigated, such as 1-1/2" core samples or radial flow models with a 30cm diameter. Ease of switching between head and body scanning depends on the machine type.

3). Energy Level

As can be seen from the equations and examples given above, it is essential for a scanner used in petroleum research to have adjustable energy levels. This is the primary criterion for scanner selection. A minimum of two distinct energy levels is required, additional levels are

desirable. The intensity of the source should also be adjustable to facilitate experiments. Some scanners (GE 8800, for example) are very difficult to operate at various energy levels.

4). Tube Design

Fixed anode, liquid-cooled tubes are preferable to rotating anode, air-cooled tubes because they have a longer lifespan and require less maintenance. Tubes are seldom covered by the maintenance contract. They are expensive (7,000 dollars average, or more), and often require extended replacement time. The fixed-anode liquid-cooled design should be preferred.

5). Installation, maintenance, and price

The price of scanners can vary from several million dollars to a few thousand. Used scanners can be found at competitive prices in the second-hand market, and this source is recommended. Installation of a scanner is complicated and should be done by specialized professionals. The purchaser should be aware of the cost of installation and try including it in the deal, because installation costs can add up to two to three times the cost of the scanner.

Maintenance is a very important consideration, as it is often the most expensive item in CT operation. Also, it is mandatory to choose a CT scanner that can be adequately maintained and calibrated by local service companies. This may affect the selection of the scanner itself.

The price and quality of maintenance contracts can vary depending on the location, the amount of use, and the brand and model of the scanner. One should survey other cat-scan users, such as radiology technicians and nurses at hospitals, research centers, and clinics, to inquire about the performance of local service companies.

There are two major types of maintenance contracts: 1) time and materials, where the cost of the contract will be the cost of parts and time spent by the repair crew, and 2) lump-sum time contract, where any repair occuring during the period under the contract will be covered by a lump sum usually paid in advance. The contract should include provisions for modifications of the scanner for dual energy use and calibration. This requires that the service company can demonstrate proven ability not only in repairing the hardware, but also in

modifying the internal CT software for petroleum applications. As no maintenance contract will cover the x-ray source, one must make sure that a supply of tubes exists, and that the maintenance contractor has the capability to replace the source. This should be specified in writing at the time of signing the contract.

d) Positioning Systems

Often several measurements of the same slice are needed, and longitudinal positioning as well as centering the cores (or core holders) has to be very accurate. Usually good centering can be obtained by the use of plexiglass or plasic holders standardized to the core holders. Lengthwise positioning can be accomplished by various means such as positioning tables, optical readers, or lasers. Repeatability of the experiments is highly sensitive to accurate postioning of the objects. Shell has an excellent positioning system described in reference 1.

Adaptation of available industrial or optical positioning systems is the best way to obtain a reliable and inexpensive system.

e) Core holder design considerations

Core holders must be constructed with x-ray-transparent materials such as aluminum, Teflon, or epoxy resin. Other plastic materials can also be used without problems with the exception of high durameter Viton, which yields excessively high attenuation values. Testing of materials used to design core holders is recommended before costly machining is started. This can easily be done by scanning a piece of the material considered and recording the attenuation. It is also a good idea to standardize the core holder dimensions, especially the diameter, to ease the centering inside the scanner gantry.

Any routine flow experiment or EOR test can easily be performed inside a scanner providing that the above criteria are met.

f) Post-Processing Computer

The post-processing computer should have enough RAM (Random Access Memory) to

be able to easily process the images. A 320x320 image usually takes about 500 kbytes. Central memory of at least 8 Mbytes is suitable, and ample storage space on disk and/or tape should be provided. Most modern mini- or micro-computers can be used as post-processors. The two main considerations are how readily the data can be transferred from the CT computer to the processing computer, and how much software for, and experience in image processing the company has on the type of machine being considered. The cost of a MacIntosh II, for example, is about 10,000 dollars for a configuration suitable for CT data processing. Interfacing (see networking) is the main consideration.

Possible applications of CT scanning

The following section covers only a few ideas of possible uses for x-ray tomograhy in a petroleum company. CT should be considered as a tool that can be used in a variety of tasks by researchers of diverse backgrounds and interests. It can also be used as a supplement to conventional analytical techniques.

a). Geology

CT allows in-depth examination of core heterogeneities in a non-destructive manner. CT data can also help reconstruct three-dimensional structures of cores from thin section data. Combined use of SEM (Scanning-Electro Microscope) and CT data allows the identification of specific minerals and chemical elements. Cementation and natural fractures can also be detected.

b). Core Analysis

The examples given above show that density and porosity can easily be calculated using CT. Sample screening by CT allows selection of representative and homogeneous samples for petrophysical studies. Problems such as end-effects or flow stabilization can be detected. CT can be used in conjunction with field data to verify logging results or study mud invasion as well as in a variety of other petrophysical research.

c) Flow experiments, EOR

Any flow experiment of a suitable size can be run in a CT scanner. The data can be used to understand the mechanisms governing the EOR process, or to verify the results obtained from numerical simulations. No other reliable technique exists to my knowledge to obtain in-situ fluid saturations in a non-destructive manner. CT can be applied to all EOR processes, without exception.

d) Some other uses

CT can be used as a diagnostic tool to detect corrosion or metal fatigue without destroying the samples. Some applications of this technology could include: verification of welding in pipes, study of corrosion inhibitors, study of metal fatigue in high pressure or high temperature containers, or study of scale inhibitors. The specific application depends on the needs of the company.

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APPENDIX

Stanford University Petroleum Research Institute CT Program

As a University with very limited resources both in manpower and money, SUPRI opted for a simple and economical program of computerized tomography.

A1) Objectives

SUPRI will operate the CT scanner located in our laboratory on a routine basis. It will be used for a variety of tasks including, but not limited to, geological and geophysical studies, core analysis, and multi-phase flow experiments for enhanced oil recovery applications. CT will be used as a tool to complement and improve existing laboratory facilities and techniques.

A2) Current Status

An EMI 5005 (2nd generation) scanner was purchased and installed. The computers associated with the scanner are two DATA General ECLIPSE 200's. A MacIntosh II was purchased and networked to the DATA General computers through video digitizing and cables.

The scanner has been operational for 3 months, and has had no maintenance problems. Images of cores have been obtained under a variety of conditions, and calibration for petroleum applications is in progress. Flow experiments have successfully been scanned. Image processing software is being acquired and modified for SUPRI use.

A3) Future Work

Long-term testing of the scanner is planned. The calibration reference library will be expanded to cover most of the fluids, rock types, and core holder materials used in SUPRI research. Simultaneously, adaptation of available software will be continued. Software development, such as programming, will be limited mostly to linking existing programs to each other and writing simple programs specific to petroleum applications. Fabrication of a positioning system is in progress. Completion is scheduled for December, 1988.

A4) Examples of Current Applications at **SUPRI**

Already in progress are CT studies on:

- verification of pack quality for unconsolidated cores prior to flow experiments
- determination of liquid saturation in foam-flow experiments
- investigation of naturally fractured cores
- Effect of core heterogeneity in the flow behavior of CO_2 flooding, water flooding, and steam with additives processes

Table 11 - SUPRI's CT System

Scanner

EMI 5005 (second generation)
price - $25,000
installation - $15,000
maintenance - $17,000 / yr

2 D6 200 Eclipse computers (32K each)

320 X 320 image with 256 gray levels

Scan field between 24 and 40 cms

Imaging 180 to 70% (high accuracy)

Intensity 0 to 40 ma

Energy 80 to 140 keV

Fixed-anode oil-cooled X-ray tube

30 Sodium iodide detectors

MacIntosh 11

16 MHz - 68020 processor

8 MB internal RAM

40 MB hard disc

10 MB floppy back-up system Jasmin Inc.

2 X 800 kB floppy disc drives

Library of software

AN INTRODUCTION TO COMPUTERIZED X-RAY TOMOGRAPHY FOR PETROLEUM RESEARCH

Supri TR 66

By

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May 1989

Work Performed Energy Under Contract No. DE-FG 19-87BC 14126

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Executive Summary

This report summarizes the state of the art in the application of medical tomography (CT) to petroleum recovery problems. A brief review of the basic principles of x-ray computerized tomography is followed by a discussion of the governing equations of the method. Calculation techniques and appropriate correlations for continued testing are described and discussed. A review of existing medical software is done. Consideration of the specific software needed for petroleum engineering as well as applications of new technologies such as image processing and computer networking are described.

Criteria for the choice of a machine suitable for most petroleum-related applications are given. Emphasis is placed on flexibility, reliability, accuracy and price of the scanner. Two separate sections discuss positioning of the core and design of the core holders. Examples of possible applications of CT scanning to problems of geology, core analysis, EOR as well as operational process problems are discussed. An appendix presents the status of the CT research at the Stanford University Petroleum Research Institute.

The basic conclusion of this work is that computerized x-ray tomography is a powerful tool for petroleum industry researchers. Present technology allows its use by major research centers in an effective manner providing that some simple criteria are met. Existing hardware is adequate and adaptation of existing medical software in combination with other sources is possible. No new technology is needed.

- Second, measure the same slice at the same energy level of the extracted core.

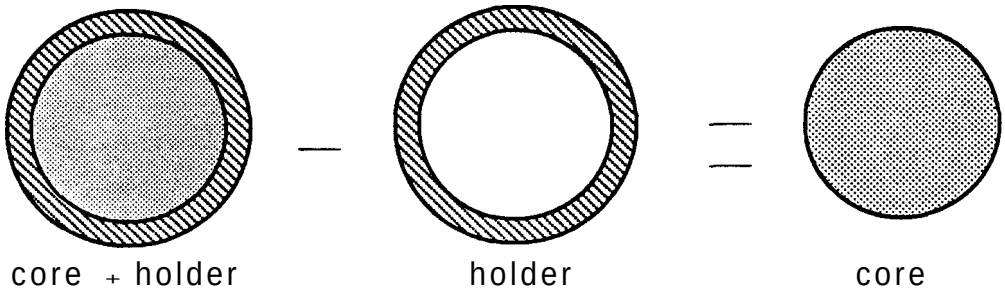
$$\log I_2 = \log I_s[\mu_R \rho_R (1 - \Phi) x]$$

- By taking the difference one obtains $\rho_f \mu_f \Phi$

In fact, the procedure is simplified by using a CT because μ and ρ are measured directly, and x is a constant. Direct arithmetic subtraction is consequently possible.

2). Spatial subtraction

For clarity, it is often desirable to remove extraneous objects from the image. Lets, for example, consider the following system:



Measurement 1 - measurement of empty holder

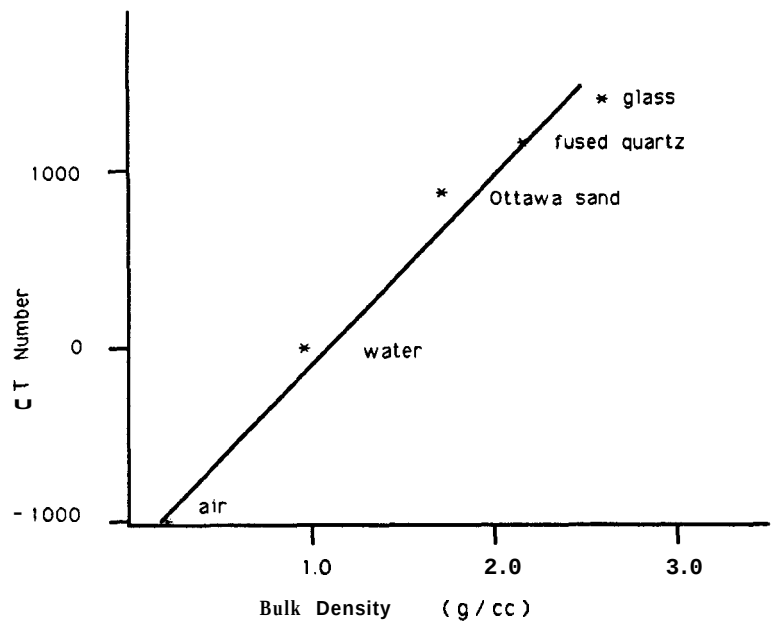
If one desires an image of only the core, the system can be decomposed into two parts by using spatial subtraction.

Most computers attached to modem scanners can perform this type of operation. It is sometimes possible to do a subtraction with only one measurement using edge detection techniques, i.e. telling the computer to remove every pixel with a CT number (or $\mu\rho$) over or under a certain threshold. Subtraction techniques are useful not only for removing core holders or the rock matrix; their use can be expanded for a variety of purposes such as numerical

b). Correlations

CT data output is not the classic linear attenuation coefficient μ (cm^{-1}). Instead, the output is read on an international standard scale in units of Hounsfields (H or CT numbers). This scale is usually defined by two points water = 0 and air is -1000. Hence, each CT unit represents about a 0.1% change in the attenuation coefficient. Medical systems are usually calibrated near the water end of the scale. For petroleum applications, we must use other phantoms as well.

It is possible to simplify the calibration in the case of rock samples with the following precautions. As rocks have higher atomic numbers than water, the linear relationship observed between CT number (H) and bulk density as observed near water must be recalibrated. For example, sandstones are mostly silica, while carbonates have an entirely different chemical composition, so a correlation derived for sandstones will not be valid for carbonates, and vice versa. As the adsorption also depends on the energy level, it is necessary to derive a correlation for each energy level studied.



(figure adapted from reference 1)

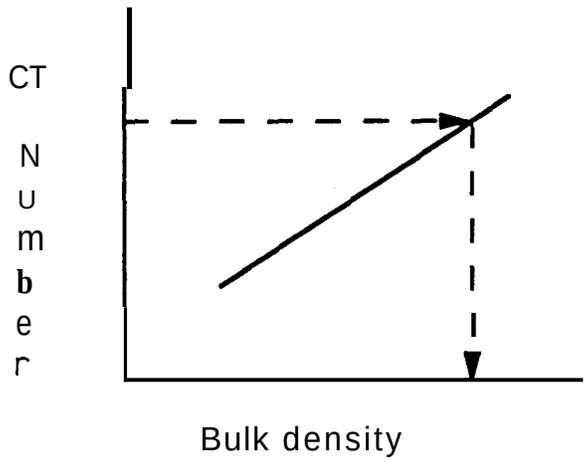
The figure shows a possible calibration for sandstones based on measurements of fused quartz, Ottawa sand, and glass. It is also possible to curve-fit results from samples of known bulk density.

c). Quick Analysis Techniques

Once correlations of the type described above are obtained, determination of parameters such as density and porosity is possible. Although these methods are not exact, they are usually accurate enough for most applications.

Examples of Density and Porosity Logs

Assume that for a given type of rock, you have calibrated the scanner as described above.



Scanning an unknown sample with the same or similar chemical composition will give you a CT number. It is possible to obtain its bulk density by reading the value directly from the correlation. Porosity can then be determined by using the formula $\rho_B = (1 - \Phi)\rho_R$, assuming that the core is saturated with gas only. ρ_R is the grain density of the rock and must be obtained independently. These techniques are valid for analysis of large numbers of samples on a routine basis. A practical application of the above example could be verification of density logs, or study of drilling mud-invaded zones.

Software

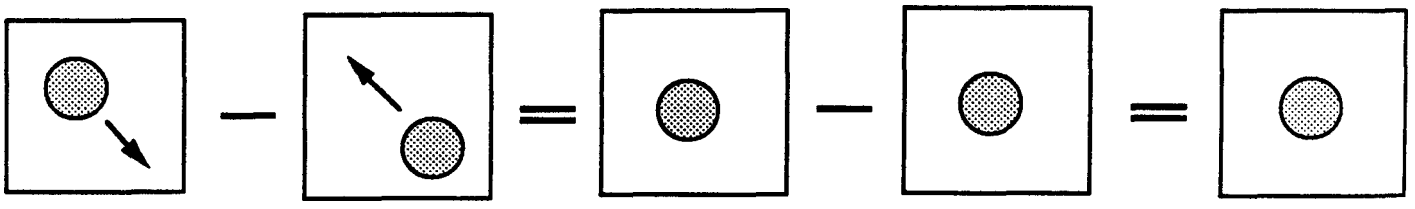
a). Existing Medical Software

All medical CT scanners are provided with a computer that performs the following functions:

- Determination of a matrix of CT numbers (or μ).
- Visualization (usually on a TV screen but also possibly on film using cameras).
- Zoom (allows study of details of an image).
- Statistics calculations such as the value of the mean and standard deviation in all or part of an image.
- Selection of one part of an image (region of interest) for statistical processing or zooming.
- Adjustments via subtraction algorithms.

Some additional options which may or may not be provided include:

- Edge detection (selection of specific areas of the image based on changes in CT numbers).
- Automatic shifting of images before subtraction.

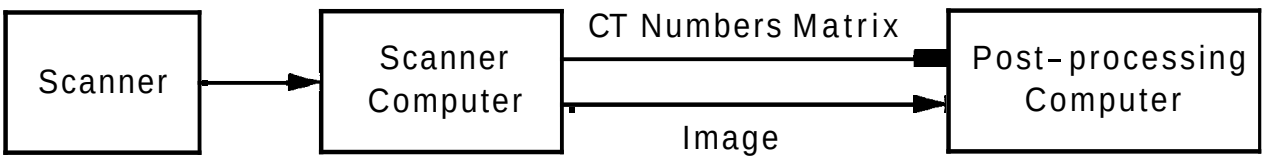


This requires edge detection algorithms.

- Correlation data files of the type described for sandstones, along with programs which automatically interpolate for geological or petro-physical data.
- Calculation routines for saturation determinations like the ones presented above.
- Special subtraction algorithms for core holders and/or rocks.
- Some statistical packages.
- Finally, possibly a program which automatically controls the scanner, especially for positioning it, such as the program used by Shell.

d). Computer Networking

The medical system computers usually work as block bases. As such, they are difficult to program for the non-technician. For image enhancement and petroleum software special applications, it is consequently useful to network a second (post processing) computer with the medical scanner in the following manner:

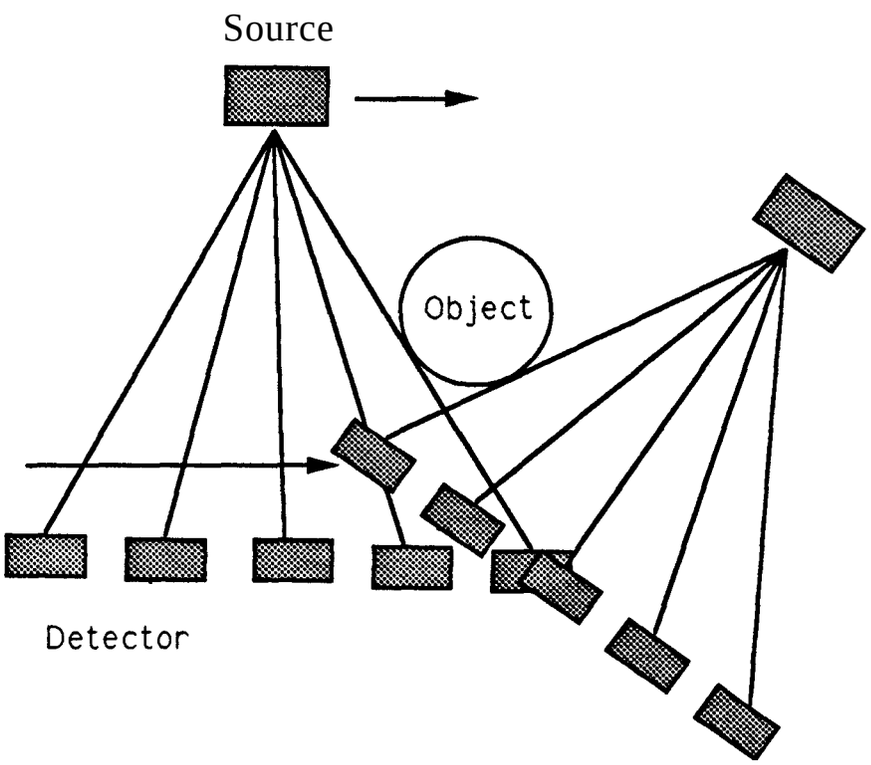


The transfer can be accomplished using either the matrix of CT numbers, or the image files provided by the medical computer. The main difficulty in this transfer is to obtain data files which are compatible with both the medical and the post-processing computer. Several techniques of networking are possible:

Second generation

This is the most extensively used type of scanner. In this system the source and detectors travel together in a translation, then rotate to start another translation. It is called a translate-rotate scanner. Although relatively old, these scanners have some characteristics that make them very suitable for petroleum applications:

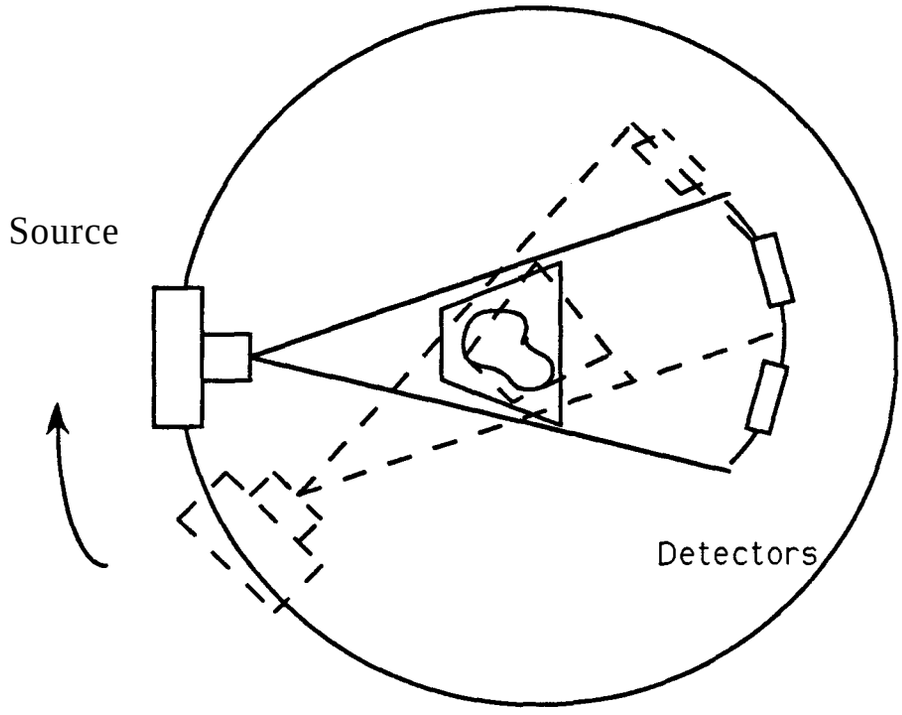
- adjustable energy levels
- easy calibration
- reasonable price and easy maintenance (see later)



The main limitation for medical use is that the speed of each scan is slow (between 18 and 80 seconds per slice). This poses no problem for our application.

Third generation

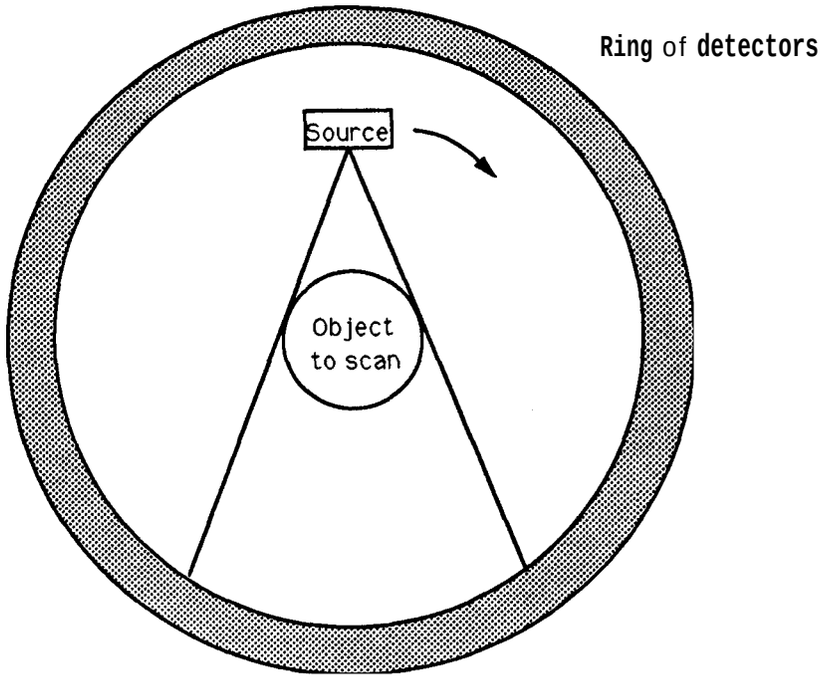
In order to improve the scan speed, some scanners have a design where the source and detector assembly rotates in concentric circles. This improves the speed of scan, but may increase costs and raise the level of required maintenance.



The computers associated with the third generation scanner usually offer more elaborate software compared to second generation computers. This is reflected in a much higher price.

Fourth generation and above

The most modern scanners are referred to as fourth generation (GE also has a 5th generation). In these designs only the source rotates inside a circle of detectors. This allows very rapid scanning, which lowers x-ray exposure. This is an important consideration for patients, but not for our application.



These scanners are equipped with very good computers, but several problems must be solved before they can be adapted to petroleum applications. Of particular importance is the fact that they often do not allow dual energy scanning.

b). Review of equipment being used for petroleum applications

A survey of companies having experience in the application of cat-scanning to petroleum-related problems was taken. The following table summarizes the results:

A4) Examples of Current Applications at SUPRI

Already in progress are CT studies on:

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