The Use of Attenuation Standards for CT Scanning

by

M. E. Coles and E. L. Muegge
Mobil Exploration and Producing Technical Center
Dallas, Texas
and
F. M. Auzerais and P. Frulla
Schlumberger-Doll Research
Ridgefield, Connecticut
and
A. Kantzas
University of Calgary

Abstract

Use of CT scanning and related technologies to view and characterize reservoir core in conjunction with routine or special core analysis is widespread and increasing. Currently, CT scanning of core materials is accomplished at many different laboratories, utilizing a wide variety of instruments. Drift in the measured attenuation response has been identified and been shown to shift CT values. This reduces the accuracy and reliability of CT results and hinders comparison of data. During the 1994 SCA workshop on CT scanning, routine calibration against attenuation standards was recommended to increase integrity, validity and comparability of results. This paper discusses the need for standards and presents methods used by three different laboratories. Overall recommendations for minimization of errors induced by drift are provided.

Introduction

CT technology was first developed for the applications within the medical arena[1], however it is now widely used within the petroleum industry to identify and characterize (1) internal structural characteristics within core material and (2) fluid saturations and distributions within core material systems.[2-7]

During the computed tomography scanning process, the attenuation of an x-ray beam is measured as it passes through a sample material. This is illustrated in Figure 1, where I_O and I represent the intensity of the x-ray beam before and after passing through the substance, x is the thickness of the material and μ is defined as the linear attenuation coefficient. The attenuation coefficient μ is defined as the fractional decrease in x-ray intensity per unit length of that material and is a function of the atomic number and bulk density of the material and the energy of the probing x-rays.

$$I / I_o = e^{-\mu x} \qquad (1)$$

Figure 1. CT scanning process x-ray attenuation measurement

Generally, the linear attenuation coefficient is normalized to that of a standard material (such as water) and is defined as the CT number of the material:

$$CT\ number = \frac{(\mu_{material} - \mu_{standard}) \bullet K}{\mu_{standard}} \qquad (2)$$

where K is a scaling factor. [1]

Within a single tomographic scan, the x-ray attenuation is measured for a multitude of different angles and a cross-sectional reconstructed image is generated which represents the x-ray attenuation (CT number) in specific voxels (volume elements) of the material in a plane perpendicular to the motion of the scan. The geometrical scanning arrangement is often referenced to one of five different generation of scanners.[1] One specific scanning arrangement is illustrated in Figure 2. In the gray scale tomographic image, light areas represent high x-ray attenuation or CT number (high density or atomic number) and darker areas represent low x-ray attenuation or CT number (low density or atomic number).

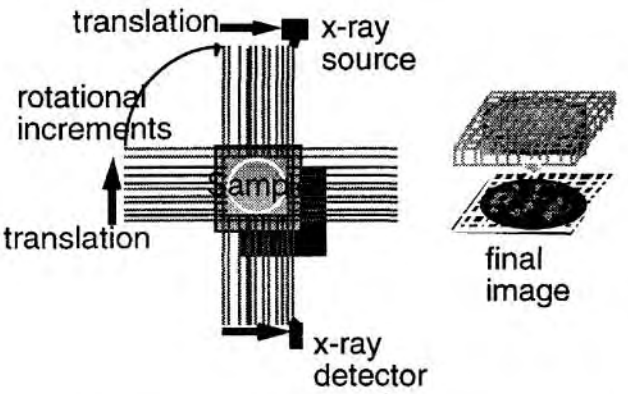

Figure 2: CT scanning process; translation - rotation tomographic mode

CT scan images represent discrete x-ray attenuation information of the material scanned. Computed tomography is used to identify and evaluate structural characteristics of core material such as core damage, mud invasion, heterogeneity.[2,4,5] In addition this qualitative (visual) assessment of the CT images, quantitative information such as density, porosity and saturation values can be obtained from CT values with appropriate processing and calculations.[2,3,6-8] This is shown in Table 1.

Table 1

Density	$\rho = \frac{CT - b_{(y\ intercept)}}{m_{(slope)}}$	: CT is measured CT value, which when plotted as a function of known density, ρ, will allow calculation of unknown ρ.	(3)
Porosity	$\emptyset = \frac{CT_{total}^{1} - CT_{total}^{2}}{CT_{fluid1} - CT_{fluid2}}$	: CT_{fluid} is the measured attenuation of a given fluid, and CT_{total} is the CT value of a given core material fully saturated with that fluid.	(4)
Two-Phase Saturation	$S_w = \frac{CT_{sat} - CT_o}{CT_w - CT_o}$	: CT_{sat} is the CT value obtained for a core material at an unknown saturation, CT_w and CT_o is the measured CT value for the same core material when saturated with water and oil.	(5)
Three-Phase Saturation	$CT_{high} = \Sigma_i (S_i CT_i)_{high}$ $CT_{low} = \Sigma_i (S_i CT_i)_{low}$	: CT_{high} (measured CT values at high energy) and CT_{low} (measured CT values at low energy) are sums of the product of saturations of each specific phase and the fully saturated value (characteristic attenuation) for that phase and energy.	(6)

In order to obtain accurate and reliable quantitative values from CT images, care must be taken to insure that accurate and reliable CT numbers are obtained. This paper (1) identifies the factors which effect the variability of measurements and therefore the accuracy and reliability of results; (2) presents methods which are being utilized to correct variability as they are performed in different laboratories; and (3) provides recommendations designed to reduce and correct for the variability and improve the accuracy and reliability of the CT method.

Accuracy and Reliability of CT Values

In order to obtain accurate and reliable quantitative values, we must insure accurate and reliable CT numbers. Accuracy is defined as the degree to which a measurement or set of measurements represents the true value of a parameter and indicates the degree of freedom from systematic error.[1] Precision is the self-consistency of a set of measurements or freedom from random error.

Through over 40 years of cumulative experience by the authors, we have found CT numbers to show variance or drift in their measured values. This drift is not predictable, is a function of the absolute attenuation and directly impacts the accuracy and precision of CT measurements. Figure 3 illustrates this variability or drift in measured CT values Plotted are CT numbers obtained at specific locations along the length of a given core sample at different times over several days.

Uncorrected drift results in increased error in calculated results and leads to inconsistent and unreliable values and underestimation of the accuracy of the CT method. Drift in measured CT numbers obtained at different times may result in significant error when those CT numbers are utilized using equations in Table 1 . A drift in CT number of as

little as 10 - 20 CT units has been shown to result in significant error when used to calculate saturation values. [8]

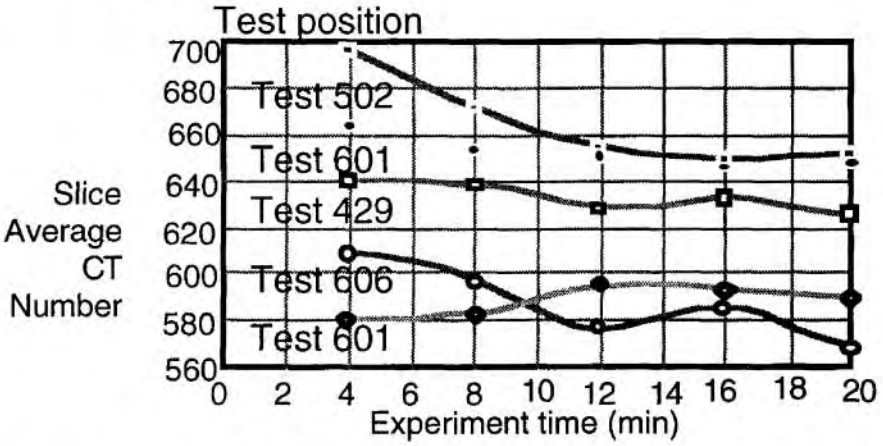

Figure 3: Drift or variance of measured of CT values obtained for a dolomite sample

Many factors lead to the variability and drift of measured CT values and therefore to the degradation of accuracy and reliability of results. These include: (1) aging of x-ray tube and detectors, resulting in changing of the beam energy profile and drift of contrast scale; (2) different beam filtration imposed by different collimators, core holders, core samples; sample size, shape, and composition; (3) temperature drift; (4) contrast enhancement; (5) artifacts imposed by beam hardening, high atomic number materials, motion or centering and (6) statistical or random noise. [1]

We have found that attenuation standards appropriate for core material can be used to correct for measurement variability. Correction results in increased accuracy and precision of measured CT values and allows comparison of values obtained at different times or with different systems. Several different methods for calibration are now in existence. Three are presented here.

Method 1 - Schlumberger-Doll Research

The focus of this study was to characterize damage on 4 inch diameter perforated cores and to examine the geometry of the perforation after bringing the CT images to their true material densities. This is necessary since images acquired by CT are uncalibrated attenuation images.[9,10]

Various expressions for the x-ray attenuation, have appeared in the literature. They all indicate a dependence of the linear x ray attenuation coefficient μ on the x-ray tube acceleration potentials (kVp), and on the average density (ρ) and mass-fraction-weighted average atomic number (Z) of the material, in the following form:

$$\mu = a'(kVp) + b'(kVp)\rho + c'(kVp)\rho Z^m \qquad (6)$$

where a'(kVp), b'(kVp) and c'(kVp) are energy-dependent coefficients, with m ranging in value from 3 to 4 for porous rock. For our purpose, advantage has been taken of the constant contribution in the atomic composition of our core samples (Berea sandstone) to simplify the relationship between density and x-ray attenuation to:

$$\mu = a\,(kVp) + b\,(kVp)\rho \qquad (7)$$

where a(kVp) and b(kVp) are coefficients to be determined.

This simplification allows us to extract quantitative density variations from CT images using a single energy level with two references of known density. It also compensates for time dependent fluctuations in the energy distribution of the x-ray source which occur while acquiring contiguous slices for 3-D reconstruction. Furthermore, when rescanning the same object at a different time with slightly different x-ray tube voltage settings, it allows us to resister in time and in space, each crossectional postreconstruction attenuation image, thereby assuring continuity in the data set. The resulting 3-D image set consists of a set of normalized dynamic features which can be identified using pattern recognition to outline boundaries in a 3-D volume.

To systematically calibrate each CT slice and correct for any time dependent fluctuation in the energy distribution of the x-ray source, two reference rods composed of plastic and magnesium were placed along side and scanned with the core sample. Other calibration samples such as water, or calcite are also possible choices. The perforated core samples were initially saturated with kerosene. Kerosene was the fluid of choice to perform flow measurements on the core before and after cleaning. This was done to keep the sample saturated and most importantly, to assure a constant Z contribution, the core and both references were placed in a PVC pipe with kerosene. The plastic and magnesium rods are in smaller pipes with wall thickness equal to the large pipe holding the core. A CT image of the setup (Figure 4, obtained using an Elscint 2002 medical scanner) reveals both the core and calibration references housed in PVC pipes.

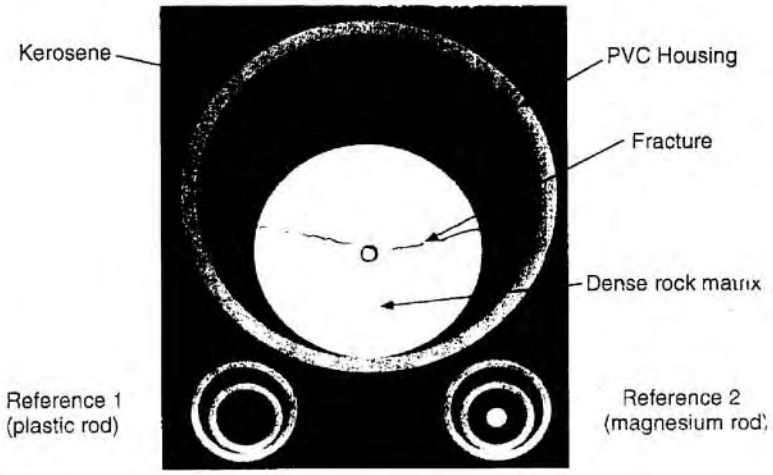

Figure 4. CT image showing core and calibration rods

After extracting the average x-ray attenuation contribution of each reference, the computation of the two constants, a(kVp) and b(kVp), is performed using equation (7) and the known density of plastic and magnesium. Again because of the purity of these reference rods, we can factor in their atomic contributions. Attenuation values of the two

references extracted over 43 contiguous slices are shown in Figure 5. Plots (a) and (b) clearly show the fluctuation of the x-ray voltage while each image was acquired.

Then, by reworking equation (7) into equation:

$$\rho = [\text{CTnumber} - a(kVp)]/b(kVp) \qquad (8)$$

with the knowledge of a(kVp) and b(kVp) for each frame, we normalize each slice by bringing the references to their true constant density, Figure 5c. Of course, at the same time we convert everything else in the slice plane to its material density, including the core attenuation data. When comparing the normalized and non-normalized data set seen in Figure 6, the differences in the structures of the geometry are noticeable and important enough to induce error in the computation of the features such as the surface area of the perforation.

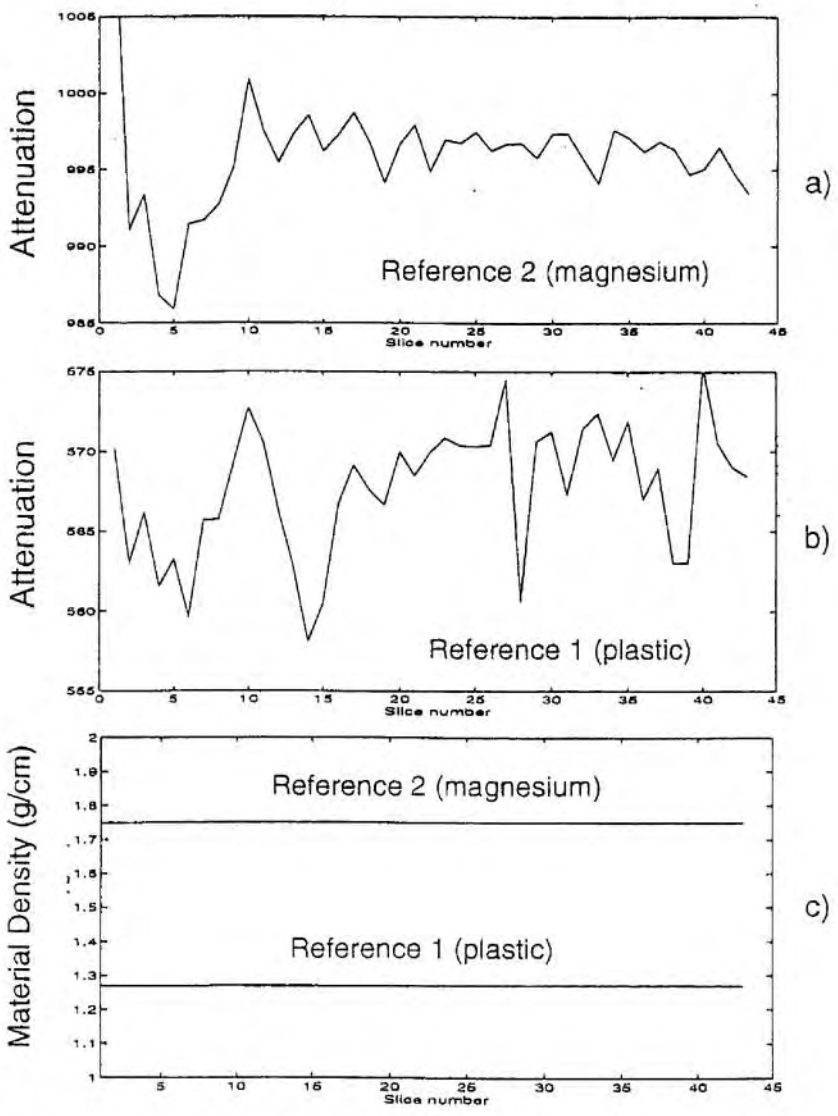

Figure 5. Figure 5a) abd 5b) show variations in measured attenuation for reference rods. 5c) shows bulk density of reference materials after normalization

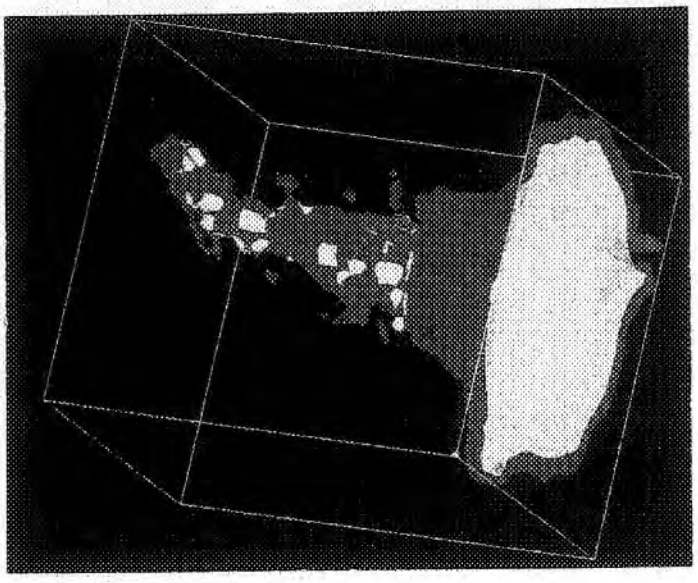

Figure 6. 3-D isosurface rendering of normalized (yellow) and unnormalized (red) CT data.

Method 2 - Mobil Exploration and Producing Technical Center

This procedure utilizes secondary attenuation standards (generally fused quartz and aluminum, although other standards have been successfully used). After instrumental calibration to water standards, these secondary attenuation standards are scanned immediately prior to scanning of the core material. The CT values of both standards are compared to their baseline attenuation values and the amount of deviation is used to correct the measured CT values of the core material. Correction is done prior to calculation of bulk density, porosity or saturation.

This method was applied to experiments which involved determination of saturation values using CT scans obtained (using an Elscint 2002 medical scanner) on different days.[8] Saturation values were calculated with and without calibration, using fused quartz and aluminum standards. Saturation values obtained after calibration were found to be in closer agreement with volumetric results than without calibration. Water saturation values calculated from CT results showed agreement with volumetric measurements to within 1%, when attenuation standards were used. Agreement when standardization is not performed was found to be about 4 %. This is illustrated in Figure 7 and summarized in Table 2.

Both accuracy and precision are improved with the use of standards. To demonstrate this, saturation values were calculated using different data sets obtained at 140 kVp and 100 kVp. Saturation values obtained with these two data sets were found to be in closer agreement with each other when standards were used (see Table 2).

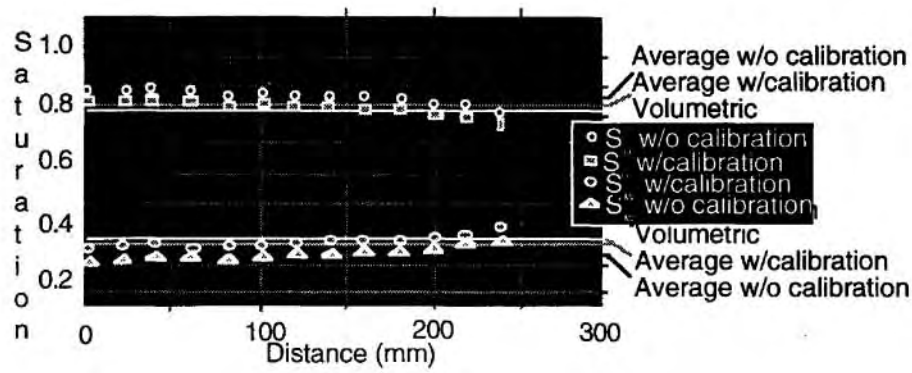

Figure 7. Two Phase Saturations Along Core Length. Average of slices shows closer agreement with volumetric when calibration is used.

Table 2
Two Phase Saturation Values

Energy	Without Standards	With Standards
140 kVp	23.76 %	27.21 %
100 kVp	25.76 %	27.42 %
Difference from Volumetric (28.30 %)		
average	3.54 %	0.98 %
maximum	4.54 %	1.09 %

As shown in Table 3, three phase saturation values obtained from subsequent core floods also showed significant improvement when standards are used.

Table 3
Three Phase Saturation Results

	Phase	Volumetric	W/O Standards	With Standards
Data set 1	Siw	28.30%	23.76%	27.21%
	Sorg	42.88%	46.17%	43.99%
	Sg	28.82%	30.07%	28.80%
Data set 2	Siw	28.30%	23.76%	27.21%
	Sorg	69.07%	69.65%	68.89%
	Sg	2.63%	6.59%	3.90%
Difference from Volumetric				
	Average		3.03%	0.80%
	Maximum		4.54%	1.27%

Method 3 - University of Calgary

This procedure is applied to the EMI 5005 second generation medical CT scanner. The CT number for an appropriate reference material (core material such as sandstone, dolomite, etc) of known density is measured. The CT number of this reference is then compared to the expected CT number for that material. Figure 8 shows the attenuation response curve for various materials. Data has been segmented to highlight responses for materials with similar effective atomic number. A response curve is selected for reference material according to its effective atomic number. Knowledge or estimation of the characteristic atomic number of the material is required.

If the measured CT number does not agree with that expected for that material composition and density, correction is made by (1) slight adjustment of the gain on CT tube or (2) rerunning of standardization routine provided with scanner until reference material results are in alignment with expected value.

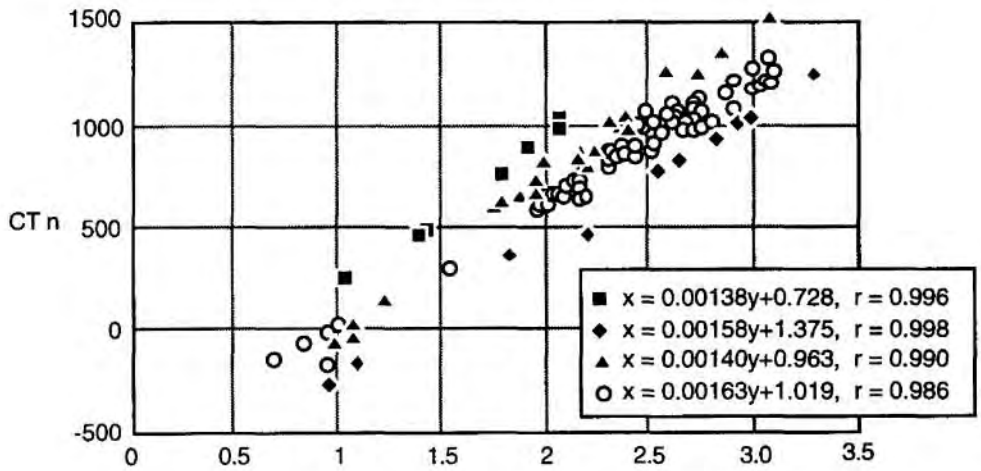

Figure 8: Bulk density calibration curve

Conclusion and Recommendations

To insure accurate quantitative values, care must be maintained to insure accurate and reliable CT measurements. The following are offered as suggestions and/or recommendations to minimize and correct for instrumental drift:

(1.) Use reference materials to identify and correct for instrumental drift or deviation to insure accuracy of results. This is especially critical for long experiments or after an x-ray tube change. Several methods have been presented.

(2.) Include information concerning reference materials and calibration method employed when releasing CT data.

(3.) Reference materials should be uniform and of similar effective atomic number to the system of interest. Therefore many reference materials should be available in any CT laboratory.

(4.) Check for internal consistencies in standardization method, i.e. does the correction, when applied to the attenuation standard, provide the correct value?

(5.) Once reference material attenuation response is established for a given setup, (collimators, filtering elements, size of sample, etc), maintain consistency. Re-characterize reference material if changes are made.

(6.) Check for repeatability of scan results by performing several (five) "dummy" scans at the beginning of the day or scan sequence.

(7.) Employ a slow warm-up time on the x ray tube. This extends tube life and allows the tube time to stabilize.

(8.) If possible, maintain power (not necessarily high voltage) to the tube and detectors during a single experimental run to minimize drift.

References

1. C. L. Morgan, 1983, Basic Principles of Computed Tomography, Baltimore, University Park Press.

2. H. J. Vinegar, "X-Ray CT and NMR Imaging of Rocks," *JPT* March 1986, pp 257-59.

3. H. J. Vinegar, S.L. Wellington, "Tomographic Imaging of Three Phase Flow Experiments," *Rev Sci Inst.* 58(1) Jan 1987, pp 96-107.

4. A. O. Hove, J.K. Ringen, P.A. Read, Visualization of Laboratory Corefloods with the Aid of Computerized Tomography of X-Rays. *SPE Res. Eng*, May 1987, 148-54.

5. P. K. Hunt, P. Engler, C. Bajsarowicz, "Computed Tomography as a Core Analysis Tool: Applications and Artifact Reduction Techniques," SPE, 16952 1987.

6. S. L. Wellington , H. J. Vinegar, "X-Ray Computerized Tomography," *JPT* , August 1987, 885- 98.

7. E. M. Withjack, "Computed Tomography for Rock-Property Determination and Fluid-Flow Visualization," SPE 16951 1987.

8. M.E. Coles, E. L. Muegge, B. F. Marek, " Use of Attenuation Standards for CAT Scanning Applications Within Oil and Gas Production Research," 1992 Society of Core Analysts Conference Paper 9223.

9. E.B. Dussan V. and F.M. Auzerais, 1993, "Buoyancy-induced flow in porous media generated near a drilled oil well. Part 1. The accumulation of filtrate at a horizontal impermeable boundary.", *J. Fluid Mech.* vol. 254, pp. 283-311.

10. F.M. Auzerais, D.V. Ellis, S.M. Luthi, E.B. Dussan V., and B.J. Pinoteau,"Laboratory Characterization of Anisotropic Rocks", SPE 20602, New Orleans, LA, Sept 23-26, 1990.