Use of Attenuation Standards for CAT Scanning Applications Within Oil and Gas Production Research

By

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Abstract

Computer Axial Tomography (CAT scanning) has been shown to be a valuable tool in production research because it provides the ability to non-destructively identify and evaluate the internal structural characteristics of reservoir core material systems. Historically, much of the information obtained from CAT scanners utilized in both the medical and other industries has consisted primarily of a visual assessment of CAT scan images. In this capacity, the scanner has been utilized within the petroleum industry to identify and evaluate internal structural characteristics and discontinuities of core material. In addition to this qualitative assessment of the CAT scan images, quantitative information such as density, porosity and saturation distributions can be extracted from CAT scan images with appropriate processing and calculations. A major emphasis of current research is the improvement of the ability to obtain quantitative information from X-ray attenuation values obtained from CAT scan images. In order to calculate accurate quantitative information from CAT scans obtained over a period of several days, CAT scans must be properly standardized to compensate for drift of the X-ray source and detectors. Many standardization techniques developed and used in medical applications are not sufficient for applications involving core sample material. This paper explains the CAT scan measurement and associated theory and the development and application of a method to properly calibrate CAT scan results, utilizing appropriate attenuation standards. Examples illustrating the resulting improvement in accuracy and precision of calculated saturation values are provided.

Introduction

Computer Axial Tomography (CAT scanning) was originally developed for the medical sector (Brooks and Di Chiro, 1975; Rutherford et al, 1976a; Dubal and Wiggli, 1977; Morgan, 1983) and has since found wide applications within the petroleum and other industries (Rutherford et al, 1976b; Vinegar, 1986; Wellington and Vinegar, 1987). Within the petroleum industry, CAT scanning technology is used to study core samples from oil and gas reservoirs, with applications both in the area of core analysis and petrophysics as well as multiphase fluid flow (Hunt et al., 1987; Withjack, 1987). CAT scanners offer researchers the capability of rapid, nondestructive visualization and analysis of the internal structure of core materials and experiments involving core material systems (Yang et al. 1984, 1985; Wellington and Vinegar, 1985; Vinegar and Wellington, 1987; Hove et al. 1987, 1988). CAT scanners are used to provide images of sleeved and preserved core, and to identify and characterize fractures, inhomogeneities, and zones of mud invasion thereby facilitating the selection of appropriate sampling intervals (Vinegar, 1986, Withjack, 1987; Hunt et al., 1987). CAT scanning of core samples has been shown to be particularly useful when dealing with core obtained from unconsolidated or friable formations, which are especially susceptible to damage or alteration imposed during the coring or handling process (Gilliland and Coles, 1990). Evaluation of damage in fragile, unconsolidated core material utilizing CAT scans, can assist in the identification of those processes which are responsible for damage to the core material and therefore minimization of core damage in subsequent coring and core handling operations. Bedding planes or other depositional features can often be identified in CAT scans and can be used to orient the core for proper slab angle. Additionally, the CAT scanner can also be used to evaluate plugging induced damage (fractures) as evidenced in images of a punch cut core plugs (Gilliland and Coles, 1990).

CAT scan images represent discrete X-ray attenuation information of the material scanned. In addition to qualitative assessment of the CAT scan images, quantitative information such as density, atomic number, porosity and saturation values and distributions can be extracted from CAT scan images with appropriate processing and calculations (Vinegar, and Wellington, 1987; Hove et al. 1987; Wellington and Vinegar, 1987; Withjack, 1987; Coles et al, 1991). Bulk density values as calculated from CT scans can be correlated to the density well log (Wellington and Vinegar, 1987) and may be used to verify or supplement the well log information. Ability to measure bulk density in specific, undamaged or non-invaded areas of a core is particularly useful in the area of unconsolidated core analysis (Wellington and Vinegar, 1981; Gilliland and Coles, 1990).

The CAT scanner's ability to spatially quantify the distribution of fluids is utilized in a wide variety of fluid flow experiments. The spatial details of fluid saturations can provide information about the effects of viscous fingering, fluid segregation and relative permeability of fluids within core materials. Prior to the advent of X-ray and CAT scan technology this information was determined gravimetrically or volumetrically assuming the saturations were distributed uniformly throughout the test sample. Development of X-ray and CAT scan technologies in recent years has allowed in-situ determination of fluid saturation distributions and in some cases, accurate quantitative saturation values for two phase systems (Hove et al. 1988; Wellington and Vinegar, 1985; Sprunt et al., 1991, Marek et al., 1991).

Accurate determination of the distribution of fluids is often important when considering the effect on experimentally measured quantities. For example, a primary assumption in obtaining electrical resistivity for calculation of saturation exponent is that the fluid saturation is uniform during electrical measurements. Recently, CAT scans obtained in conjunction with electrical resistivity measurements revealed, under some conditions, non-uniform saturations along the length of the core sample (Sprunt et al. 1991). Saturation profiles showed the formation of a moving front which could be correlated to nonlinearities in the log-log resistivity index/ water saturation crossplot.

In order to obtain accurate and reliable quantitative values from CT images, care must be taken to insure appropriate calibration over the complete range of measured attenuation values. This paper provides a generalized theory about the CAT scanning process, and the calculations necessary to obtain saturation information from CAT scan measurements. Development and application of a method to properly calibrate CAT scan results, utilizing attenuation standards, is presented.

Theory and Measurement Process

As described in previous references, during the CAT scanning process the attenuation of an X-ray beam is measured as it passes through a sample material. When a parallel monochromatic X-ray beam passes through a substance of uniform density and atomic number, it is attenuated in an exponential manner such that:

$$I=I_0 exp^{-\mu x} \qquad (1)$$

where I_0 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. Figure 1 illustrates the CAT scanning process. The linear 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. 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:

where K is a scaling factor and is discussed in more detail by Morgan, 1983.

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

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 (as illustrated in Figure 2). In the 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).

Using CAT scanning technology, we can accurately determine the saturation and distribution of fluids within a core sample. As described by Vinegar and Wellington, 1987 and Withjack, 1987, when two immiscible phases (for example oil and water) are present within a core sample, the X-ray attenuation can be described as:

$$CT_{total} = CT_o S_o + CT_w S_w \tag{3}$$

where S_o and S_w are the oil and water saturations and CT_o and CT_w represent the X-ray attenuation for the core when it is fully saturated with oil or with water. The entire pore volume is assumed to be totally filled with the fluids, therefore:

$$1 = S_o + S_w \,. \tag{4}$$

By combining equations (3) and (4), the oil and water saturations can be easily calculated from X-ray attenuation data.

$$S_w = \frac{CT_{total} - CT_o}{CT_w - CT_o} \tag{5}$$

Extending equation (1) to a system containing three immiscible phases, (gas, oil, and water) the X-ray attenuation can be described as:

$$CT_{total} = CT_o S_o + CT_w S_w + CT_g S_g \tag{6}$$

where S_o, S_w and S_g are the oil and water and gas saturations and CT_o, CT_w and CT_g represent the X-ray attenuation for the core when it is fully saturated with oil, water or gas. As in the two phase system, the entire pore volume is assumed to be totally filled with the fluids, therefore:

$$1 = S_o + S_w + S_g \,. \qquad (7)$$

Equations (6) and (7) describe a system that contains three unknowns. In order to solve for all variables, an additional equation is needed and is generally obtained by scanning the sample at an additional X-ray probing energy. Vinegar and Wellington, 1897 reported a technique for calculating saturation distributions in a three phase system using dual energy scanning techniques and discusses the dopant requirements for maximum sensitivity.

Alternatively, a flow strategy can be designed in which one of the three phases is maintained constant and immobile. For example, consider a core sample initially saturated with water which has been flooded with oil to irreducible water saturation. At irreducible water, equation (3) becomes:

$$CT_{total} = CT_o S_o + CT_w S_{iw} \qquad (10)$$

and S_{iw} is calculated as in equation (5). Irreducible water can be maintained immobile and therefore constant with appropriate pressure and flow rates. Equation (6) and (7) then reduce to

$$CT_{total} = CT_o S_o + CT_w S_{iw} + CT_g S_g \qquad (11)$$

$$1 = S_o + S_{iw} + S_g \qquad (12)$$

where CT_{total}, CT_o, CT_w and CT_g are measured and S_{iw} is calculated in an initial two phase measurement. In this manner, three phase saturation information can be obtained.

Accuracy Requirements

In order to obtain accurate and reliable values, we are generally concerned with the issues of beam hardening effects and appropriate use of chemical dopants and attenuation standards. Equation *(1)* describes the X-ray attenuation for a monochromatic source of X-rays. However, the X-rays produced in any commercially available CAT scanner are polychromatic. Preferential attenuation of the lower energy components of the X-ray beam leads to an effect known as beam hardening and results in incorrectly measured CT values. This effect becomes especially pronounced when dealing with higher attenuating samples such as core material. Although beam hardening can be compensated for with improved pre-reconstruction algorithms, it is generally easier to preharden the X-ray beam by surrounding the sample with sand, an attenuating fluid (Hunt et al., 1987) or aluminum. For our purposes, we have found aluminum rings or an aluminum core holder adequately prehardens the beam and minimizes beam hardening effects.

To increase measurement sensitivity, chemical dopants (compounds highly attenuating to x-rays) are added to one or more phases or fluids to increase the X-ray attenuation of that phase. An iodated hydrocarbon can generally be used to dope the oil phase and a bromide or iodide salt can be used to dope the aqueous phase. Xenon gas may be used to tag the gas phase. When doped solutions are used, care must be taken to insure that the system to be scanned falls within the working dynamic range of the source and detectors and that any changes in beam hardening characteristics induced by the dopant materials are properly corrected for.

The X-ray source and detectors are prone to day to day instrumental drift in their attenuation response. We have found that the effect of the drift on measured CT response is itself a function of the absolute attenuation measured (greater drift for greater CT number). In other words, not only does the attenuation response measured by the detectors shift, but the slope of that response also changes. This drift is not predictable and if not properly corrected can result in increased error in quantitative calculations if those calculations use measured values obtained over a multi-day period. This error is especially notable if the instrumental drift is large for a series of scans which are then used as baseline values for subsequent scanning steps (for examples CT_O in equation 5)

Conventionally, in medical X-ray tomography, a water sample is used as an attenuation standard (equation 2). However, when higher attenuating core samples are scanned, additional standards are necessary for reference attenuating media. The reference material must be of uniform density and composition and should exhibit attenuation characteristics close to that of the material to be measured. This laboratory and others have previously used aluminum as a secondary reference because it is uniform in composition and attenuates slightly more than most core systems. Fused quartz has also come to be utilized as a secondary reference (Wellington and Vinegar, 1987; Coles et al., 1991). The density and X-ray attenuation characteristics of fused quartz are close to that of many sandstones. Fused quartz is uniform in composition and is readily available through optical supply distributors. Use of both fused quartz and aluminum provides us with standards of attenuation both lower and higher than most core systems and allows us to adequately compensate for instrumental drift.

A method has been developed to compensate for instrumental drift utilizing secondary standards (fused quartz and aluminum) to calibrate the CAT scan data obtained over several days. This method of calibration is straightforward. Secondary attenuation standards are scanned immediately prior to scanning of the core material (we have found that once before a series of slices is adequate). The CT values of both standards are compared to their baseline attenuation values. The amount of deviation from their baseline values is used to correct the measured CT values of the core material. This correction is done prior to calculation of bulk density, porosity or saturation. As an example, consider application of this method in a specific experiment involving determination of saturation values which required CAT scans obtained on several different days.

Experimental

A Berea core sample, approximately 2" in diameter and 12" in length, sealed within a Lucite core flood cell was used in this experiment as shown in Figure 3. A flow strategy was employed in which irreducible water saturation is attained in an initial two phase flow step and was maintained throughout several subsequent flooding steps. A schematic illustrating the sequence of flooding and scanning steps is provided in Figure 4. CAT scans were obtained along the length of the core for each step in the flow strategy. In each step, scans of the fused quartz and aluminum standards were obtained.

The fluids used were 25,000 ppm sodium chloride (water phase), 50/50 (by weight) hexadecane/iododecane (oil phase) and air (gas phase). The sample was scanned dry and 100% saturated with 25,000 ppm NaCl and 100% saturated with 50/50 hexadexane-iododecane. The sample was then cleaned and resaturated with 25,000 ppm NaCl (100%) and then flooded with the 50/50 hexadecane-iododecane mixture to irreducible water saturation (S_{iw}). CAT scan and volumetric measurements were used to calculate irreducible water saturations (step 3 of Figure 4).

The sample was gas (air) flooded to irreducible oil saturation (S_{org}) (step 4 of Figure 4). CAT scans (Figures 5a and 6a) revealed nonuniform saturations. The nonuniform distribution is expected, since the core flood was not at equilibrium. CAT scan and volumetric measurements were used to calculate the three-phase saturations. The sample was then flooded with oil to irreducible gas saturation (S_{gr}) and CAT scanned (step 5 of Figure 4, Figures 5b and 6b). Once again, CAT scan and volumetric measurements were used to determine the three phase saturations.

The attenuation values of the standards obtained on the first scanning day were assumed to represent baseline attenuation values for all subsequent standards. For each of the other series of scans, the CT numbers obtained for the standards were compared to these baseline values. The differences in attenuation values when compared to baseline attenuation were fit as a function of CT number (see Figure 7). The equation resulting from this fit was utilized to correct the average CT values obtained for each slice along the core length. The saturation values were calculated using equations 3 - 12 and compared to volumetrically determined saturations. Use of a third standard with measured attenuation between fused quartz and aluminum is currently under investigation.

All CAT scan data were obtained on a Elscint Excel 2002 translate-rotate body scanner. Scans were obtained at both 140 and 100 KV with a slice width of 10 mm. Average CT numbers were obtained from each scan in a consistent location to reduce beam hardening effects.

Results

Water Saturation in a Two Phase System

Irreducible water saturations were calculated along the length of the core using equations 4, 5 and 10. Saturation values were calculated using the same CAT scan data both with and without application of the calibration method described in the previous section. The results for the CAT scans obtained at 140 KV are presented in Figure 8. Saturation values calculated from the calibrated CAT scan data showed nonuniform saturation along the core length with irreducible water saturation values ranging from 24.49% to 32.29%. The average of the CT measured water saturation values (27.21%) agreed well with the volumetrically measured value of 28.30%. The average of the CT measured water saturation values without calibrating was found to be 23.76%.

Water saturation values were independently calculated using CAT scan data obtained at 140 KV and then at 100 KV scanning energy and are shown in Table 1. As can be seen, water saturation values obtained when the CAT scan data was calibrated, using independent data sets (140 and 100 KV scanning energy) result in values closer to each other than when the data are not calibrated (range is 2.54 saturation percent without calibration and is 0.88 saturation percent when data is calibrated prior to saturation calculation). Additionally, both values obtained with calibration were in closer agreement with the volumetrically determined value than those obtained without calibration (average and maximum difference is 3.54 and 4.54 saturation percent without calibration and 0.98 and 1.09 saturation percent with calibration).

Saturation Values for a Three Phase System

After flooding the sample with air (step 4 of Figure 4), S_{iw} was assumed to remain constant from the previous step and the residual oil (S_{org}) and gas S_g saturations were calculated for each location along the core length using equations 11 and 12. The saturation values were calculated with and without prior calibration of the CAT scan data and were compared to values obtained volumetrically. The results for the calibrated case are plotted in Figure 9. Oil saturation values were found to range from 52.83% to 35.49% and gas saturation values ranged from 22.45% to 33.59%. Averaging CAT scan saturation data along the core length, provides an oil saturation value of 43.99% compared to 42.88% for volumetric measurements and a gas saturation value of 28.80% compared to 28.82% as determined volumetrically. For this set of three-phase saturations, the average difference of CAT scan and volumetric saturation values was 0.74 saturation percent.

After flooding the sample with oil again (step 5 of Figure 4), oil saturations were again determined from CAT scan results (Figure 10) and indicated an average oil saturation of 68.89% compared to a volumetric value of 69.07% and was found to range from 76.78% to 36.73%. The gas saturation was not well determined here, because of its low value and low attenuation contribution with respect to the total signal. In this situation, volume averaging effects and statistical noise can lead to a higher relative error in CAT scan values. Additionally, volumetric balance errors are higher at low gas saturation. The average gas saturation was found to be 3.90% compared to 2.63% volumetrically. Even in this case where the gas saturation is not well determined, average difference between CAT scanned volumetric saturation values was 0.84 saturation percent.

As can be seen in Table 2, the saturation values obtained are in better agreement with volumetric results when the data is calibrated prior to calculation (average and maximum is .74 and 1.09 saturation percent in one case and .85 and 1.27 saturation percent in another case) as compared to saturation values calculated without calibration of the CAT scan data (average and maximum deviation of 3.09 and 4.54 saturation percent).

Conclusions

A new method of calibrating CAT scan data utilizing secondary attenuation standards to identify and characterize instrumental drift has been developed and successfully applied in several systems. This analysis showed CAT scan measured saturations in a two-phase oil/water system to be in agreement with volumetric results to within 1.1 saturation percent. Results obtained by comparing the values calculated from CAT scan data to volumetric measurements of the same experiment indicate that application of this calibration technique increases the accuracy of the CAT scan results (from 4.54 saturation units to 1.09 saturation units) when it is applied to the same CAT scan data prior to calculation of saturation values. Results obtained from independent calculations using CAT scan data obtained at two different scanning energies indicate that the application of this method results in an increased precision (range of calculated values dropped from 2.54 to 0.88 saturation units upon application of this technique to the same CAT scan data).

Three phase saturations determined from CAT scan data were in good agreement with volumetric results for a single dopant two mobile liquid saturation system. With the exception of systems containing very low gas saturation and high concentration of a doped phase, the agreement is within 1.1 saturation percent. The average deviation of all phases was found to be 0.77 saturation percent.

Systems containing very low gas saturation and high concentration of a doped phase are not well determined with respect to the gas saturation. Within such systems, which are expected to possess higher relative error, the two methods still agree, but the maximum deviation was found to be 1.27 saturation percent. Conversely, the oil saturation is well determined, resulting in agreement of the CAT scan and volumetric results to within 0.18 saturation percent. Average deviation of all phases was found to be 0.84 saturation percent.

This technique is general: it can be applied to any set of scans or experiments and can easily be incorporated into routine scanning procedures. Both two and three phase saturation results show an increased accuracy. The increase in accuracy (and therefore sensitivity) which is realized by using this technique is especially useful when dealing with systems of low attenuation contrast and may ease somewhat the stringent requirements of dual dopant (three phase) systems.

Summary and Discussion

This method of calibrating CAT scan data utilizing secondary attenuation standards to identify and characterize day to day drift of the X-ray source and detectors and compensating for that drift serves to standardize all CAT scan measurements taken in multi-day experiments to the same baseline attenuation. This is necessary if subsequent calculations and comparisons are to be carried out. Instrumental drift is not predictable. Scans of the standards may indicate only a small drift over the period of several days and therefore may only require a small correction, while other sets of standard scans may indicate a rather large drift (greater than 10 CT units) and require greater correction to maintain accuracy. Calibration is especially important when instrumental drift is large for a series of CAT scans which are subsequently used as a baseline to other scanning steps (for example, CAT scans of a fully saturated core are used to calculate saturation for several steps of a given experiment). The error induced by the instrumental drift is therefore propagated through all subsequent calculations and leads to inconsistent and unreliable values and underestimation of the accuracy of the CAT scanning method.

This technique provides a generalized and routinely applicable method to insure internal consistency of CAT scan results even though the scans may be obtained under different X-ray beam and detector response conditions. With rigorous and appropriate calibration of CAT scan measurements, we increase our ability to accurately assess spatial variations of core properties and fluid distributions within core material systems. Use of attenuation standards allows comparison of quantitative values and measurement accuracy when using different experimental systems.

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Table 1

Comparison of results with and without standardization
Two phase results

Calculation of water saturation (volumetric value found to be 28.30%)

Scanning Energy	Without Standards	With Standards
140 KV	23.76%	27.21%
100 KV	25.76%	27.42%
average	24.76%	27.32%
range	2.54%	0.88%

Difference from volumetric value (28.30%)

Scanning Energy	Without Standards	With Standards
140 KV	4.54%	1.09%
100 KV	2.54%	0.88%
average	3.54%	0.98%
maximum	4.54%	1.09%

Table 2

Comparison of results with and without standardization
Three phase results

Calculation of Oil Saturation Residual to Gas (Step 4 of figure 4)

Saturations	Volumetric Results	CAT Scan (Without calibration)	CAT Scan (With calibration)
S_{iw}	28.30%	23.76%	27.21%
S_{org}	42.88%	46.17%	43.99%
S_g	28.82%	30.07%	28.80%

Difference from volumetric values

	CAT Scan (Without calibration)	CAT Scan (With calibration)
S_{iw}	4.54%	1.09%
S_{org}	3.29%	1.11%
S_g	1.25%	0.02%
Average	3.03%	0.74%
Maximum	4.54%	1.09%

Saturation subsequent to oil flood (Step 5 of figure 4)

Saturations	Volumetric Results	CAT Scan (Without calibration)	CAT Scan (With calibration)
S_{iw}	28.30%	23.76%	27.21%
S_{org}	69.07%	69.65%	68.89%
S_g	2.63%	6.59%	3.90%

Difference from volumetric values

	CAT Scan (Without calibration)	CAT Scan (With calibration)
S_{iw}	4.54%	1.09%
S_{org}	0.58%	0.18%
S_g	3.96%	1.27%
Average	3.03%	0.85%
Maximum	4.54%	1.27%

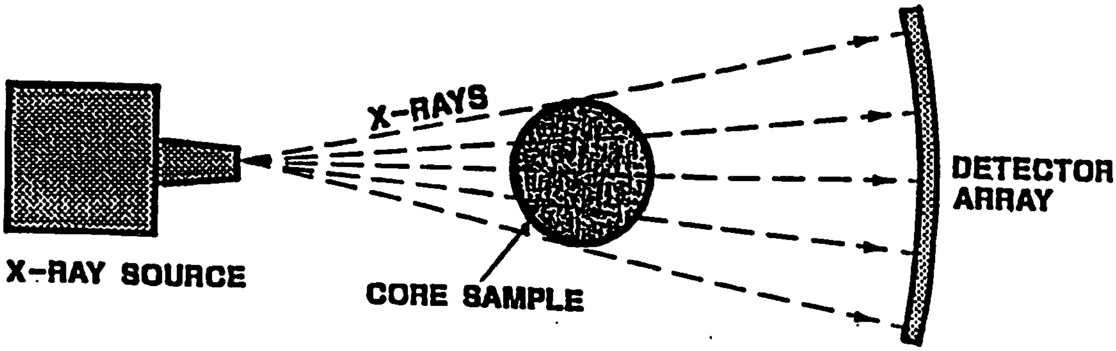

Figure 1. X-Ray attenuation measurement process

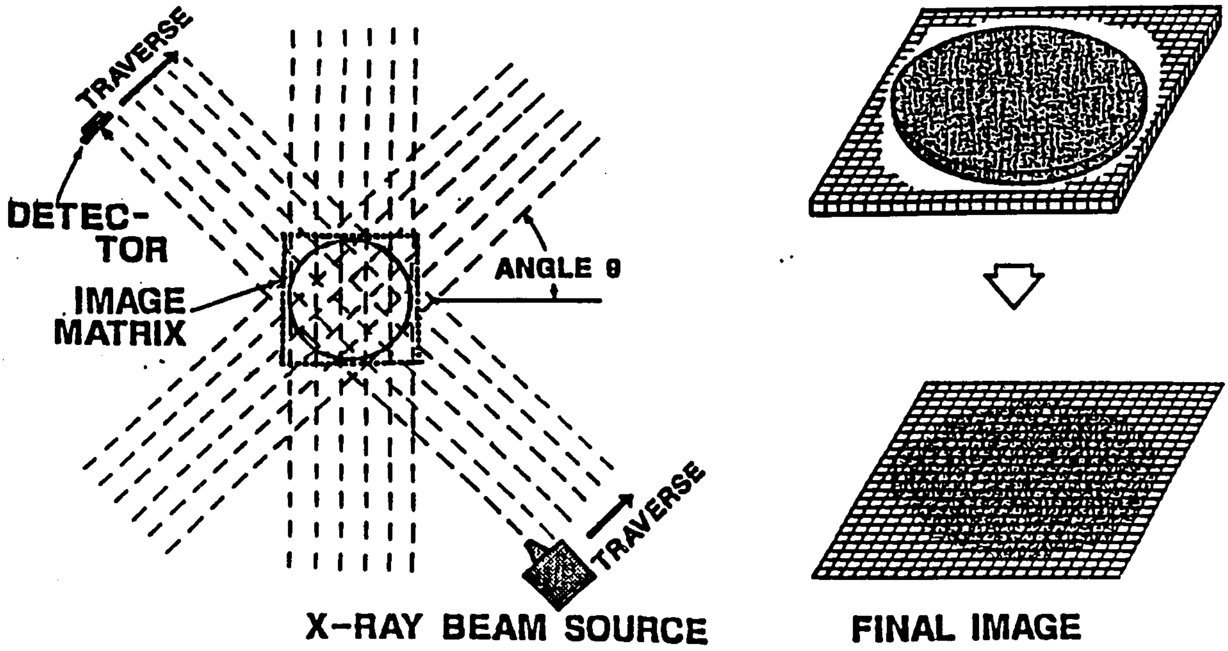

Figure 2. CAT scanning process. Tomographic (slice) mode

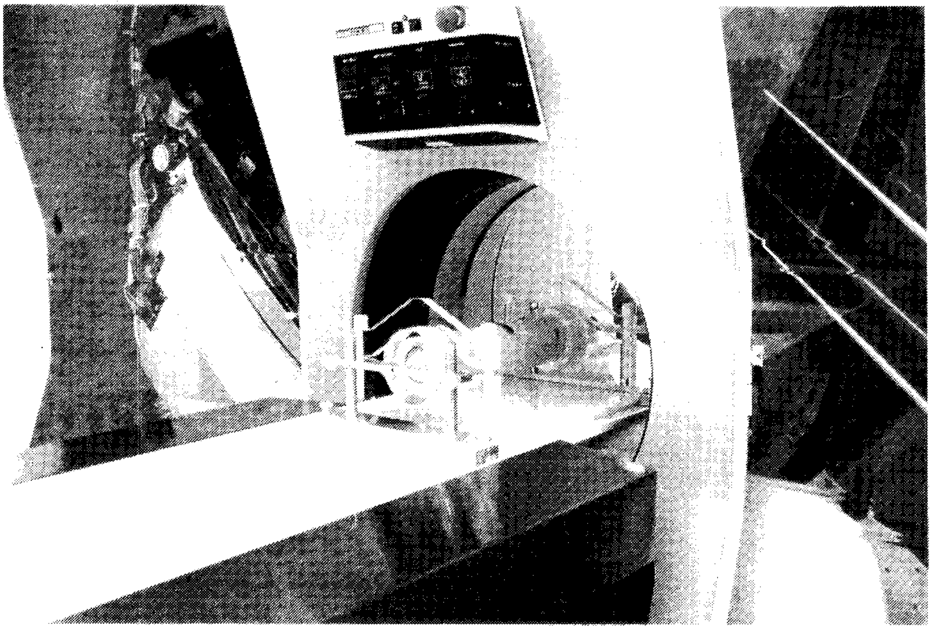

Figure 3. CAT scan slices were obtained along the length of a Berea core which was contained in Lucite.

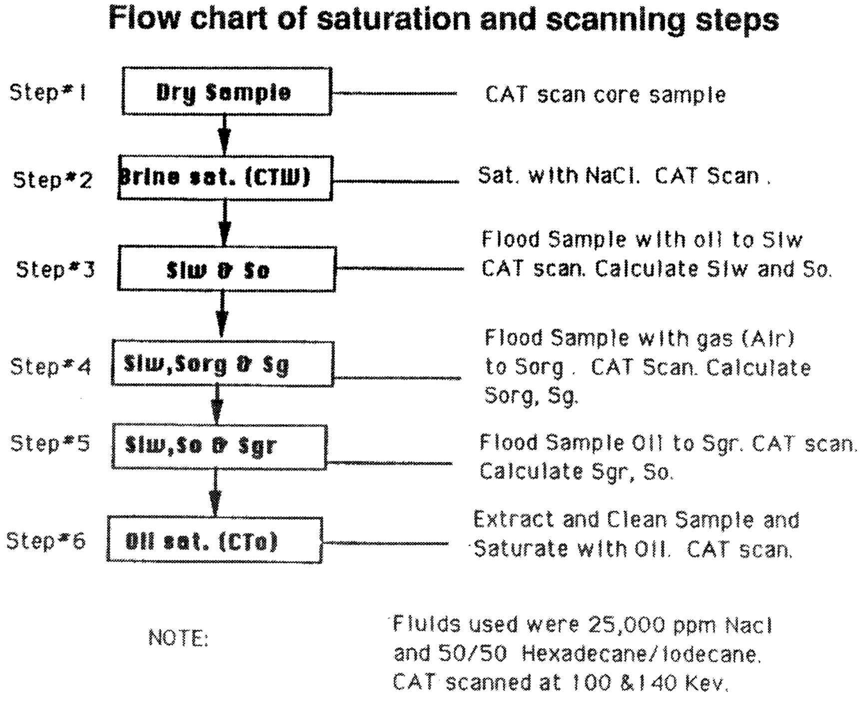

Figure 4. Flow chart illustrating flooding and scanning steps

Figure 5a

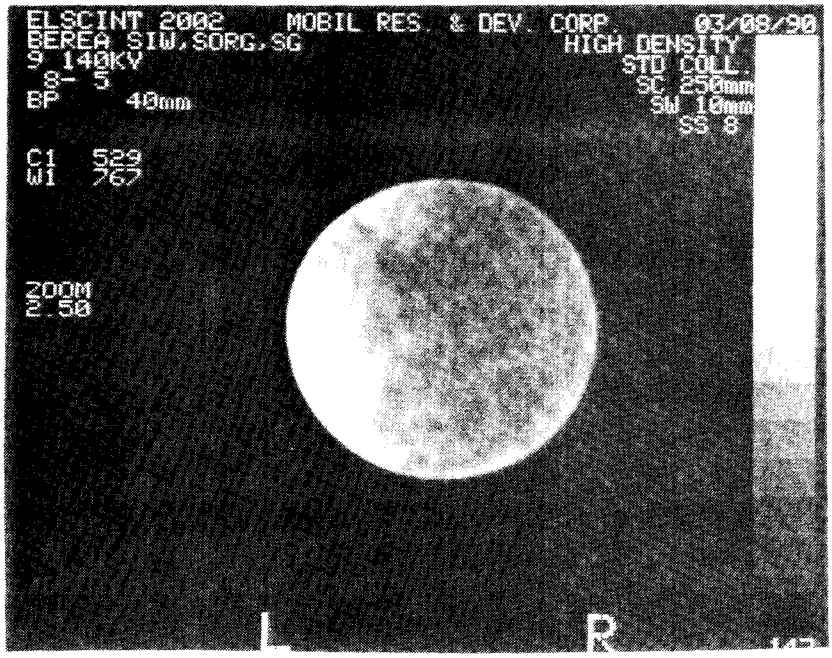

Figure 5b

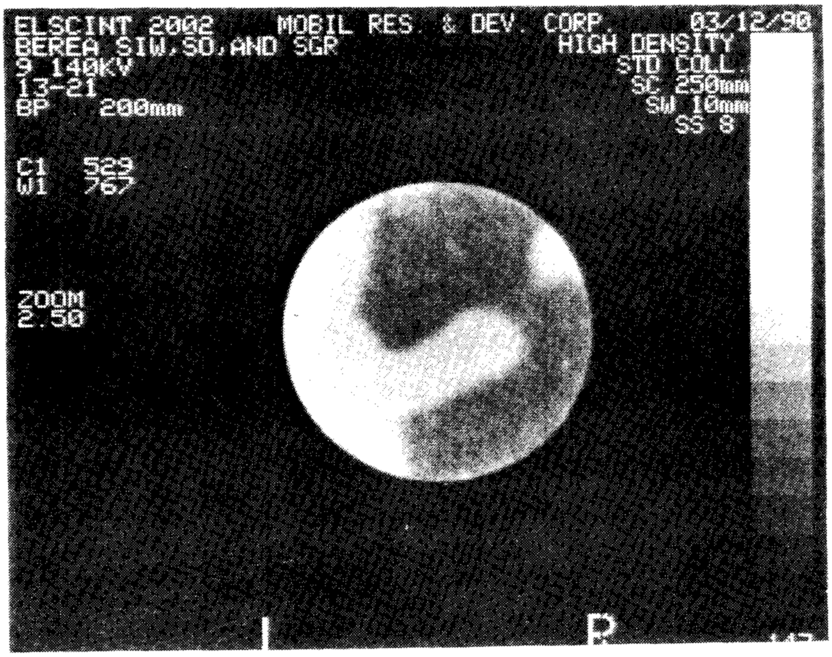

Figure 5. Examples of CAT scan images obtained for step 4 (figure 5a) and step 5 (figure 5b) flooding steps. Light, intermediate and dark shading indicate oil, water and gas phases.

Figure 6a

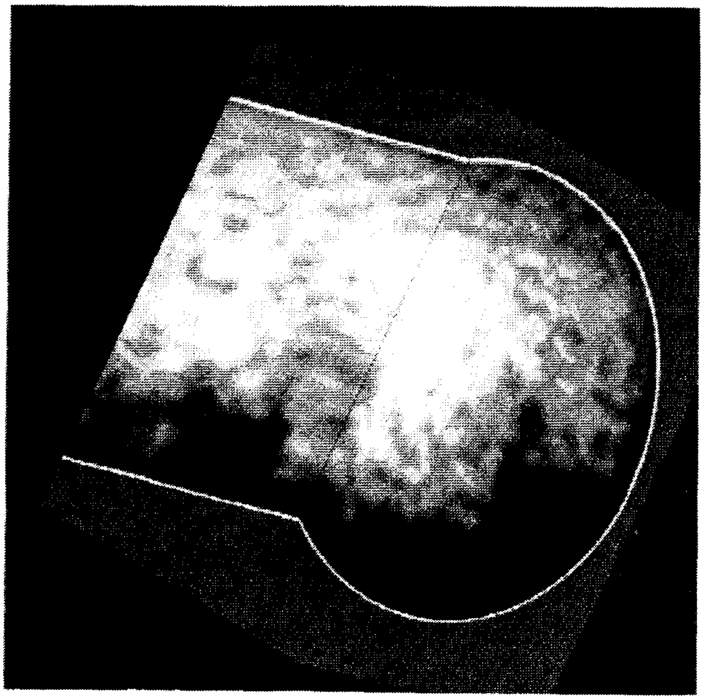

Figure 6b

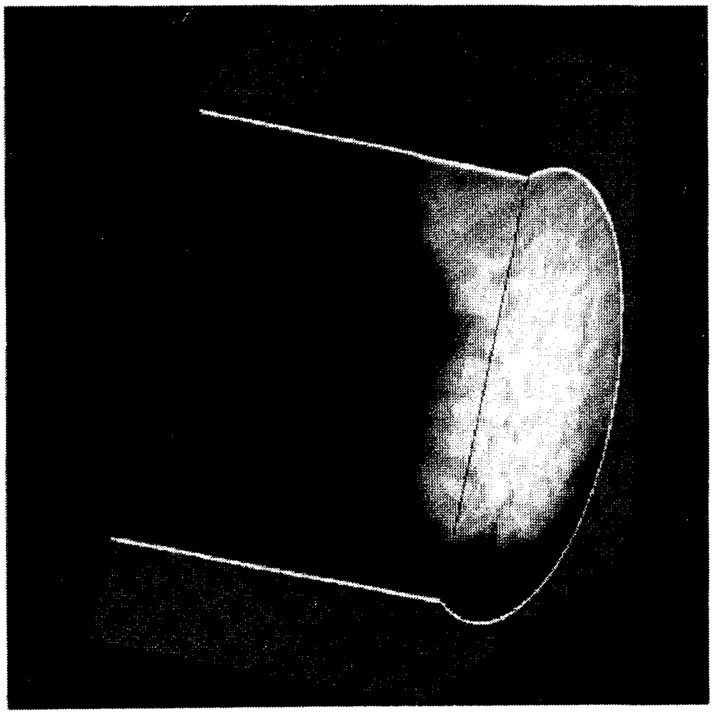

Figure 6. Cutaway views of CAT scan volume images created from slices obtained in step 4 (figure 6a) and step 5 (figure 6b). Note non-uniform saturation along the length and across the face of the core.

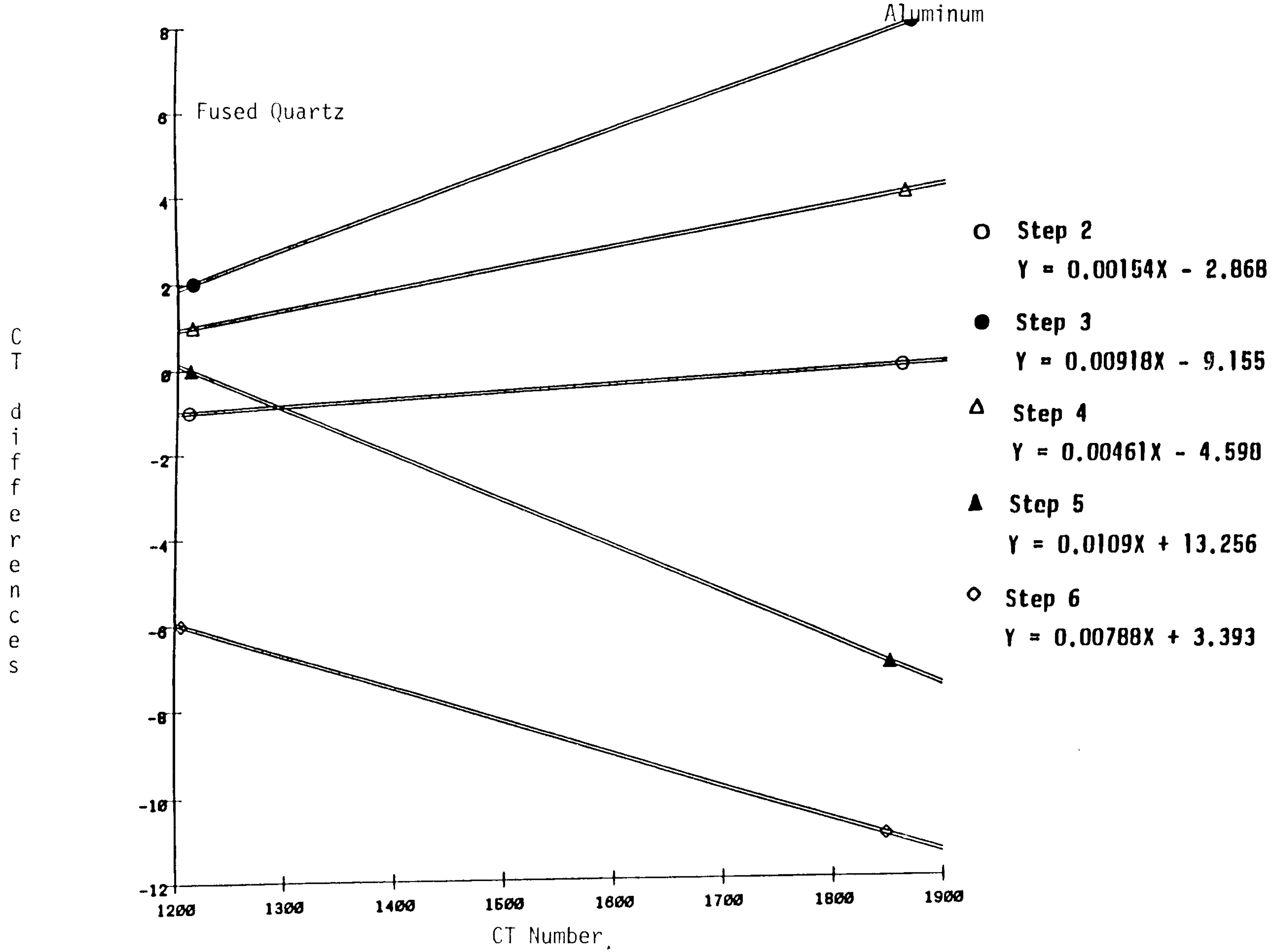

Figure 7. Plot showing amount of deviation of standards from their baseline values for each flow step. Linear fits (as listed) were utilized to correct the CT values obtained for each step.

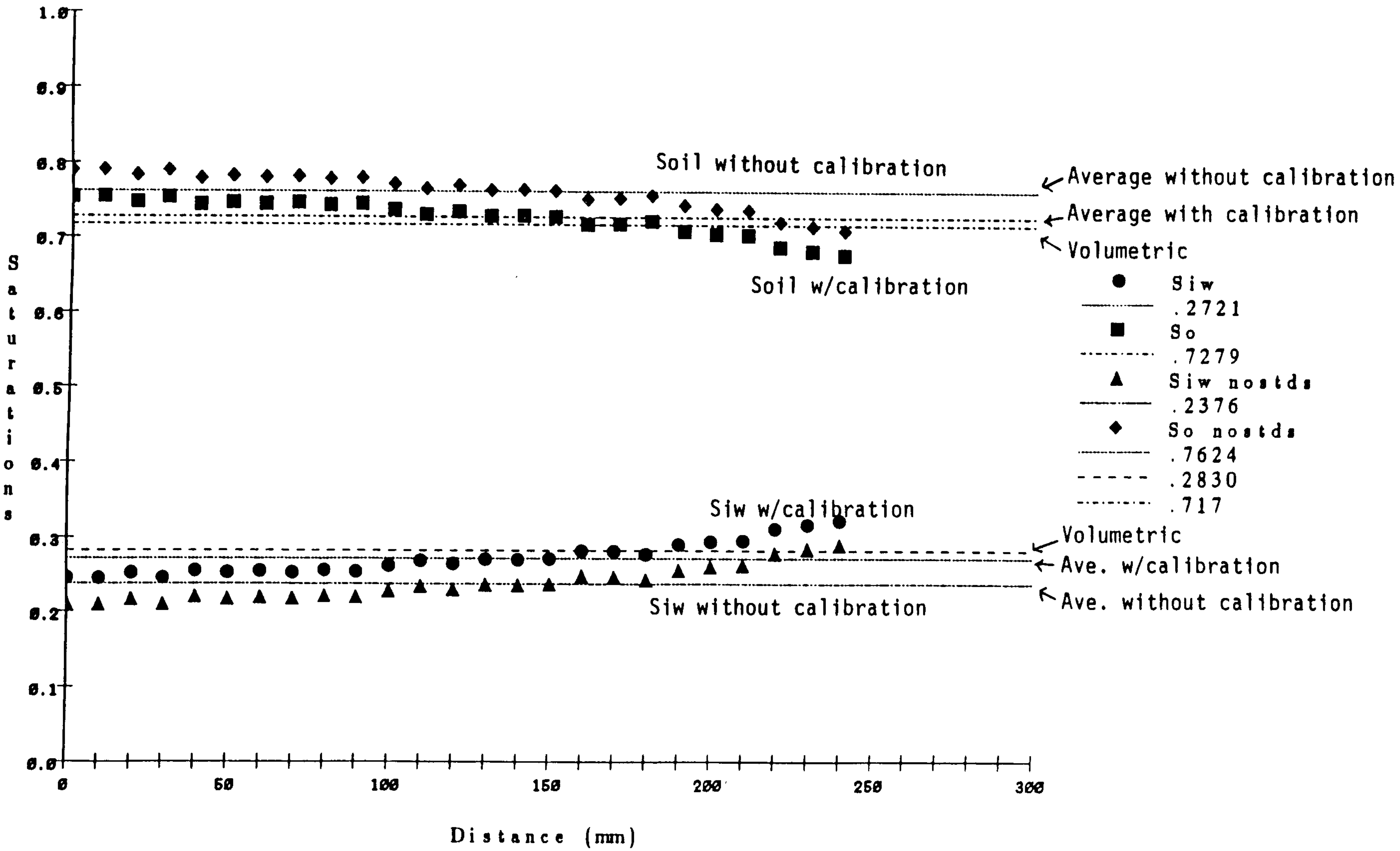

Figure 8. Saturations calculated along core length for two phase system (step 3). Note the average value obtained for the calibrated data is closer to the volumetrically measured value than is the average for the uncalibrated data.

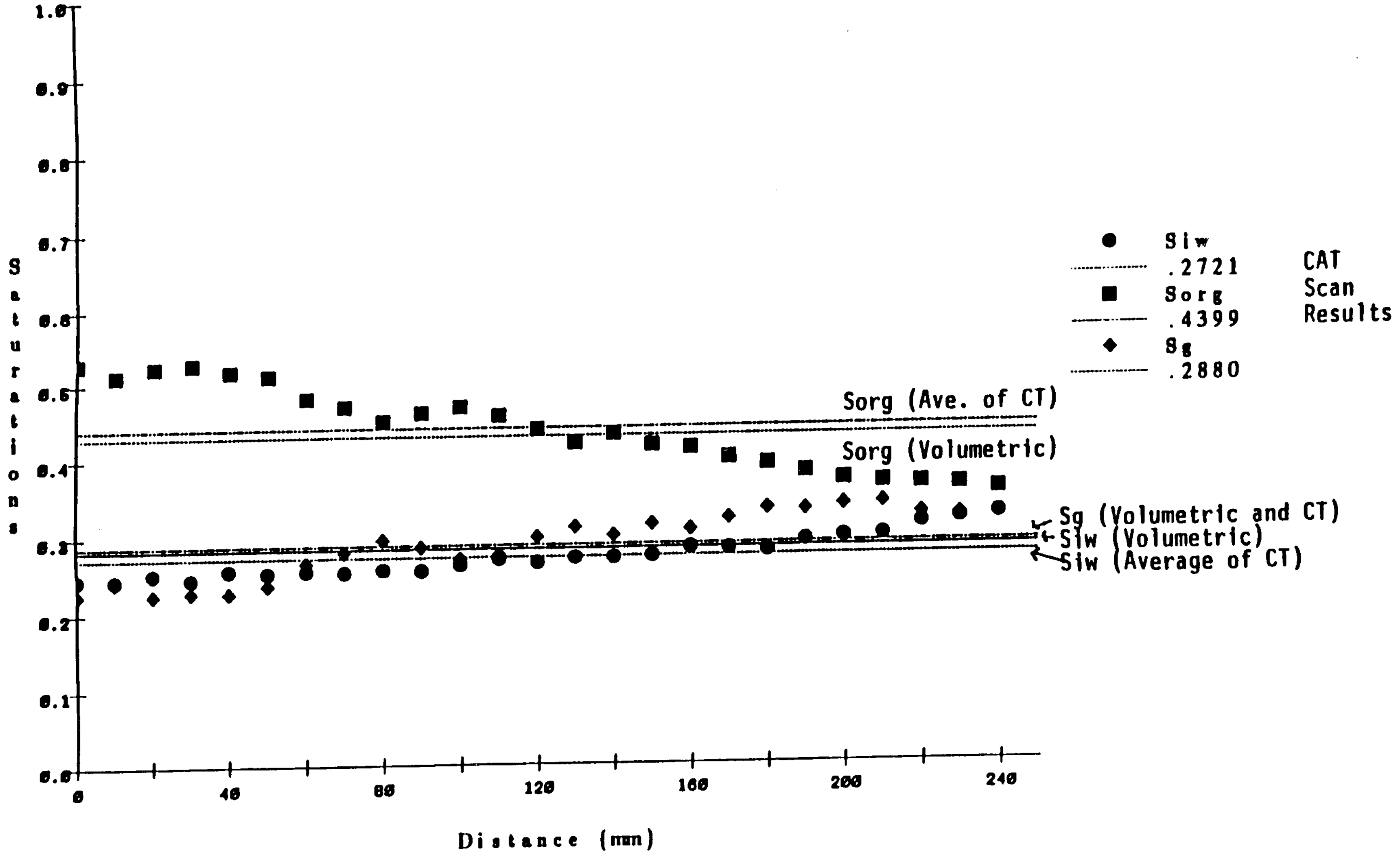

Figure 9. Three phase saturations calculated along the length of core (step 5) after calibration. Average of saturation values (calculated from CT results) agreed with volumetrically measured values to within 1.09 saturation units.

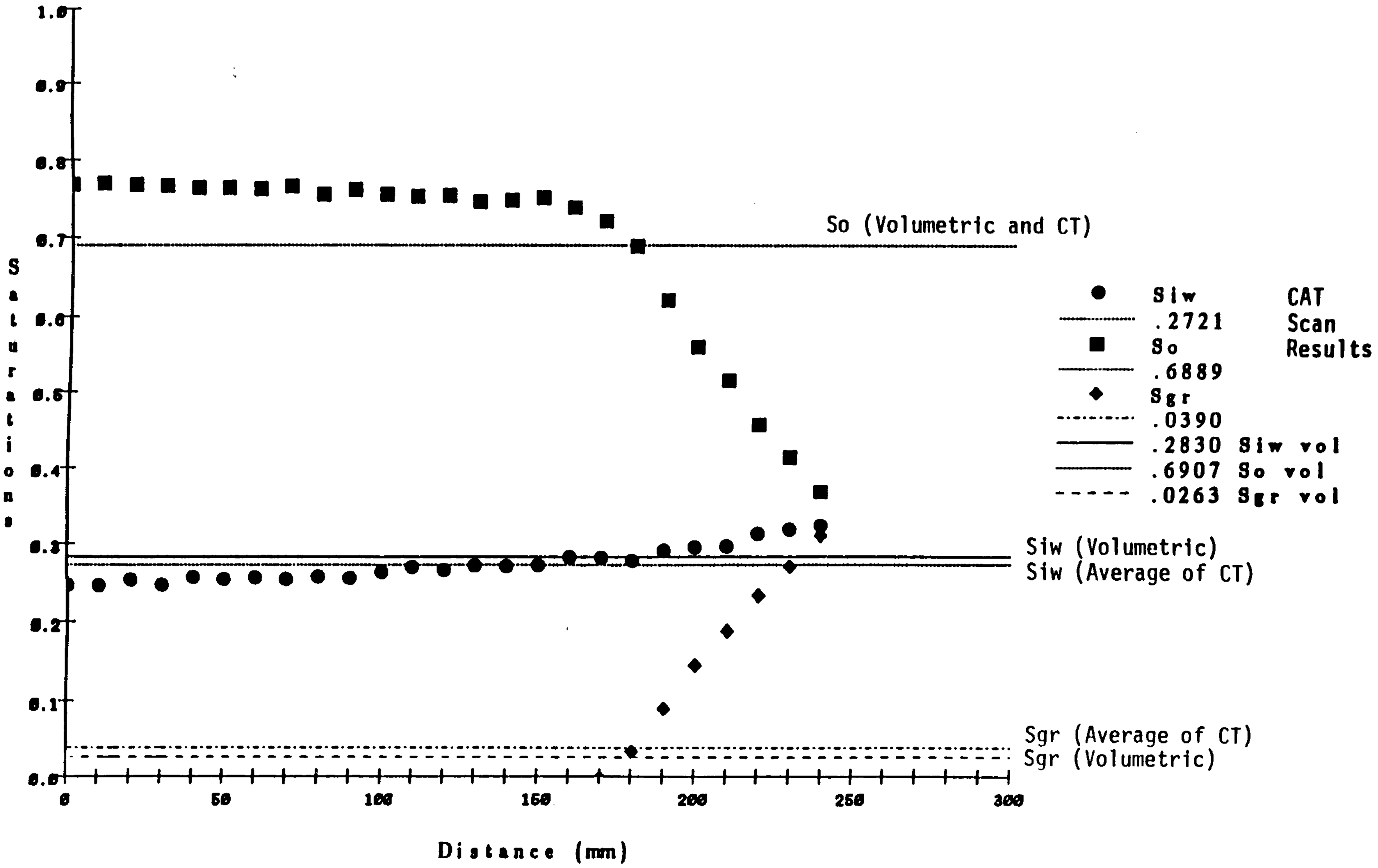

Figure 10. Three phase saturations calculated along the length of core (step 6) after calibration. Average of saturation values (calculated from CT results) agreed with volumetrically measured values to within 1.27 saturation units.

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