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Relative Evaluation of the Independent Volume Measures of Caverns

Darrell E. Munson

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RELATIVE EVALUATION OF THE INDEPENDENT VOLUME MEASURES OF CAVERNS

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ABSTRACT

Throughout the construction and operation of the caverns of the Strategic Petroleum Reserve (SPR), three types of cavern volume measurements have been maintained. These are: (1) the calculated solution volume determined during initial construction by solution mining and any subsequent solutioning during oil transfers, (2) the calculated sonar volume determined through sonar surveys of the cavern dimensions, and (3) the direct metering of oil to determine the volume of the cavern occupied by the oil. The objective of this study is to compare these measurements to each other and determine, if possible, the uncertainties associated with a given type of measurement. Over time, each type of measurement has acquired a customary, or an industry accepted, stated uncertainty. This uncertainty is not necessarily the result of a technical analysis. Ultimately there is one definitive quantity, the oil volume measure by the oil custody transfer meters, taken by all parties to the transfer as the "correct" ledger amount and for which the SPR Project is accountable. However, subsequent transfers within a site may not be with meters of the same accuracy. In this study, a very simple theory of the perfect relationship is used to evaluate the correlation (deviation) of the various measures. This theory permits separation of uncertainty and bias. Each of the four SPR sites are examined, first with comparisons between the calculated solution volumes and the sonar volumes determined during construction, then with comparisons of the oil inventories and the sonar volumes obtained either by surveying through brine prior to oil filling or through the oil directly.

The analysis is centered about the Phase II and III caverns, which were those caverns with very similar geometries purpose-built for the SPR. Existing commercial caverns purchased by the SPR in Phase I were not usually considered. Of the four sites, Big Hill not only had an extensive database, but provided the best conditions for comparison. At this site, the construction of the caverns was completed prior to filling with oil. The conditions for Bayou Choctaw, which has only one SPR Phase II cavern, were also uncomplicated, and gave similar results to Big Hill. The results for West Hackberry and Bryan Mound, the first caverns of the SPR to be constructed, were somewhat compromised by concurrent solutioning and filling. The results for Big Hill

suggested behavior that was confirmed by the data of the other sites. The comparisons showed that a bias, or systematic deviation from the perfect relationship, which depends upon the sonar survey operator, exists for the sonar surveys. This bias is quite different for different datasets, it can be either negative or positive, and varies in most cases from –9% to +9%, but may be even greater. After adjusting for bias, the remaining uncertainty was consistent with values of +/-3% in the solutioning volume and +/-2% in the sonar survey volumes. Historically, survey operators have given an uncertainty of +/-5%, or greater for both of these measurements, values in excess of the those determined in this report. Statistical analysis of the solutioning and sonar data conform quite well to a normal distribution with a standard deviation of 5.78%, which is essentially equivalent to the sum of the two experimental uncertainties of +/-3% and +/-2%.

Correlation between sonar volumes and oil inventories was quite good, perhaps within +/-2%. The statistical analysis of these results, while more complicated, suggests a normal distribution with a standard deviation of 1.68% essentially all attributable to the sonar survey, substantiating the sonar uncertainty value of +/-2% found from the comparison of sonar and solution volumes.

The study suggests a well defined method for evaluating the data comparisons. The indication is that the measurement of volume may contain both a systematic bias and a random experimental uncertainty. With this knowledge, it may be possible to further refine the measurement methods.

Analysis of the cavern records also yielded data from which the insoluble contents of the dissolved salt could be determined. Typically, the volume percent of insolubles assuming compaction to a solid density are from 3 to 6% in most of the caverns, the exception being Bayou Choctaw with less than 2%. These are in general agreement with other measures of the insoluble contents of domal salts.

While this study provides no absolute measures of cavern volume uncertainties, it has provided a theoretical basis for comparison and reasonable estimates of the uncertainties in volume measures of the caverns of the SPR. These estimates indicate that the various measurements are actually quite good, with uncertainties equivalent to those customarily accepted within the technical community.

A major recommendation for improvement of the measurements concerns the need for an independent calibration of the sonic velocity measurement associated with sonar surveys.

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TABLE OF CONTENTS

ABSTRACT 3
ACKNOWLEDGEMENTS 5
TABLE OF CONTENTS 6
LIST OF FIGURES 8
LIST OF TABLES 9
EXECUTIVE SUMMARY 10
1 INTRODUCTION 13
2 MEASUREMENTS 15
2.1 Solution Volume Measurement 15
2.2 Sonic Volume Measurement 17
2.3 Oil Volume Measurement 20
3 PERFECT CORRELATION 21
4 RELATIVE COMPARISON OF VOLUMES 22
4.1 Big Hill (BH) 22
4.1.1 Solution Volumes and Sonar Volumes 22
4.1.2 Equivalent Sonar Volumes and Oil Inventories 27
4.1.3 Summary Remarks for Big Hill 31
4.2 West Hackberry (WH) 32
4.2.1 Solution Volumes and Sonar Volumes 32
4.2.2 Equivalent Sonar Volumes and Oil Inventories 37
4.2.3 Sonar Volumes in Oil and Oil Inventories 39
4.2.4 Summary Remarks for West Hackberry 41
4.3 Bayou Choctaw (BC) 41
4.3.1 Solution Volumes and Sonar Volumes 42
4.3.2 Equivalent Sonar Volumes and Oil Inventories 44
4.3.3 Summary Remarks for Bayou Choctaw 47
4.4 Bryan Mound (BM) 47
4.4.1 Solution Volumes and Sonar Volumes 49
4.4.2 Equivalent Sonar Volumes and Oil Inventories 53
4.4.3 Summary Remarks for Bryan Mound 53
5 STATISTICAL ANALYSIS 56
5.1 Solution and Uncombined Sonar Data Statistics 56
5.2 Solution and Combined Sonar Data Statistics 61
5.3 Equivalent Sonar and Oil Inventory Data Statistics 63
5.4 Statistical Analysis of Surveys through Oil 68
6 SUMMARY 69

TABLE OF CONTENTS (CONT.)

7 REFERENCES 71
8 APPENDIX – INDEPENDENT OBSERVATIONS ON INSOLUBLES 72
DISTRIBUTION 78

LIST OF FIGURES

Figure 1. Solution Volume vs. Sonar Volume (w and w/o Blanket Oil), Big Hill 25
Figure 2. Solution Volume Deviation from Sonar Volume (Three Operators), Big Hill . 26
Figure 3. Equivalent Sonar Volume in Brine vs. Oil Inventory, Big Hill 29
Figure 4. Equivalent Sonar Volume in Oil vs. Oil Inventory, Big Hill 31
Figure 5. Solution Volume vs. Uncombined Sonar Volume, West Hackberry 34
Figure 6. Solution Volume Deviation from Uncombined Sonar Volume, West Hackberry 35
Figure 7. Solution Volume vs. Combined Sonar Volume, West Hackberry 36
Figure 8. Solution Volume Deviation from Combined Sonar Volume, West Hackberry . 37
Figure 9. Equivalent Sonar Volume in Brine vs. Oil Inventory, West Hackberry 39
Figure 10. Equivalent Sonar Volume in Oil vs. Oil Inventory, West Hackberry 40
Figure 11. Solution Volume vs. Sonar Volume, Bayou Choctaw 43
Figure 12. Solution Volume Deviation from Sonar Volume, Bayou Choctaw 44
Figure 13. Equivalent Sonar Volume vs. Oil Inventory, Bayou Choctaw (BC101) 45
Figure 14. Equivalent Sonar Volume vs. Oil Inventory, Bayou Choctaw (All Caverns) ... 46
Figure 15. Solution Volume vs. Sonar Volume, Bryan Mound 50
Figure 16. Solution Volume Deviation from Sonar Volume, Bryan Mound 50
Figure 17. Solution Volume vs. Combined Sonar Volume, Bryan Mound 51
Figure 18. Solution Volume Deviation from Combined Sonar Volume, Bryan Mound 52
Figure 19. Equivalent Sonar Volume vs. Oil Inventory, Bryan Mound 55
Figure 20. Adjusted Deviation of Solution from Uncombined Sonar Data, Big Hill 58
Figure 21. Adjusted Deviation of Solution from Uncombined Sonar Data, West Hackberry 58
Figure 22. Adjusted Deviation of Solution from Uncombined Sonar Data, Bayou Choctaw 59
Figure 23. Adjusted Deviation of Solution from Uncombined Sonar Data, Bryan Mound 59
Figure 24. Cumulative Distribution for All Solution and Uncombined Sonar Data..... 60
Figure 25. Adjusted Deviations of Solution from Combined Sonar Data, West Hackberry 61
Figure 26. Adjusted Deviations of Solution from Combined Sonar Data, Bryan Mound .. 62
Figure 27. Cumulative Distribution for All Solution and Combined Sonar Data 63
Figure 28. Unadjusted Deviation of Equivalent Sonar from Oil Inventory, Big Hill 64
Figure 29. Unadjusted Deviation of Equivalent Sonar from Oil Inventory, West Hackberry 64
Figure 30. Unadjusted Deviation of Equivalent Sonar from Oil Inventory, Bayou Choctaw 65
Figure 31. Unadjusted Deviation of Equivalent Sonar from Oil Inventory, Bryan Mound .. 66
Figure 32. Mixed Adjusted Deviation of Equivalent Sonar from Inventory, Bayou Choctaw 66
Figure 33. Mixed Adjusted Deviation of Equivalent Sonar from Inventory, Bryan Mound . 67
Figure 34. Cumulative Distribution for All Equivalent Sonar and Oil Inventory Data 67

LIST OF TABLES

Table I. Calculated Solution, Sonar, and Oil Volumes, Big Hill 23
Table II. Equivalent Sonar Volumes in Brine and Oil Inventories (10/99), Big Hill 28
Table III. Special Sonar Survey Volumes in Oil and Oil Inventories, Big Hill 30
Table IV. Calculated Solution, Sonar, and Oil Volumes, West Hackberry 33
Table V. Equivalent Sonar Volumes in Brine and Oil Inventories (10/99), West Hackberry 38
Table VI. Equivalent Sonar Volumes in Brine and in Oil and Oil Inventories, West Hackberry 40
Table VII. Calculated Solution, Sonar, and Oil Volumes, Bayou Choctaw 42
Table VIII. Special Sonar Survey Volumes and Oil Inventories, Bayou Choctaw 45
Table IX. Calculated Solution, Sonar, and Oil Volumes, Bryan Mound 48
Table X. Equivalent Sonar Volumes in Brine and Oil Inventories (10/99), Bryan Mound 54
Table XI. Summary of Bias Adjustments and Remaining Scatter 57
Table XII. Insoluble Contents from Stage Solutions and Sump Build-Up, Big Hill 73
Table XIII. Insoluble Contents from Stage Solutions and Sump Build-Up, West Hackberry 74
Table XIV. Insoluble Contents from Stage Solutions and Sump Build-Up, Bayou Choctaw 75
Table XV. Insoluble Contents from Stage Solutions and Sump Build-Up, Bryan Mound .. 76

EXECUTIVE SUMMARY

Throughout the history of the Strategic Petroleum Reserve (SPR) Project, there have been three independent measures of cavern volume maintained. These are: (1) a calculated solution volume determined by raw water injections and brine extractions during construction and any subsequent fluid transfers or additions, (2) a calculated volume obtained from the geometric dimensions of the cavern as determined by sonar measurements, and (3) a partial cavern volume as determined from the metered quantity of oil occupying that volume. The intent of this study is to evaluate the various measures to obtain an indication of the uncertainties. This is accomplished through relative comparisons of the volume measurements against each other, and against the hypothetical perfect correlation. A hypothetically perfect correlation occurs when the measurements are in absolute agreement. From the comparison to the hypothetical perfect correlation, it was found that the volume measurements errors could be resolved into a bias produced by a systematic error and scatter produced by a random error. The random error, or scatter, could then be treated using statistical methods to give the apparent uncertainty of the various volume measurement methods.

Because of the separation of the bias and the random errors, it is possible for these two errors to be discussed separately. Even though some of the more significant effects can be attributed to the biases observed, the random errors will be discussed first. In fact, random errors reflect the true uncertainty in the measurement methods and therefore are potentially of the most concern.

Comparative analyses of the data produced either combined uncertainties of the calculated solution volumes with the sonar volumes or the combined uncertainties of the sonar volumes with the oil metering volumes. Statistical analyses then permits determination of the standard deviations which can logically be separated into the expected uncertainties of the individual measurement methods. From the statistical analyses it appears that the uncertainties from oil metering are quite small, essentially consistent with the +/-0.25% uncertainty associated with the oil custody transfer measurements. Random uncertainties in the sonar volume determination are essentially +/-2%, somewhat less than, but still consistent with, the values of +/-5% customarily given by the sonar survey operators. Random uncertainty in the calculated solution volume determined from this study appears to be about +/-3%, which is reasonable. However, this is slightly less than the +/-5% customarily estimated by the cavern construction engineers.

There are four SPR sites: Bryan Mound, West Hackberry, Bayou Choctaw, and Big Hill, listed in the order of their construction. Of the four SPR sites, the data from Big Hill show the least amount of scatter, probably because the two well caverns of this facility were constructed last and were not complicated by the need to fill them concurrently with oil. Also, by this time both the construction and sonar techniques had undoubtedly evolved and improved. In contrast to Big Hill, the Bryan Mound data show the greatest scatter. Bryan Mound caverns were the first to be constructed and were complicated not only by the need for concurrent oil filling, but also by the use of three wells for construction. Moreover, the measurement technology was probably less well developed, not to mention the need for refinement in the volume accounting. Interestingly, the uncertainties induced by the random errors seem to be same for all operators involved in the sonic surveys.

Systematic errors in the measurements may produce deviations from the hypothetical perfect relationship. These systematic errors or biases can range from about –9% to +9%, with some isolated data in excess of these values. While these deviations could potentially arise within any of the measurement methods, the form of the governing equations suggest that the sonar surveys would be most susceptible, because here the data reduction requires a concurrent sonic velocity measurement in addition to independently determined physical constants. As a result, the data of

the individual sonar survey operators involved may show different bias values. Moreover, different operators performing surveys on the same caverns, within the same time frame, produced data with different bias values, and even bias values of different sign. Although the cause of the bias is unidentified, it is most probably caused by a fixed error in the sonic velocity measurement performed concurrently with each survey and therefore producing an inaccuracy characteristic of each survey tool.

The relatively large amount of data from the volume measurements enables a statistical analysis, the results of which are quite interesting. By using one measurement type as the basis, the fractional discrepancy of the other measurement type was determined. Significantly, this fractional discrepancy contains the uncertainty in both of the measurements, as well as the bias. Eliminating the apparent bias from the data permits the random uncertainty to be represented statistically. Statistic distributions were determined for comparisons of (1) solution volume to sonar (uncombined) volume, (2) solution volume to sonar (combined) volume, and (3) equivalent sonar volume to oil inventory. The uncombined sonar volume is the sonar survey of the entire cavern, whereas, the combined sonar volume is the sum of a partial survey and the contained oil inventory of a cavern. It was found that the random uncertainty in each of these comparisons conformed well to a normal distribution. The statistical analysis for the solution to uncombined sonar volumes comparisons had a mean of +0.90% and a standard deviation of 5.78%. Since this standard deviation is the sum of the uncertainties of the sonar and solution measurements, it suggests that +/-2% is attributed to the sonar measurements and +/-3% to the solution measurement. The +/-3% clearly supports the customary assumed uncertainties of +/-5% in the solution measurements. The statistical analysis of the comparisons of solution to combined sonar volumes produced a mean of –1.20% and standard deviation is 4.72%, where the somewhat narrower distribution reflects the contribution of the smaller uncertainty in the oil inventory to the combined sonar volume uncertainty. Because this comparison actual involves three measurement types, separation of the uncertainties is difficult. However, the standard deviation is consistent with what would be expected. The statistical analysis of the comparisons of equivalent sonar volumes to oil inventories resulted in a distribution with a mean of -0.83% and a standard deviation of just 1.69%. This uncertainty is somewhat less than, but still consistent with, the customarily accepted +/-5% uncertainty in the sonar surveys and with the +/-0.25% associated with the custody transfer meters used for the oil inventories. These results suggest that the greater uncertainty thought to be associated with individual site cavern meters is not reflected in the data.

Although peripheral to the main objective of the study, the analysis of the cavern records also yielded data from which the insoluble contents of the dissolved salt could be determined. These results give information on the bulk insolubles which is difficult to obtain by other means. They indicate that the calculated <u>solid</u> density insoluble content of the salt from the SPR caverns was in the range of 3 to 6% for most of the caverns, with Bayou Choctaw having somewhat less than 2%. These contents are consistent with other determinations of domal salt insolubles.

In summary:

(1) One of the most important findings of this study was that the measurements appear to contain two distinct kinds of error, a systematic deviation (bias) from the perfect correlation and a scatter (uncertainty) caused by experimental error. As a result, it is possible to make assumptions about contributions of these factors in any given data set.

(2) In the comparison of the calculated solution volumes to the sonar survey volumes, there are two groups of data: the <u>uncombined</u> sonar data involving only small amount of blanket oil included in the total sonar volume, and <u>combined</u> data involving significant amounts

of fill oil included in the total sonar volume. When the uncombined data are adjusted for the assumed biases and analyzed statistically, they conform well to a normal distribution. The distribution has a standard deviation of +/-5.78% with a mean of +0.90%. With the standard deviation being a vector sum of the uncertainties, this suggests a possible +/-2% uncertainty in the sonar volume and a +/-3% in the solution volumes. These numbers are consistent with, although somewhat less than, the commonly accepted +/-5% for sonar, and the +/-5% uncertainty commonly quoted for solution volumes.

The results of this study, in general, indicate that measurement methods are really quite good, and in fact support those values of uncertainty customarily associated by the technical community with each type of volume measurement. While these comparisons of the measurement methods used at the SPR to determine the cavern volumes really acted to support the commonly accepted random uncertainties in the measured volumes, they suggest also a specific bias error within the data. The recognition of the bias, and the potential cause of the bias, can lead to refinements in the measurement methods, particularly in the sonar survey methods. The reality of measurement bias should be kept in mind, with the possibility that the bias is an experimental factor that perhaps can be eliminated. It is important in the future that the measurements be compared to each other in the context of the perfect correlation relationship.

At this point, one of the more beneficial refinements would appear to be in the sonic velocity determination methodology. As a result, one major recommendation is that a method be found to independently calibrate the device used to make concurrent sonic velocity determinations on each sonar survey tool.

1 INTRODUCTION

With the intent of providing greater insight into the interior conditions of the large storage caverns of the Strategic Petroleum Reserve (SPR), this study was undertaken to evaluate the measures of cavern volume and uncertainties in volume determination. Characteristically, three measures of cavern volume have been maintained since the inception of the SPR. These are: (1) the calculated solution volume based on metering of the input raw water quantity, together with the density analysis of the extracted brine, to obtain a total volume of salt dissolved; (2) the sonar survey volume based on the measurement by reflected sound waves, usually through the brine, to give the physical dimensions of the cavern, which leads to a computed volume; and (3) the metering of oil into the cavern, to give a measured volume of that portion of the cavern filled with oil. The metering of oil also requires an independent measurement of the vertical location of the oil/brine interface, which then permits evaluation of the volume of the appropriate portion of the cavern. The purpose of this work is to make comparisons between these three measurements and, where possible, make relative comparisons of the uncertainties. All of the volume measurement methods have specific uses during the construction and operation of the SPR. They are used to determine ullage or available storage space, to assess preferential solutioning to modify cavern geometry during operational fluid transfers, and to assure compliance with regulatory maximum cavern filling percentage limitations. While these uses are necessary, it must be clear, however, that the definitive measure of volume is always the volume of oil determined through the custody transfer meter, a volume that all parties agree upon, and which becomes the ledger amount for which the SPR Project is accountable. The uncertainty of the calibrated custody transfer meter is well known and accepted by the parties involved in the transactions. Calibration of the custody transfer meters is by direct measurement of a known collected volume. However, custody transfer normally takes place at a location quite remote from the facility exterior boundary, which means any subsequent distribution of oil and oil transfers within the site boundary may occur with less precise cavern meters. These cavern meters are normally believed to have greater uncertainty.

Beyond the simple comparison of the data, one would normally suppose that there would be very little analysis possible. Interestingly, a very simple theoretical basis can be stated for the perfect correlation relationship for the comparisons. Deviation from the perfect correlation relationship can occur only through quite limited errors, specifically through a systematic error or a random error. The mathematical development is related to the data reduction functions used for the interpretation of the actual measurements.

In attempting to make comparisons of the three types of cavern volume measurements, various factors make the comparisons of volumes somewhat difficult. These factors range from comparatively large uncertainties possible in some of the individual measurements to operationally dictated time offsets between the various measurements. While some of these timing discrepancies can be resolved from the records, the measurement uncertainties are not specifically documented. Some individual uncertainties can appear to be quite large, often large enough to be of some concern. There is a potential contributor to the observed discrepancies that is not related to the instruments used to make the measurements. This contributor is a complicated problem in accounting while determining the volumes. This is simply the difficulty in discovering and adding together all the necessary parts of volume. The sonar volumes are especially subject to this kind of difficulty because the individual volumes that must be added may have been obtained at quite disparate times. In addition, sometimes a divergence in the accounting practice occurred, most often through an attempt to correct apparent discrepancies in the absence of actual data.

Sources of data for the study are unpublished reports maintained in the Strategic Petroleum Reserve Project Library in New Orleans, Louisiana, or maintained in the Division 6113 SPR Library of Sandia National Laboratories in Albuquerque, New Mexico. The principal sources are the individual sonar survey reports, together with the cavern engineer's summary of the details of solutioning volumes and bottom locations. Construction details are also found in DOE [1991]. General domal site characteristics can be found in Hart et al. [1981], Magorian and Neal [1988], and Neal et al. [1993a] for Big Hill; Magorian et al. [1991] for West Hackberry; Hogan (ed.) [1980] and Neal et al. [1994] for Bryan Mound; and Neal et al. [1993b] for Bayou Choctaw. Oil inventories were taken from selected SPR Project Oil Inventory Summary Reports. Some of the oil inventory and equivalent sonar volumes were based on private communications from DynMcDermott, the SPR operating contractor under contract to the Department of Energy. Private communications and other published references are as noted in the text.

In the presentation of this work, the three types of measurements are detailed. Then, the simple theory behind the perfect correlation relationship is briefly discussed. Next, the volume data for each of the facilities or domal sites are presented, using a process of correlation of the data types against each other. In this process, the calculated solution volume is initially compared to the sonar volume determined from a series of sonar surveys as the caverns were constructed. Comparisons of the inventory volumes of oil are made to the sonar volumes determined either directly through the oil or through the equivalent volume of brine prior to oil filling. These comparisons are accompanied by some preliminary analysis, suggestions of uncertainty, and possible uncertainty sources. Of course, it is necessary to realize that the definitive measure of volume is the custody transfer meter used to determine the received volume of oil. Discussions of the results of the individual sites are presented in some detail. Deviations from the perfect correlation relationship may suggest the nature of the uncertainties observed. But, in general, the agreement of the various measurements to the perfect correlation relationship are demonstrated to be quite good. In fact, the results appear to be reasonable compared to those uncertainties of the various measurement techniques customarily stated or assumed, usually without real analysis, by the facility or measurement equipment operators. Then, the complete statistical analyses of the deviations for the various comparisons were determined, except for the data obtained from sonar surveys through oil. Both standard deviations and means were determined. In general, the statistical analysis indicated that the uncertainties conformed to normal distributions. The standard deviations give support to the observational estimates of uncertainties of the data and substantiate, where possible, each other from the various volume comparisons.

While all of the original volumes were reported to the nearest barrel, this implies an unrealistic accuracy. Here, these reported volumes have been truncated to values more commensurate with the number of significant figures warranted by the measurement.

The work concludes with a summary and suggestions for the sources of error, and where some potential improvements in technique or analysis may be possible.

Although peripheral to the main objective of the study, the analysis of the cavern records also yielded data from which the insoluble content of the dissolved salt could be determined. These results give information which is difficult to obtain by other means. The results are discussed in terms of previous works on the creep and fracture behavior of the salt.

2 MEASUREMENTS

The measurements involved in the determination of cavern volume are all straightforward in the sense that they are adapted to field operating conditions, to be used somewhat routinely by the facility operators, to obtain information about the cavern system. Each of the three principal methods: solution volume, sonar volume, and metered oil volume are discussed in some detail. Of these, only the last is a direct measure, while the others require intermediate calculations.

2.1 Solution Volume Measurement

Historically there was often very little attention paid to the details of the solutioning process during solutioning of commercial caverns. Of principal concern was the salinity of the delivered brine, and sometimes the total volume produced. The simple chemical analysis of the output brine, when combined with metering of the input raw water, permits one to calculate the equivalent volume of dissolved salt, or total cavern volume. In a sense, this cavern volume knowledge has provided some major aspects of control over the solutioning process. Over time, the technology has changed significantly with the advent of numerical codes for prediction of solutioning, which in turn permits greater precision in attaining a desired cavern geometry. These codes require a thorough knowledge of the amount of salt dissolved as part of the prediction process. This technology was applied extensively in the development of the SPR. All of those caverns constructed specifically for the SPR used solutioning designs based on a numerical prediction code. As a consequence, they are of reasonably well defined cylindrical geometry. In contrast, the older commercial caverns purchased by the SPR tend to be geometrically irregular since they were solutioned before the general use of prediction codes to guide the construction process. For purposes of this development, however, it is essential to remember that the simple calculation of the solutioned salt volume is actually independent of these numerical codes.

There are two necessary input measurements for calculation of solutioned volume: the metered volume of the input raw water and the salinity of both the input raw water and output brine. Typically, input raw water is metered through a calibrated plate venturi meter, although other types of meters can be used. Salinity of the brine is determined from the brine density. The former is a continuous measure, and the latter is through batch sampling. In the simple situation of pure salt, the volume of the cavern is just the volume of the salt removed, as given by

$$V_s = \frac{1}{\rho}(C - 1)V_w \qquad 1$$

where C is the density of the output brine, ρ is the density of salt, and V_w is the volume of raw water input.

Although this seems straightforward, several factors can contribute to an uncertainty in this calculation. An uncertainty can occur if the raw water, itself, contains impurities so that the raw water density (specific gravity) is different than 1.0. In general, this uncertainty can be eliminated by measuring the density of the input raw water, in order to determine the change in brine density though the cavern. Perhaps even a greater uncertainty is introduced by impurities contained within the salt being dissolved. These impurities present no problem if the insoluble impurities remain within the cavern by falling to the cavern sump. Then the correct solution volume is calculated because the volume of insolubles is conserved in the system. However, insoluble impurities have the potential of being partially or wholly swept out of the cavern in the

brine stream. The evidence for this process is the accumulation of insoluble material in the brine pond. This represents removal of mass from the cavern which is independent of the solutioning process. This volume, although probably not great, has the effect of increasing the apparent solution volume above that from Eq. 1.

It is possible to elaborate on the formulation in Eq. 1, by expanding it to incorporate the details of the input water and the insolubles in the output stream. Consequently, the total measured volume, V_t, is given by

$$V_t = \frac{1}{\rho}(C_b - C_w)V_w + kV_i \qquad 2$$

where the subscripts, b and w, reflect the density of the output brine and the input water. This allows for the potential brackishness of the input water source. In some cases, such as Bryan Mound, the raw water source was from a channel that at certain times was flooded by the salt water tide. Thus the input water already was at a density of about 1.03 Mg/m^3. The total volume of insolubles is contained in V_i, where k is the fraction of insolubles removed during solutioning. Insolubles can be either clay particles or anydrite and polyhalite second phases. In general, V_i is small compared to the total volume of salt removed, typically less than 10 %. These quantities can be determine from the accumulation of insolubles in the cavern sump during solutioning. The amount of the insolubles remaining in the cavern is reduced by the k loss ratio. Even though the quantity of impurities that reach the brine ponds is not very well documented, these quantities are demonstrably much smaller than the insoluble quantities available in the cavern. Consequently, k is typically very small, and approaches zero, for most cavern construction.

Clearly, the concepts behind the measurement of the cavern solution volume are quite simple. However, the accuracy of the various quantities are not really well documented. It was believed that the raw water meters, although calibrated routinely, were accurate to only about +/- 5%. The uncertainty in the gravimetric measure of the input and output brine would be less than +/- 0.001 or about +/- 0.1%. The uncertainty in the amount of impurity contribution to the volume was based on the determination of the volume of anhydrite in the brine pond, usually obtained from an estimation during disposal of the residue brine pond solids. The uncertainty of impurity content certainly does not exceed the amount of initial impurity content of the domal salt. Clay and associated particles in the salt dome itself do not appear to exceed 1-2%, most of which probably remains in the cavern during solutioning. The second phase insolubles could possibly be as high as 10%, with only a few percent actually appearing in the brine output. One would expect the amount of second phase insolubles in the brine output to be somewhat proportional to the original domal composition. Possibly this proportionality would diminish as the cavern volume increases, because local brine velocities would decrease and the cavern settling capacity would increase.

The only constant in Eq.2 is the density of salt. While any error in the quantity would introduce a systematic error, one would expect the salt density term to contribute very little to the uncertainty because the density can be determined to better than +/-0.01%. The likelihood of error being introduced by uncertainty in salt density is even less considering the highly pure salt of the Gulf Coast domes.

Although a quantitative evaluation is not possible, the uncertainties in the solutioning process should arise primarily from the metering errors and from the loss of insolubles to the brine stream. The meter errors are probably random, but the loss error is not. This would suggest that

the resultant net error would most likely cause the actual cavern volume to be somewhat greater than the calculated solution volume, on the average. However, in reality, random uncertainties probably mask any trend produced by the loss of insolubles from the cavern.

2.2 Sonar Volume Measurement

Sonar measurements are attractive because they offer a direct, and quite detailed, method of determining the volume, as well as the geometry, of a cavern. They can be extremely useful during the solutioning of a cavern because the knowledge of the geometry permits appropriate alteration of the solutioning method and water insertion hanging string locations. However, they are also somewhat complicated and depend upon sophisticated technology application and subjective interpretation. For this report, the technical details of the suppression of the multilobe mechanical antenna to obtain a single lobe beam, the burst mode of operation, the control of the reach of the beam, etc, will not be treated. These aspects are beyond the purpose of this study, but detailed information can be found elsewhere [Benjamin, 1966; Kock, 1973]. However, here, it is important to realize that the survey accuracy depends critically upon the ability to measure or calibrate the sonic velocity of the fluid.

The fundamental concept of the sonar device is that a sonic pulse transmitted from a known location of a transmitter/receiver will travel through the fluid media in the cavern to the cavern salt surface and reflect. Detection of the reflected wave at the transmitter/receiver location then permits a determination of the travel time of the sound wave. Detection of the return signal is however a function of all of the technical details noted previously, as well as the skill of the operator. The simple expression for the distance between transmitter and salt surface becomes

$$D_n = c_f \left(\frac{\Delta t}{2} \right) \qquad 3$$

where c_f is the velocity of sound in the fluid and Δt is the transit time of the wave between the transmitter and receiver. All that is necessary is that the sonic velocity of the sound wave in the fluid media be known. This is done concurrently with the survey by a separate measurement gage with an accurately known path length mounted on the main sonar survey tool. While the separate measurement gage utilizes the same principles as the main survey tool, it solves the alternative problem for a known transit distance and an unknown media sonic velocity. A number of complications immediately arise, however. The velocity of sound in the fluid depends upon the type and density of the fluid and is sensitive to fluid temperature. Because of potential thermal and density gradients in the cavern, the velocity may become a spatially dependent parameter. Also, the transmitted pulse amplitude undergoes attenuation in the fluid, which progressively weakens the intensity of the pulse. The amount of attenuation depends primarily upon the fluid type and density and the distance the pulse travels. Because of limitations on the transmitter power and the transmitter/fluid coupling conditions, the pulse strength from any given transmitter is limited. As a consequence, the total attenuation a pulse can undergo and still be detected at the receiver effectively determines the maximum range of the sonar. For a given transmitter/receiver system, the range is greatest in brine, where attenuation is less, than in crude oil, where the attenuation is greater. Actually, other losses of beam intensity occur because of the beam geometry and the quality of the reflective cavern surface. Even though the sonar beam configuration can be limited at the transmitter to achieve the equivalent of a small aperture, the beam will diverge as it travels outward to the target and back, with a consequent loss of pulse intensity. Furthermore, the return reflection will be scattered and dispersed at the reflecting salt

surface because the surface is imperfect in orientation and smoothness. Hence, the magnitude of the return signal includes dispersion and divergence effects as well as attenuation. When this return signal is no longer viable with relation to the noise, the limit of the technique has been reached.

In practice, special methods to enhance the basic technology are typically used. The initial signal generated is usually a "burst" involving several packets of waves which reinforce each other. Also special parametric methods where a non-linear response is used to increase accuracy can be implemented [Van Trees, 1971a]. Special discrimination sampling methods for separation and detection of the reflected pulse to improve the ratio of the signal to the random background noise can also be employed [Van Trees, 1971b]. While further improvement could be obtained with phased arrays and spectrum analysis, these technologies are complex and not used in current cavern survey technology. Nevertheless, modern sonar transmitter/receiver systems are relatively sophisticated. They have considerable power with good electronic systems and have an approximation to aperture control of the beam. Often the return signal is gated to assure the same pulse magnitude and location is being utilized for the arrival time of the pulse. However, the most important aspect of modern sonar probes remains the concurrent determination of the sonic velocity in the fluid.

Sonar horizontal distance determinations are made at fixed depths, or stations, as the transmitter is lowered or raised through the fluid media. Station depths are chosen by the operator, typically with 10 ft separations, although the separation interval may be as little as one foot. At each depth, the target surface distance is determined as a function of azimuth angle, again with the angles of separation of individual measurements as desired by the operator. Typically, readings are taken at some 128 azimuth angles at a given depth, although some older surveys may have fewer. This gives an azimuth separation of about 2.8°. At certain locations, such as the roof and the floor, the transmitter cannot be placed close enough for horizontal measurements, however, the transmitter can be tilted or deflected as much as 90° from horizontal to permit measurements of angular distances. In this manner, parts of the roof and the floor can be surveyed.

With the measured distances and the known depth increments and angles, an approximation method based on triangles can be used to calculate the volume of segments at a given location and azimuth. Summation of these over the height of the cavern then yields a cavern volume.

In the determination of the cavern volume, it is possible to assign some reasonable uncertainties. In the sonar determination of distance there is the uncertainty in the sonic velocity and the uncertainty of interpretation of the timing of the return pulse. Sonic velocity, as obtained from the attached measurement gage, if all of the system components are at their stated optimum, has a fundamental accuracy that probably exceeds 0.1%. This simultaneously determined velocity will potentially characterize the fluid at a given depth provided that the fluid is homogeneous and the temperature gradients are small. However, the sonic velocity measurement system in the field may not always be at its stated optimum. When this happens, it is possible that the measurement will contain a systematic error. In fact, as shall be demonstrated, the uncertainty from the velocity measurement may be more complex than thought, involving both a scatter and a bias.

Another of the most probable sources of uncertainty is the uncertainty in the determination of the transit time of the pulse. Not only is there a fixed system error but there is also a subjective error in the determination of the arrival time of the return signal. The fixed system error is really the least detectable time or time resolution of the system. A not unreasonable detection limit is about one-millisecond. Although the transit time depends upon the cavern radius, the system error remains fixed. Thus, the percentage error decreases as the cavern radius increases. For a one

hundred foot cavern radius and a typical sonic velocity, the transit time fixed uncertainty can correspond to about 2%. Normally, the system resolution is better than this example. Moreover, even if this system resolution in improved, the other errors from the subjective determination of arrival time may dominate the uncertainty. As in the case of the system error, the subjective determination of the pulse arrival time can introduce uncertainty. The time of arrival of the signal can be difficult to locate because of signal attenuation and broadening of the pulse. Even though the detection may be automatic, the operator will be required to make judgments based on experience. Again, because the uncertainty in arrival time detection is roughly a fixed quantity, the actual percentage uncertainty decreases with the cavern radius. The uncertainty might normally be expected to be on the order of 2%.

In assigning the relative importance of the uncertainties, it would appear that the uncertainty in the subjective determination of the arrival time of the return signal is expected to be much greater than the system timing uncertainty. Also it would appear that the subjective uncertainty would be greater than the uncertainty in the sonic velocity in an optimum system.

Another source of uncertainty may be simply geometry. The effective angular width of the beam is probably on the order of 2°, which means that it is about the same as the 2.8° difference in the azimuth angle of the survey. Under these conditions, there is no overlap of the beam at the various azimuth stations. The beam paints a spot about 3.5 ft in diameter at 100 ft. As this spot traverses the circumference of the cavern, it will encounter a rough or undulating surface. The surface can be thought of as various planes offset from each other in the radial direction. As the beam passes over the surface, it will progress across these planes, sometimes from a plane nearer the source to a plane further from the source, or vice versa. However, the planes closest to the source can always reflect some portion of the beam even though a plane further from the source may be reflecting also. Because nature of the detection of the return signal, the tendency is for the nearer surface distance to be recorded, to give a smaller than average cavern radius. The result of this tendency would be for the calculated sonar volume to be somewhat smaller than the actual volume. The actual uncertainty would of course reflect differences in the character of the surface roughness, as well as the cavern radius. It is difficult to estimate this uncertainty, because it will be a function of the radius, with larger caverns producing a smaller uncertainty. It is biased in one direction (minus) and may be as high as a few percent for small radius caverns. These differences are very difficult to quantify, and clearly, unless there is a comparison to an absolute volume, the exact uncertainty is unknown.

While there is no way to suggest the appropriate difference between the calculated sonar volume and the actual volume because of the surface roughness, it is probably some combination of the beam arrival detection uncertainty and the uncertainty introduced by the surface effects. It is possible to make an estimate for a reasonable assumed wall roughness condition. For a 100 ft radius cavern, a uncertainty in the average radius of 1% (1 ft) will produce an uncertainty of 2% in the cavern volume. In terms of the sonar reflections from a roughness of this order, the under prediction of the cavern volume would be somewhat less than 2%.

Under these instrument and cavern conditions, it could be argued that the expected overall uncertainty of the sonar survey to be somewhere around +/-2%, with a potential bias of approximately 2% (minus) in volume.

Some additional comment is appropriate on the sonar equipment and techniques when these are adapted for use directly in oil. Because of the extremely large attenuation of the signal in oil, it is necessary to reduce the operating frequency, perhaps by as much as a factor of ten. This has proven to be difficult and produces sonar tools markedly different in design and response from

the tools developed for surveys in brine. In fact, the current developments suggest that the uncertainties determined for sonar through brine will have little relationship to the uncertainties of the tools used in oil.

2.3 Oil Volume Measurement

Cavern volume, at least in part, is also measured by the quantity of oil that it contains. Because of the need to maintain some brine below the hanging string, as well as limitations imposed by the relevant governmental agencies, only a fraction of the total cavern can be filled with oil. Governmental limits are in the 90-95% range, and are normally the controlling factor.

Accurate measure of the physical inventory of crude oil is a crucial operation of the SPR. The principal measurement of oil quantity is by a custody transfer meter. This is a calibrated flow meter of the orifice type. Corrections for viscosity and line pressure are made. The meter is routinely flow calibrated using an off-line test, where the time to capture a measured volume is determined. In this manner, the calibrated flow rate is obtained. The stated uncertainty in these meters is +/- 0.25%, a value which is carefully maintained. All parties must have confidence in this accuracy because the custody transfer meters are the basis for monetary payments.

For the SPR, the custody transfer meters are normally on the main pipeline into the oil terminal, such as the St. James terminal. Typically, the main transfer pipeline from offsite leads to a manifold system within the SPR site boundaries that can be used to distribute the incoming crude oil among the various caverns. Each cavern is supplied with an individual meter, typically of less quality than the custody transfer meter. In fact, the individual cavern meters were not always even the same type nor are they as routinely calibrated. Principal types of meters are sonic and orifice, but others are also used. It appears that the individual cavern meters may be quite inaccurate, perhaps with uncertainties of up to several percent. In addition, in the split-streaming through the manifolds, there may be some attempt to reconcile any discrepancies from the known total custody transfer quantities. Any reconciliation could potentially exacerbate the uncertainties in individual caverns. As a result, only under special circumstances can the precise custody transfer metered quantity be directly associated with a specific cavern. Ultimately, however, the SPR is responsible for the total oil inventory as determined by the custody transfer meters.

In order to translate the quantity of oil into an equivalent cavern volume, it is necessary to know the depth of the oil/brine interface. Typically this is measured using a density logging tool that uses the neutron return scatter to determine the fluid density. The oil/brine interface appears as a reasonably sharp (+/-2 ft) transition in the record. In a typical full Phase II or III cavern, a 2 ft error is on the order of only 0.1% uncertainty in the oil volume. However, the interface location measurement produces a fixed error and as the oil volume changes the uncertainty changes. The uncertainty will be largest when the oil volume is small. In some instances, especially recently, the logging tool has been able to detect two interfaces, an oil/emulsion and an emulsion/brine interface. These are typically several feet apart.

It appears that the uncertainty in oil volume for any given cavern may be as large as a few percent at the extreme. This is the result of calibration and accuracy problems with the individual cavern oil volume meters. Oil transfers occur routinely between caverns of a site and involve the same higher uncertainty because the individual cavern meters utilized. Little additional uncertainty is introduced by the error in determining the oil/brine interface. However, in the end, the total oil inventory of a site is determined by the custody transfer meters alone, and as a consequence, the cavern inventory sum must be within the +/-0.25% uncertainty of these meters.

3 PERFECT CORRELATION

Interestingly, correlation of volume quantities has a very simple theoretical formulation. Over the relatively brief intervals of time required for the measurements, the actual cavern volume, even though it is unknown, is essentially constant. Consequently, different types of measurements taken within the same brief interval are measuring this quasi-constant volume. The various measured quantities, can and do differ from the actual value. This difference can be expressed as a systematic deviation and a random uncertainty according to the following

$$V_a = m\left(V_x + \left(\pm \Delta\varepsilon\right)\right) \qquad 4$$

where the actual volume, V_a, is compared to the measured volume, V_x, and has a systematic deviation given by m and an uncertainty or scatter given by $\Delta\varepsilon$. The systematic deviation is related to the bias, which is $1\text{-}m$.

Comparison of two measurement types involves two expressions of the form of Eq. 4. Thus,

$$m_1\left(V_{x1} + \left(\pm \Delta\varepsilon_1\right)\right) = m_2\left(V_{x2} + \left(\pm \Delta\varepsilon_2\right)\right)$$

or, after reframing

$$V_{x1} = V_{x2}\frac{m_2}{m_1} + \frac{m_2}{m_1}\left(\pm \Delta\varepsilon_2\right) + \frac{m_1}{m_1}\left(\mp \Delta\varepsilon_1\right)$$

Because the ratio of the systematic errors is typically very nearly one, the multiplier on $\Delta\varepsilon_2$ can be ignored. As a result the uncertainty errors of the two measures simply add. Thus, the resultant equation is just

$$V_{x1} = V_{x2}m' + \left(\pm\Delta\varepsilon_2\right) + \left(\mp\Delta\varepsilon_1\right) \qquad 5$$

where the m' is the combined systematic error of m_2 / m_1. The uncertainty errors should be random and when taken over a large database will form a distribution.

The interesting feature of this simple theory is when the systematic deviation factor is one and the uncertainties are zero, the correlation is perfect. This perfect correlation line will appear in many of the data presentations and discussions which follow.

In addition to the perfect correlation line, often a very simple "trend line" is included in the data presentations. A trend line is just a straight line emanating from the zero origin and passing through the relevant data points.

Through the use of this simple theory, it may be possible to separate errors into systematic or bias errors and random or scatter errors. These trends will be investigated as the data are presented.

4 RELATIVE COMPARISON OF VOLUMES

Clearly one of the unique aspects of these comparisons is that "true" or actual volumes of the caverns are fixed, but unknown, over the relatively brief time intervals where the measurements are compared. While all measurements contain uncertainties, oil quantities as measured by custody transfer meters are "definitive" values taken as the true quantities within relatively narrow uncertainties. Nevertheless, it is still instructive to make relative comparisons between the various methods of determining approximate volumes. Consequently, comparisons will be made between calculated solution volumes and sonar volumes, and between metered oil volumes and sonar volumes. The three types of volume measurements are all involved. Solution volumes were calculated continuously during the construction of the caverns, and thereafter whenever raw water was used to displace oil. Sonar surveys were take as necessary after a completion of a solutioning phase to determine cavern size and shape to guide the proper placement of hanging strings to achieve the desired cavern geometry and thereafter whenever operational considerations required. Obviously, oil metering volumes were determined during oil filling, and any subsequent oil transfers. Comparisons will be grouped according to the facility, beginning with Big Hill, because these data are not influenced by concurrent oil filling. West Hackberry follows because the data here are extensive and include several sonar surveys taken through oil. Bayou Choctaw, with its single SPR constructed cavern is examined next. The data from the remaining facility, Bryan Mound, which are complicated, are examined last. The Phase II and III SPR constructed caverns were utilized preferentially because construction histories and surveys are not generally available for the Phase I commercial caverns purchased by the SPR.

4.1 Big Hill (BH)

Big Hill was a somewhat ideal situation for the SPR because the caverns were constructed to completion before being filled with crude oil. In the other, earlier caverns of the SPR at the other facilities, the caverns were filled as they were constructed, in response to the pressures to obtain a crude oil reserve as quickly as possible. All Big Hill caverns are two well caverns.

At Big Hill the solutioning of the caverns progressed through the several phases beginning with sump development by direct leaching and then through several reverse solutioning phases with repositioning of the raw water injection points as necessary. The solution volume of the cavern was essentially calculated continuously during the construction. Between each of the phases, a sonar survey was used to obtain the cavern geometry and guide relocation of injection points. Typically, there were three or four sonar surveys obtained before completion of a cavern.

4.1.1 Solution Volumes and Sonar Volumes

The sonar surveys are interesting because they involve three different wireline companies. Most of the surveys were made by MicroGage (MG) and Sonarwire (SW). One other company, which appeared under two names, Dowell (DW) and Sonar and Well Testing Services, performed one of the surveys. Predominantly, MicroGage performed the earlier surveys, when the cavern volumes were smaller, and Sonarwire performed the later surveys, when the caverns were near completion. A few exceptions occurred, however, with Sonarwire making some very early surveys. These same companies tend to be associated with the SPR sonar surveys over relatively long periods of time. This is also true of the various technicians responsible for the sonar equipment operation. These surveys, and related data for Big Hill, are summarized in Table I.

In making the comparisons of calculated solution volumes to sonar volume, it is essential to understand the potential differences in these two volumes. The solution volumes are a good

Table I. Calculated Solution, Sonar, and Oil Volumes, Big Hill.

Cav.No.	Co.* (Oper.)	Date	Sol.Vol. (MMb)	Ratio (w/(s+o))	Sonar Vol. (MMb)	Oil Vol. (MMb)	Remarks
BH101A	SW(U)	01/91	12.901w	1.007mix	12.690s	00.116o	9.66%insol. ***
	MG(B)	03/89	04.768w	0.960	04.965s		7.69%insol.
	MG(B)	11/88	03.007w	0.926	03.249s		
	SW(U)	03/88	00.562w	0.937	00.600s		
BH102A	SW(M)	12/93	13.034w	1.038mix	06.163s	06.393o	**
	SW(U)	02/91	12.900w	1.089mix	11.704s	00.140o	11.2%insol. ***
	MG(B)	04/89	05.089w	1.037	04.907s		12.8%insol.
	MG(C)	12/88	03.024w	1.021	02.962s		
BH103A	SW(U)	12/90	12.901w	1.042mix	12.225s	00.158o	8.46%insol. ***
	SW(U)	04/90	09.426w	1.050mix	08.877s	00.103o	0.98%insol. ***
	MG(C)	12/88	03.044w	1.012	03.007s		
B	MG(C)	05/89	05.166w	1.022	05.054s		5.53%insol.
	SW(U)	05/88	00.634w	1.081	00.586s		
	SW(U)	02/88	00.355w	1.114	00.319s		
BH104A	SW(U)	01/91	12.901w	1.024mix	12.480s	00.118o	10.2%insol.***
	MG(C)	03/89	04.989w	0.976	05.109s		
	MG(C)	10/88	02.633w	0.990	02.660s		
BH105A	SW(U)	07/90	12.939w	1.061mix	12.166s	00.025o	6.65%insol.***
	MG(B)	11/88	04.455w	0.918	04.855s		12.0%insol.
	MG(B)	07/88	02.758w	0.943	02.927s		
BH106A	SW(U)	01/91	12.902w	1.029mix	12.499s	00.038o	11.2%insol. ***
	SW(U)	05/90	10.613w	1.009mix	10.494s	00.023o	9.44%insol. ***
	MG(W)	03/89	05.383w	0.984	05.469s		10.2%insol.
	MG(B)	11/88	03.016w	0.891	03.385s		
BH107A	SW(U)	12/90	12.907w	1.039mix	11.786s	00.627o	14.7%insol. ***
	MG(C)	10/88	04.255w	1.004	04.239s		12.4%insol.
	MG(B)	07/88	02.726w	1.051	02.591s		
	DW(F)	01/88	00.491w	1.129	00.435s		
BH108A	SW(U)	12/90	12.924w	1.027mix	12.222s	00.353o	8.76%insol. ***
	MG(B)	01/89	05.026w	0.840	05.981s		15.7%insol.
	MG(B)	09/88	02.605w	0.906	02.874s		
BH109A	SW(U)	01/91	12.903w	0.977mix	13.156s	00.045o	6.99%insol. ***
	MG(B)	12/88	05.052w	0.953	05.300s		10.6%insol.
	MG(B)	07/88	02.714w	0.998	02.720s		
	SW(U)	01/88	00.588w	0.953	00.617s		
BH110B	SW(U)	08/90	12.924w	1.004mix	12.485s	00.384o	6.52%insol. ***
	MG(U)	11/88	04.477w	0.946	04.735s		
	MG(B)	07/88	02.623w	0.984	02.667s		
BH111A	SW(M)	08/91	12.900w	0.976mix	13.091s	00.123o	9.28%insol. ***
	MG(B)	03/90	05.371w	0.974	05.513s		10.3%insol.
	MG(C)	10/89	03.128w	1.121	02.789s		
BH112A	SW(M)	07/91	12.918w	1.068mix	12.038s	00.055o	8.60%insol. ***
	MG(C)	02/90	05.022w	1.012	04.962s		13.8%insol.

Table I (Cont.). Calculated Solution, Sonar, and Oil Volumes, Big Hill.

Cav.No.	Co.* (Oper.)	Date	Sol.Vol. (MMb)	Ratio (w/(s+o))	Sonar Vol. (MMb)	Oil Vol. (MMb)	Remarks
BH113A	SW(M)	06/91	12.911w	1.010mix	12.636s	00.154o	10.6%insol. ***
	SW(U)	11/90	10.301w	1.042mix	09.788s	00.094o	8.96%insol. ***
	MG(C)	03/90	05.510w	1.002	05.498s		4.52%insol.
	MG(B)	12/88	00.423w	1.032	00.410s		
BH114B	SW(U)	02/91	09.589w	0.978mix	09.722s	00.084o	8.40%insol. ***
	MG(B)	05/90	05.637w	0.947	05.952s		9.84%insol.
	MG(C)	10/89	02.763w	0.969	02.851s		

* Companies are SW = Sonarwire, DW = Dowell (also Sonar and Well Testing Services), MG = MicroGage, Inc. (part of Boeing, initially Digital Surveys).
Technicians are B = Broussard, C = Childress, F = Free, M = McCool (younger), U = Unknown Operator (here it is the elder McCool), W = Ward.

** Mixed (combined) volume where the oil (o) makes up a considerable fraction of the total volume, so that the solution (w) /sonar (s) volume ratio is compromised.

***The blanket oil is a minor contributor to the total volume, so that these solution (w) /(sonar (s) +oil (o)) volumes are the most accurate. These values are plotted in Figure 1.

accounting of the total volume of salt removed during the construction and should give the total volume of the cavern. In contrast, the sonar volumes are calculations of the amount of volume accessible to the sonar survey. Typically, these sonar surveys can be easily obtained only through brine, and not oil, thus, any crude oil in the cavern prevents a sonar survey of the volume it occupies. To obtain a total sonar survey may require summation of the surveys from different time stages of the cavern. To obtain the total cavern sonar volume then requires the addition of the metered oil and sonar volumes, this mixed quantity is considered the combined volume. It must be remembered that the metered oil volume is a measure of only that part of the cavern filled with the oil.

Solution volumes are those volumes calculated using the specific gravities of the brine and input raw water, and raw water volumes. Even though the raw water input quantities were measured routinely, contemporary notes indicate that the operators thought them to be frequently in error. In some instances the meters were out of service and the raw water input was estimated. In other instances, the meters were probably out of calibration. What we will assume is that these types of problems, at this well developed stage of the SPR program, were essentially randomly distributed. Therefore, their magnitude will tend not change with time. That is, the problems with raw water meters did not diminish with time; nor is there any reason to suppose that the gravimetric measurement procedures for water and brine densities were changed during the course of the program or that the uncertainty associated with these measurements changed.

When a significant portion of the cavern volume is occupied by oil, the total cavern volume obtained by combining the metered oil volume and the surveyed sonar volumes is not a really proper volume for determining the uncertainty. The difficulty arises because the combined volume involves actually two discrete but unseparated measurement uncertainties. The oil volume is a metered volume compared to the calculated volume of the survey.

During construction of the Big Hill caverns, only relatively small amounts of oil were used as a blanket to protect the cavern roof from solutioning. Sometimes this small amount of blanket oil was recorded, sometimes not. When it was recorded, the small volume of blanket oil can be added to the sonar volume determination without inducing significant error into the relative sonar volume uncertainty. When it was not recorded, little error is introduced if the relatively small volume of blanket oil is ignored in equating the total cavern volumes with the cavern sonar volume. This is especially true of most of these sonar surveys, where the oil blankets volumes were typically small, 500 (0.004%), but on occasion could be up to 600,000 (5.0%), barrels in a 12 MMb cavern. Those total volumes, which for completed caverns have only the small amounts of blanket oil added or where it was neglected, are noted in the Table I. There are four groups of data: Sonarwire (SW***) which is the total combined volume data with small volumes of blanket oil, Sonarwire (SW) which is the early sonar volumes taken in just one of the wells of the two well caverns and where the large relative amount of blanket oil is unknown, MicroGage (MG) which involved early sonar volumes where the blanket oil volume is unknown and is probably relatively small, and Dowell (DW) which is involved early in the development of one cavern. Data in Figure 1 are the sonar results of just two companies, Sonarwire and MicroGage. Sonarwire data (SW***), diamond symbols in Figure 1, are thought to be very high quality data. These data appear only in the upper right part of the graph because they were all obtained late in the construction process. MicroGage (MG) data, the squares in Figure 1, were the earlier surveys, where the unknown small amount of blanket oil is not included.

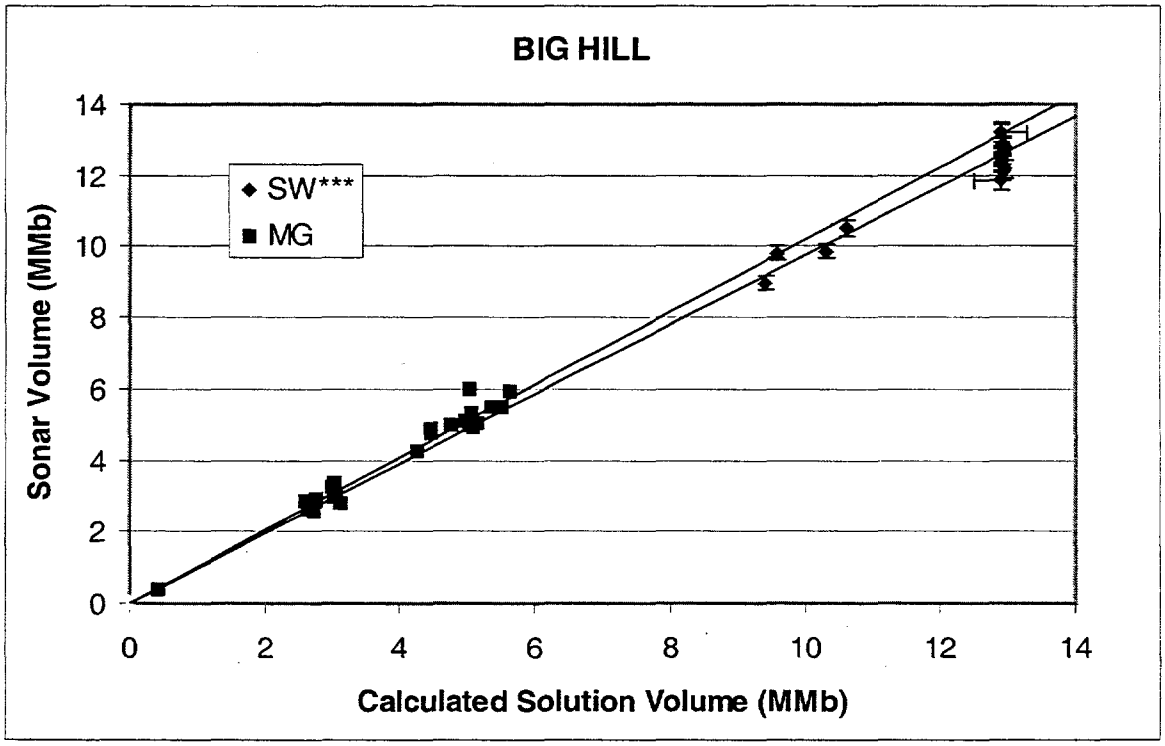

Figure 1. Solution Volume vs. Sonar Volume (w and w/o Blanket Oil), Big Hill.

The results in Figure 1 are very instructive. As is clear, there is a certain amount of scatter in the data. Whether this scatter is excessive or not is not clear. Two trend lines are shown, one of which seems to represent the SW*** data reasonably well, and the other which seems to represent the MG data reasonably well. The error bars shown on the SW*** data are +/-3% in

the solution volume and the customary +/-2% error bars for the sonar survey volume, which are almost obscured by the data points. These error bars seem sufficient to bring all of the data into agreement. The rather odd vertical alignment of some of the data is caused by the fact that the target for the maximum solution volume was the same for a number of the caverns. Implications of the trend lines, which are just straight lines emanating from the origin and passing through the data, will be discussed later.

Later in the cavern operation, some sonar surveys were made when the unknown blanket oil or inventory volumes were potentially a large fraction of the total volume. Consequently, there are two different types of combined volumes, those with small relative amounts and those with large relative amounts of oil involved. Those remaining surveys in Table 1 where the oil fill volume made up a large fraction of the total (combined) volume are not plotted in Figure 1.

The data, in general, appear very well behaved. The deviations in Figure 1 suggest what appears to be relatively marked scatter. However, to examine the scatter in greater detail, it can be characterized in an exaggerated form by taking the ratio of the deviation of the calculated solution volume from the sonar volume divided by the sonar volume and plotting this fraction against the sonar volume. This plot, as shown in Figure 2, contains a few more data points than Figure 1 because it includes all of the combined cavern volumes. Even though the sonar volume has been taken as the basis measure for normalization, it is essential to realize that the fractional deviation ratio still contains the uncertainties of both the calculated solution volume and the sonar volume.

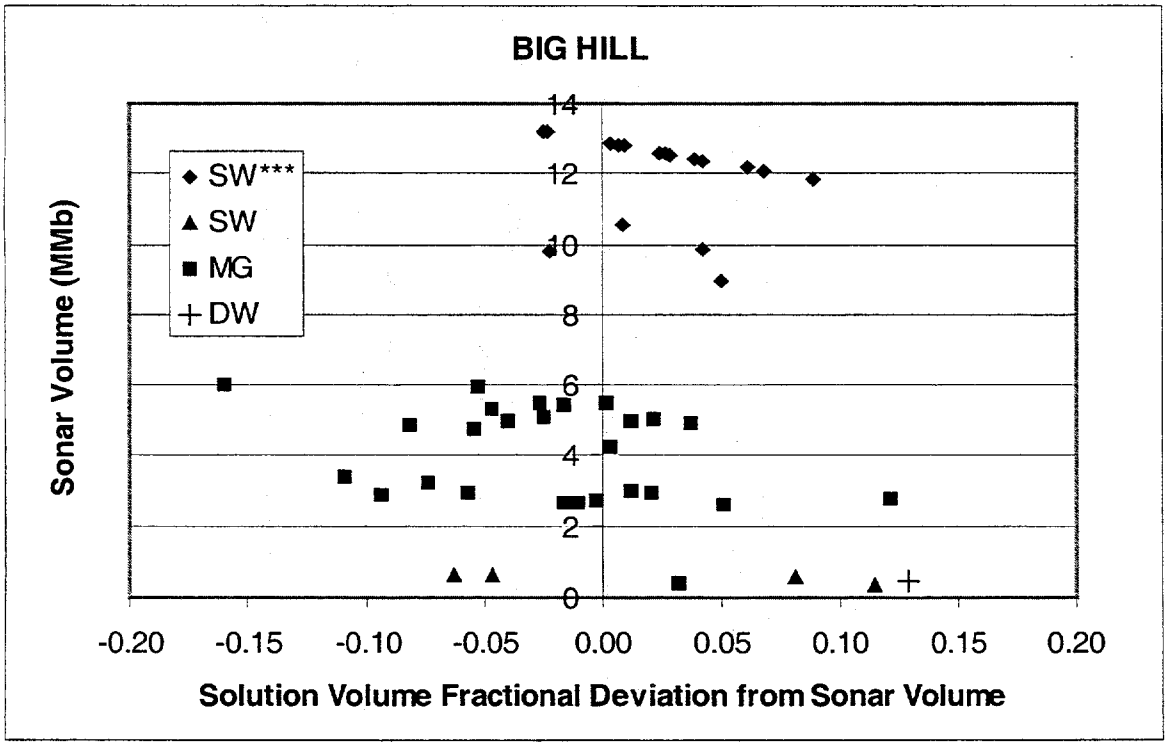

Figure 2. Solution Volume Deviation from Sonar Volume (Three Operators), Big Hill.

These deviation results are quite interesting because, although the scatter is large, as much as 17%, they suggest some trends that can be interpreted, at least hypothetically. The MG and SW data at small cavern volumes (less than 6 MMb) is uncombined; however, as noted previously,

the volumes of blanket oil at these stages were on the order of 500 barrels (0.012% at 4.0 MMb), hardly enough to markedly change the ratio. If these blanket oil volumes were to be included, they would shift the data slightly to the left. Further observation suggests there may be an apparent decrease in scatter as the volume of the cavity increases. This is probably the tendency of the uncertainty to arise from occasional problems in metering of the raw water, and to average out as the total amount of raw water accumulates. In other words, as the amount of raw water used increases, random directional uncertainties in metering will average over time. Even the effect of the loss of metering during a small time interval will diminish as the raw water volume accumulates. However, the observation that is the most apparent is the difference between the results of different operators. In terms of the perfect relationship concept, the slopes of the trend lines in Figure 1 can define the biases. The solution volumes are typically greater (average ***m'*** is +0.975) than the SW sonar volume data, but the solution volumes are less (average ***m'*** is +1.021) than the MG sonar volume data. The bias values are therefore +0.025 and -0.021, respectively.

In summary, the Big Hill results are enlightening because the caverns were fully solutioned prior to oil filling, and therefore the measurements of volume are relatively uncomplicated. It appears from the averages of Figure 2, that the sonar surveys of the two principal companies differ in a consistent manner. This bias in the averages are probably a true reflection of the differences in sonic velocities, techniques, or interpretation of the various operators. This is most probably a difference in the determination of the sonic velocity constant, although the exact cause is difficult to identify. The two trend lines in Figure 1 then both potentially reflect systematic errors in the techniques of the operators involved. As is evident, the reported data group very well around the respective trend lines for the two contractors, as shown in Figure 1. Error bars of 3% are shown on the SW*** calculated solution volume data and error bars of 2% error bars are shown in the sonar volumes. These error bars indicate this error range would bring all of the their data onto the trend line. Normally, cavern engineers quote an accepted error for the calculated solution volume that is somewhat greater than the one observed here, perhaps on the order of 5%. Again, the fact that all of the caverns were constructed to the same calculated solution volume accounts for the rather unusual vertical distribution of data points. Nevertheless, these points still exhibit the same uncertainty in the solution volume. Error bars of 2% in the sonar volumes is certainly within the +/-5% value typically quoted intuitively by the operators. The equivalent error bars are not shown on the MG data, but, would bring the data into better agreement with the trend line.

It appears that these uncertainties in solutioning and sonar volumes would be adequate to reduce the reported SW*** data, and most of the MG data, to the trend lines in Figure 1. The scatter or uncertainties about the two different trend lines are similar. However, as would be expected, somewhat greater uncertainties are associated with smaller accumulated volumes of the MG data. As noted previously, the progressive effect of the water accumulation during construction would be to minimize the scatter due to estimates and meter outages.

Although all of the sonar volume data are probably adequate, one would expect that the solution volume should always be slightly greater than the sonar volumes. This is the result of the preference of the return signal to be weighted by the closest reflecting surface, giving a somewhat smaller radius on the average. However, only the SW*** data support this expectation.

4.1.2 Equivalent Sonar Volumes and Oil Inventories

Another set of measurements that are of importance are the oil volumes, which are the inventories reported for the individual caverns. However, the history of the reported oil volumes is rather difficult to follow because, as noted previously, the custody transfer meters measure only the oil delivered to the site boundary. Individual cavern oil meters, which are less accurate and may be

of a different gage type than the custody transfer meters, are used when the incoming oil to the site is placed into the individual caverns within the site boundaries. Often the delivery of oil to the individual caverns is split-streamed at the manifold so that there is no correspondence between the custody transfer and the individual cavern meters. Under these circumstances, only the total oil in the caverns involved in the split-streamed distributed quantities could necessarily be compared to the custody transfer amount. Transfer of oil between caverns of a site also occurs but only through the individual cavern meters.

Oil inventory of a cavern is essentially the sum over the cavern history of all oil emplacement from offsite and all internal site transfers of oil between the cavern and other caverns. The sweet and sour crude types should be separated because split-streaming, if it occurred, would take place only within a given type of crude oil. In addition to the uncertainties from split-streaming, there is another potential problem caused by a possible adjustment of oil/brine interface depths. The interface depth determines how much of the volume is taken up by oil. In general, the interface depths are known to within a few (2 to 8) feet, which is equivalent to an uncertainty within 10,000 to 40,000 barrels. This uncertainty is small (0.08 - 0.3%) compared to the total 12 MMb of a typical cavern inventory, but must increase as the inventory in the cavern decreases. It is possible to obtain a comparison of the current inventory and the related sonar cavern volume. In making this comparison it is necessary to assure the sonar volume is unchanged between the time of the sonar survey and of oil emplacement. Subsequent oil movement involving injection of raw water will make earlier sonar surveys invalid. Some data are available for metered oil volumes and the equivalent sonar volumes obtained by truncating the survey at the oil/brine interface depth. A tabulation of these inventory and equivalent sonar volumes is given in Table II.

Table II. Equivalent Sonar Volumes in Brine and Oil Inventories (10/99), Big Hill.

Cav.No.	Oil Inv. (MMb)	Sonar Vol. (MMb)	Sonar Discrep. (MMb)	% Diff.	Remarks[#]
Sweet Caverns					
BH101	2.776700	2.721000	-0.055700	-2.01	
BH102	6.566500	6.649700	+0.083200	+1.27	
BH103	0.306700				Brine Filled
BH104	0.142100				Brine Filled
BH105	9.006500	9.172000	+0.165500	+1.84	
			Vol. Ave.	+1.04	
Sour Caverns					
BH106	9.749200	9.214000	-0.535200	-5.49	
BH107	5.999700	6.145481	+0.145800	+2.43	
BH108	8.865600	9.147372	+0.181800	+2.05	
BH109	8.731100	8.752635	+0.021500	+0.25	
BH110	4.698500	4.531400	-0.167100	-3.56	
BH111	9.006000	8.929000	-0.077000	-0.86	
BH112	7.793100				No Sonar
BH113	8.235200	8.111700	-0.123500	-1.50	
BH114	0.154700				Brine Filled
			Vol. Ave.	-1.01	

[#]Data from Osborne [1999].

In Figure 3, the data for Big Hill are plotted, with the equivalent sonar volume truncated at the depth of the oil. The sonar volumes are from sonar surveys in brine prior to oil emplacement. The error bars are for the assumed +/- 0.25% of the custody transfer meters and the previously deduced +/- 2.0% for the sonar survey. In this graph, only 10 of the 14 caverns are presented, the remainder either are brine filled (BH103, BH104, and BH114) or do not have the necessary sonar data available (BH112). Also shown on Figure 3 is the perfect proportionality relationship line with a slope of one. These caverns are essentially within the stated uncertainty of the perfect

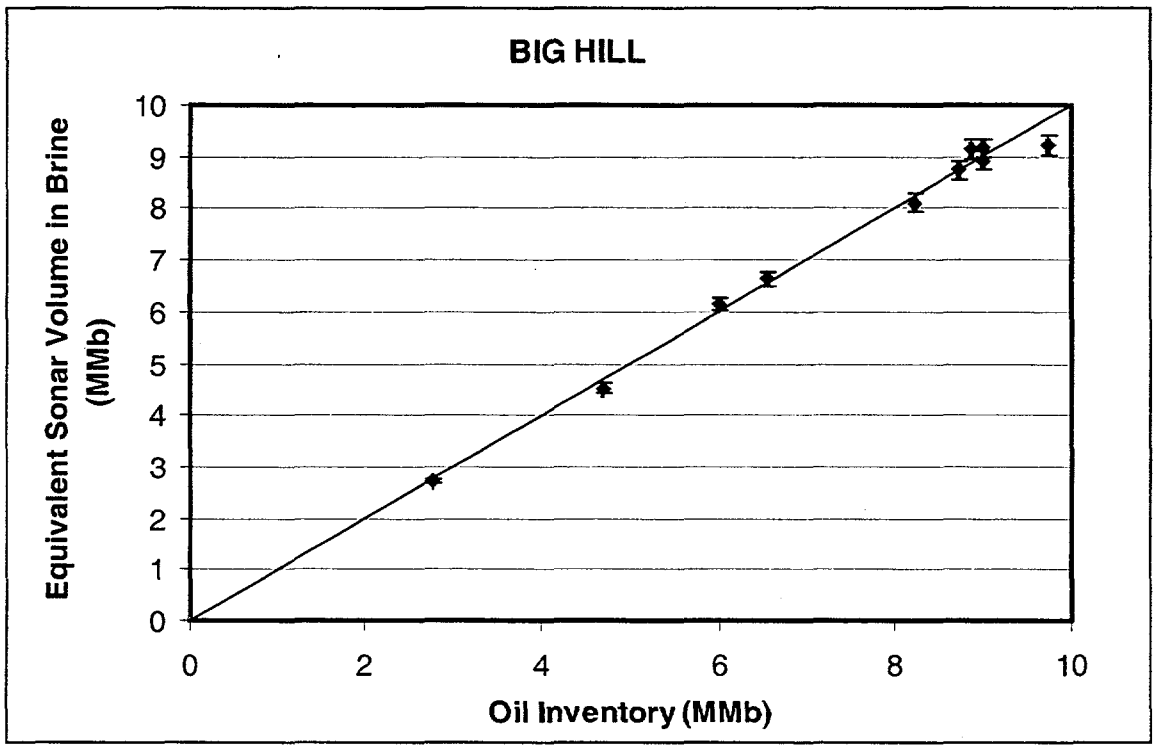

Figure 3. Equivalent Sonar Volume in Brine vs. Oil Inventory, Big Hill.

relationship trend line, except for cavern BH106, which shows significant deviation from the perfect relationship line. Although it appears possible that some error has occurred in determining the equivalent sonar, perhaps because of an error in the oil/brine interface location, the exact cause of the discrepancy is unknown. As noted later, deviations of the magnitude, and direction of BH106, are unusual in comparisons of equivalent volumes to oil inventories.

Clearly, the sonar volumes determined from surveys in brine and the depth of the oil/brine interface are in general agreement with the oil inventories determined through the metering of oil into the cavern. The error bars imposed on the data of Figure 3 are +/-2% for the sonar volume and +/-0.25% for the oil inventories (again assuming the error of the custody transfer meter). Errors of +/-0.25% on the oil inventory are within the data point and therefore unseen. This means that the deduced +/-2% uncertainty in sonar volumes explains the general discrepancy, except for the very large uncertainty for cavern BH106. On the average the volume discrepancy between the sonar volumes and the inventory is –0.49% (value is +0.03% when BH106 is excluded), which indicates the sonar volumes are very slightly greater than the oil inventories. However, it is really difficult to assign any significance to this small discrepancy. Interestingly, it seems that the cavern meters must be very consistent with the custody transfer meter uncertainty.

There are some very limited data that permit a comparison between the sonar volumes taken through the crude oil and measured oil volumes. These data are given in Table III. The results of three of these comparisons are shown in Figure 4. Clearly, these data give the most direct indication of the accuracy of the sonar surveys, because the accepted custody transfer meter uncertainty is only +/-0.25%, essentially undetectable on these plots. It is believed that the measured oil volumes were all determined using an oil custody transfer meter. However, this belief is based on very limited evidence. The more normal situation would be that the inventory data was determined by the individual cavern meters. If the measurements were by custody transfer meter, then as a consequence, all of the uncertainty can be assigned to the sonar

Table III. Special Sonar Survey Volumes in Oil and Oil Inventories, Big Hill.

Cav.No.	Co.* (Oper.)	Date	Sol.Vol. (MMb)	Ratio	Sonar Vol. (MMb)	Oil Vol. (MMb)	Remarks#
BH102A							
Son/Oil	SW(M)	12/93			04.465s		
					04.763so		s/so 0.937
Oil/Mea	SW(M)	12/93			06.327so		
						06.393o	so/o 0.990
BH105A							
Oil/Mea	SW(M)	03/99			09.186so		
						09.007o	so/o 1.019
					03.729s		
		06/99				09.007o	12.914261 sum
BH108A							
Oil/Mea	SW(M)	03/99			8.953so		
						08.865o	so/o 1.010
					02.409s		
		06/99				08.865o	11.362393 sum

The following indicators are used, so is sonar in oil, s is sonar in brine, and o is oil meter measurement. The sum indicates the sum of the sonar and oil volumes. No solution volumes could be determined for these dates.

* All of these sonar surveys were by Sonarwire, where the technician was McCool (the younger).

determination. The line shown is a perfect correlation line, where the proportionality relationship is one. In order of increasing measured oil volume, the discrepancies between the ratio of the sonar to the measured oil volumes are –1%, +1% and +2%, respectively. This implies a +/-2% uncertainty in the sonar volumes, with the average indicating the sonar volumes are slightly greater than the measured oil volumes. The reason for the sonar volumes exceeding, on the average, the measured oil volumes is not really apparent at this time. From earlier arguments, the sonar volume would more logically be smaller than the associated inventory. However, the significant result of the comparison is that the sonar volume appears representative of the measured oil volume. This certainly supports a measure of confidence in the sonar results.

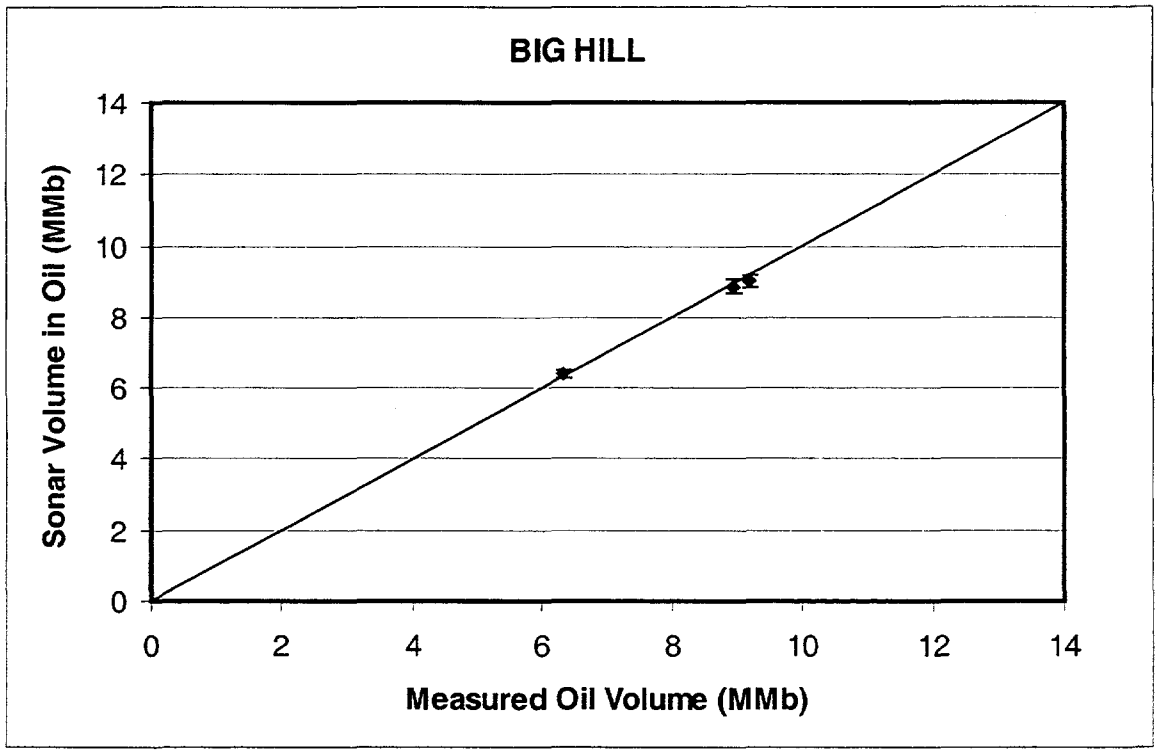

Figure 4. Equivalent Sonar Volume in Oil vs. Oil Inventory, Big Hill.

4.1.3 Summary Remarks for Big Hill

In summary, there are three independent methods of determining cavern volume. These are (1) the solution volume calculated from the raw water input and chemistry and the brine output chemistry, (2) the calculated volume from sonar determined cavern radii, and (3) the volume of metered oil input to the cavern and the oil/brine interface depth. The comparison begins with measures of the first two of these methods, where extensive data exist.

It appears that the solution volumes have the greatest uncertainty, perhaps as a result of the lack of consistency in the metering of the raw water input. In addition, the criticality of these raw water inputs was not considered high, so with loss of a gage for short intervals, the input was estimated. However, because the net effect of these inconsistencies diminishes as the total accumulation of raw water increases during solutioning, the scatter at the final cavern volumes may be reduced (these are the SW*** data of Figures 1 and 2). At the maximum cavern volumes, the effective error appears to be about +/- 3% for the solutioning volumes, although the maximum scatter is greater, on the order of +/- 7%.

The comparison of the sonar volumes where the sonar survey was taken through the brine and the known oil inventory of the cavern also produced quite reasonable correlation. The deduced uncertainty on the sonar results is an effective +/- 2%, which seems to encompass the plotted results (Figure 3). Because the uncertainty guaranteed by the custody transfer meter is no more than +/- 0.25%, essentially zero, most of the deviation can be assigned to the sonar error. Even when this is done, it appears that the sonar volumes cluster nicely around the perfect correlation line. Only BH106 has what could be considered a significant deviation, the cause of the deviation however is unknown.

There are a few sonar surveys taken through the oil that can be compared directly to the metered volume of oil (Figure 4). The oil volumes are believed to be metered with custody transfer meters. Thus, if the data scatter is +/- 2%, this must be all attributed to be the uncertainty in the sonar measurements. These results are especially relevant because they provide a nearly direct validation of the sonar method and an independent check on the metered volume.

It should be remembered that the oil inventories, if they are obtained from measurements through the custody transfer meters, are certainly the most accurate. Of course, the custody transfer quantities are the definitive values. All of the other volumes as derived from solutioning measurements, sonar survey measurements, and individual cavern oil volume meters are secondary. With this in mind, the examination of the Big Hill caverns has proven quite enlightening, principally because of the rather close correlation observed between the various measures of cavern volume. Perhaps the most significant finding was from comparison of these measurement results to the perfect correlation relationship. Discrepancies from this relationship calls attention to questionable results and, even more importantly, suggest a distinction between bias and scatter.

4.2 West Hackberry (WH)

In contrast to the Big Hill data analyzed above, the West Hackberry volume data constitutes a much more complex situation. These caverns were constructed at an earlier date than the Big Hill caverns and the demands of that time required that the oil filling and solutioning be carried out simultaneously. As previously noted, concurrent filling and solutioning could cause some difficulty in interpretation of volumes. The SPR constructed caverns at West Hackberry include 16 Phase II single well caverns and one Phase III two well cavern (WH117).

4.2.1 Solution Volumes and Sonar Volumes

Even though the cavern construction situation is more complicated, the data can be separated into reasonably distinct categories, uncombined and combined data. As a result, true comparisons between the calculated solution volumes and the uncombined sonar volumes are available for the early stages of solutioning. Thereafter, the sonar volumes, at least when these caverns were surveyed in the later stages of construction, were restricted to just the volume in the brine. Furthermore, it is not always possible to identify the additional solutioning volume, which would correspond to the sonar volume. Consequently, for the late development stages in the West Hackberry caverns, the only sonar volumes that can be obtained are the combined volumes, where the amount of oil is relatively large. As noted previously, the combined volume is a sum of the sonar volume in brine and the metered volume of oil in the cavern. Thus, the uncertainty comparisons in the reported cavern volumes are compromised by the volumes involved being significant fractions of the total volume and by the uncertainty in the location of the interface. In general, one would expect the apparent uncertainty in combined data to decrease compared to uncombined data. On the other hand, because solution volumes depend only on the input raw water and extracted brine, calculated solution volumes are unaffected by the simultaneous filling.

Tabulated values of the various volume determinations for West Hackberry are given in Table IV. Most of these data are for early cavern development states when the total volumes are small but the sonar quantities are still uncombined. Only two uncombined values are for caverns at the final development volumes. The calculated solution volumes are compared to the sonar volumes in Figure 5. There are four different sonar companies involved in these surveys: the diamonds are from Dowell (DW) and associated companies (Dowell-Schlumberger (DS) and Sonar and Well

Table IV. Calculated Solution, Sonar, and Oil Volumes, West Hackberry

Cav.No.	Co.* (Oper.)	Date	Sol.Vol. (MMb)	Ratio (w/(s+o))	Sonar Vol. (MMb)	Oil Vol. (MMb)	Remarks
WH101	DW(S)	07/83	09.951w	1.075mix	04.981s	04.277o	08.50%insol. **
	DW(V)	07/82	05.183w	1.049	04.940s		
	DW(W)	12/81	02.317w	1.140	02.033s		
WH102	DW(S)	08/83	05.926w	0.982	06.032s		10.33%insol.
	DW(V)	11/82	03.066w	0.978	03.134s		
WH103	DW(T)	03/84	11.041w	1.011mix	03.755s	07.164o	10.78%insol. **
	DW(W)	07/83	09.133w	1.067mix	04.574s	03.986o	09.35%insol. **
	DW(W)	08/82	05.563w	1.172	04.747s		
	DW(T)	01/82	02.537w	1.046	02.425s		
WH104	DW(S)	04/84	11.464w	1.005mix	03.228s	07.644o	08.99%insol. **
	DW(S)	08/83	09.888w	1.125mix	04.742s	04.044o	06.19%insol. **
	DW(T)	09/82	05.782w	1.144	05.054s		
WH105	SW(U)	05/86	11.377w	1.005mix	01.374s	09.949o	?? **
	DW(F)	04/84	11.265w	1.048mix	04.249s	06.505o	03.24%insol. **
	DW(W)	08/83	09.087w	1.013mix	04.107s	04.865o	05.73%insol. **
	DW(W)	10/82	04.891w	0.858	05.766s		
	DW(W)	02/82	02.261w	0.905	02.498s		
WH106	DW(S)	10/84	01.456w	0.886	01.644s		
	DW(T)	10/83					?
WH107	DW(W)	05/83	06.761w	1.056	06.373s		09.74%insol.
	DW(W)	09/82	03.764w	1.089	03.457s		
WH108	DW(S)	01/84	08.230w	1.045mix	05.140s	02.734o	08.53%insol.
	DW(S)	05/83	05.769w	1.116	05.171s		06.59%insol.
	DW(T)	11/82	02.796w	1.083	02.581s		
WH109	SW(M)	03/97	11.988w	1.022mix	05.592s	06.141o	?? **
	DW(V)	05/85	02.806w	0.956	02.936s		
WH110	DW(F)	02/83	02.901w	1.200	02.418s		
WH111	SC(F)	10/88	10.565w	1.099	09.615s		05.39%insol.
	SC(S)	07/86	04.137w	1.049	03.950s		Duplicate
	SC(F)	01/86	04.137w	1.047	03.950s		Duplicate
	DS(S)	12/84	04.137w	1.053	03.934s		06.88%insol.
	DS(S)	08/84	02.8122w	1.157	02.430s		
WH112	SW(U)	10/87	11.4351w	1.068mix	00.834s	09.868o	06.46%insol.
	SC(V)	06/85	06.619w	1.010	06.556s		09.35%insol.
	DS(V)	12/84	03.054w	1.025	02.980s		
WH113	MG(C)	07/89	11.826w	1.033mix	05.649s	05.790o	07.70%insol.
	DW(W)	02/84	05.764w	1.040	05.542s		
WH114	SW(U)	02/87	11.223w	1.018mix	01.527s	09.175o	06.39%insol.
	DW(S)	09.84	06.551w	1.004	06.523s		
WH115	SC(S)	10/85	07.098w	1.009	07.038s		06.34%insol.
	SC(F)	02/85	02.689w	1.051	02.557s		
	SL(H)	02/85	02.689w	1.038	02.591s		Duplicate
WH116	SW(U)	04/86	11.276w	0.958mix	04.340s	07.432o	?? **
	DS(S)	11/84	06.683w	1.043	06.403s		04.61%insol.
	DS(T)	08/84	05.785w	1.017	05.224s		04.14%insol.

Table IV (Cont.). Calculated Solution, Sonar, and Oil Volumes, West Hackberry.

Cav.No.	Co.* (Oper.)	Date	Sol.Vol. (MMb)	Ratio (w/(s+o))	Sonar Vol. (MMb)	Oil Vol. (MMb)	Remarks
	DS(T)	06/83	02.802w	1.102	02.542s		
WH117	MG(C)	02/89	12.313w	0.907	13.582s		07.71%insol.
	SW(U)	01/88	06.373w	1.031	06.179s		05.00%insol.
	SW(U)	08/87	04.224w	1.028	04.110s		
	SW(U)	10/86	02.881w	1.155	02.494s		
	SC(F)	10/85	00.321w	1.069	00.300s		

* Companies are: MG = MicroGage (a Boeing Company), DW = Dowell, DS = Dowell Schlumberger, SC = Sonar and Well Testing Services, Inc. (forerunner of DW), SW = Sonarwire, SL = Sonar Logging Company.
Technicians are: U = Unknown Operator (operator is probably the elder McCool), B = Broussard, C = Childress, F = Free, H = Holland, M = McCool (younger).

** Mixed (combined) volumes where the oil (o) makes up a considerable fraction of the total volume, so that the solution (w) /sonar (s) volume ratio is compromised.

Testing Services (SC)), the squares are from Sonarwire (SW), and the triangles are from either MicroGage (MG), a Boeing company for WH117, or Sonar Logging Company (SL) for WH115.

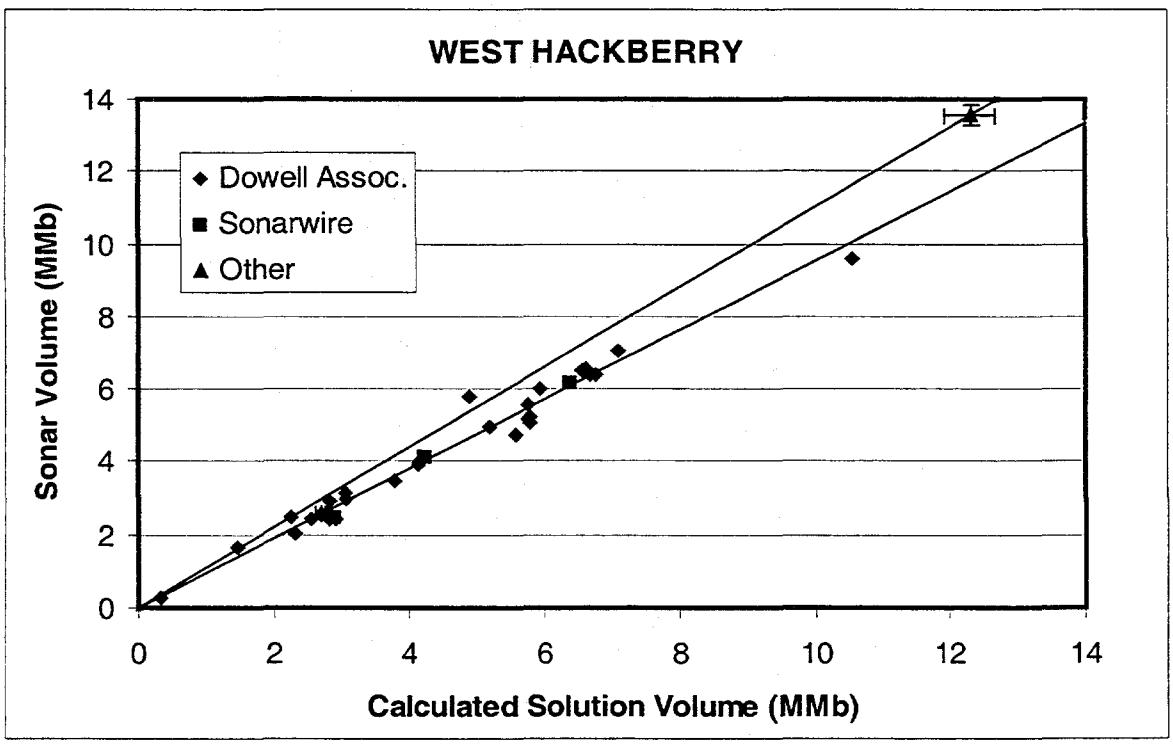

Figure 5. Solution Volume vs. Uncombined Sonar Volume, West Hackberry.

As shown, the trend line with the average slope (*m'*) of 0.95 determined for the DW (and associated companies), SW, and SL fits the data reasonably well. However, the 5% bias offset from the perfect relationship line is accompanied by significant scatter. It should be remembered that these results predated the Big Hill data. At this stage of the development of the sonar technique, the sonar results were undoubtedly obtained with far fewer survey stations and azimuth settings, resulting in greater uncertainty. The transducers may have been somewhat less developed, as perhaps were the sonic velocity measurement procedures. The sole MicroGage result (the large volume "Other" point) for WH 117 would suggest a trend line with a slope (*m'*) of 1.10, an offset in the opposite direction from the other results. Although these different offsets may represent true differences in the techniques and velocity factors of the sonar surveys involved, the single datum nevertheless could still be within the actual scatter range experienced by the other data. However, deduced errors of +/-3% in solution volume and +/-2% in the sonar volume, as shown on the MG data point would suggest that this datum is quite an exception. As the trend lines indicate, it is possible the data of the different operators are in fact biased. The bias direction of the MG and SW data appear to be opposite. This of course is the same as the previously presented Big Hill data where the MG and the SW data had biases of opposite sign.

When the deviation of the calculated solution volumes from the sonar volumes are plotted for West Hackberry, the offset is clear, as is the scatter. These results are given in Figure 6. The offset essentially confirms the bias of one of the trend lines as given previously, about 5%. It appears that the scatter range is +/-20%. Again, the sole result from MicroGage stands out, but not as significantly as might be supposed. On the one hand, certainly, the MicroGage datum is contained within the scatter band of the remaining data. On the other hand, as already suggested, the datum may be biased, with the sole MicroGage result having a significantly different bias, or trend line.

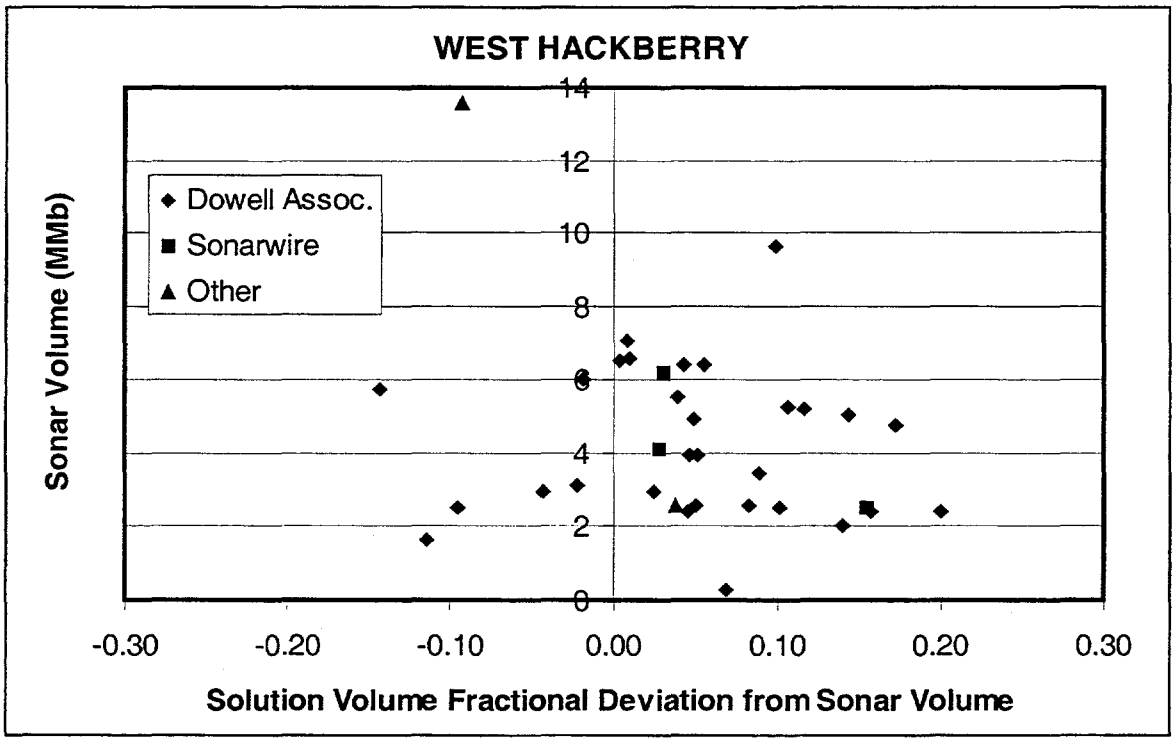

Figure 6. Solution Volume Deviation from Uncombined Sonar Volume, West Hackberry.

To this point, the primarily concentration has been on the potential differences in the various operators (actually techniques and systems) performing the sonar surveys. However, it is necessary to recognize the potential for uncertainty in the solution volumes. In fact, most often the discrepancy between calculated solution volumes and the sonar survey volumes has been typically assigned by the operators to the difficulty in defining the raw water input quantities. These notations at the time were perhaps somewhat subjective, rather than objective. Certainly, because of lack of clear separation between different surveys, it is possible to argue that the sonar results for the most part are supportive of each other, with a few exceptions. This might suggest that the most significant contribution to scatter is really the uncertainty in the calculated solution volumes. However, it is difficult to know the basis for such a conclusion because of the apparent bias of the comparisons. Upon examination of the governing equations, bias in the solutioning equation can come only from well known or independently determined constants within the equations. Moreover, there would be little, if any, reason to alter these constants during the course of the SPR Program cavern development. Opposed to this, the sonar transit time equation contains a velocity that must be determined during each application of the sonar technique. No independent checks under actual cavern conditions are possible. Based on this logic, one would suspect that the reason for the bias is to be found in the sonar technology. The scatter however is equally likely from either the solutioning or sonar technology.

The combined volume results are given in Figure 7. By their nature, these results are all limited to the volumes near the completion of construction of the caverns. The apparent scatter is clearly diminished from the uncombined results shown previously, as already indicated. There are only two survey companies represented in the data, the diamonds are Dowell (DW) and the squares are Sonarwire (SW). One could argue that the single trend line as drawn is appropriate for the data of either operator. This suggests that the Dowell and Sonarwire data are biased offset with a slope

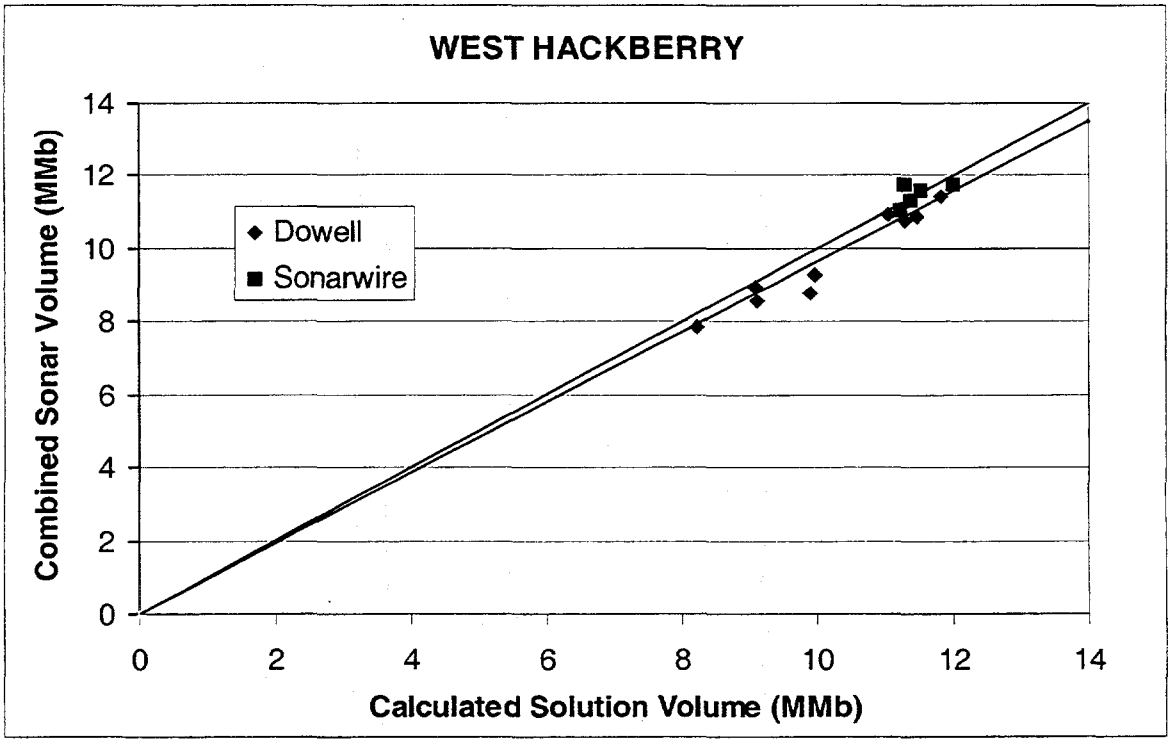

Figure 7. Solution Volume vs. Combined Sonar Volume, West Hackberry.

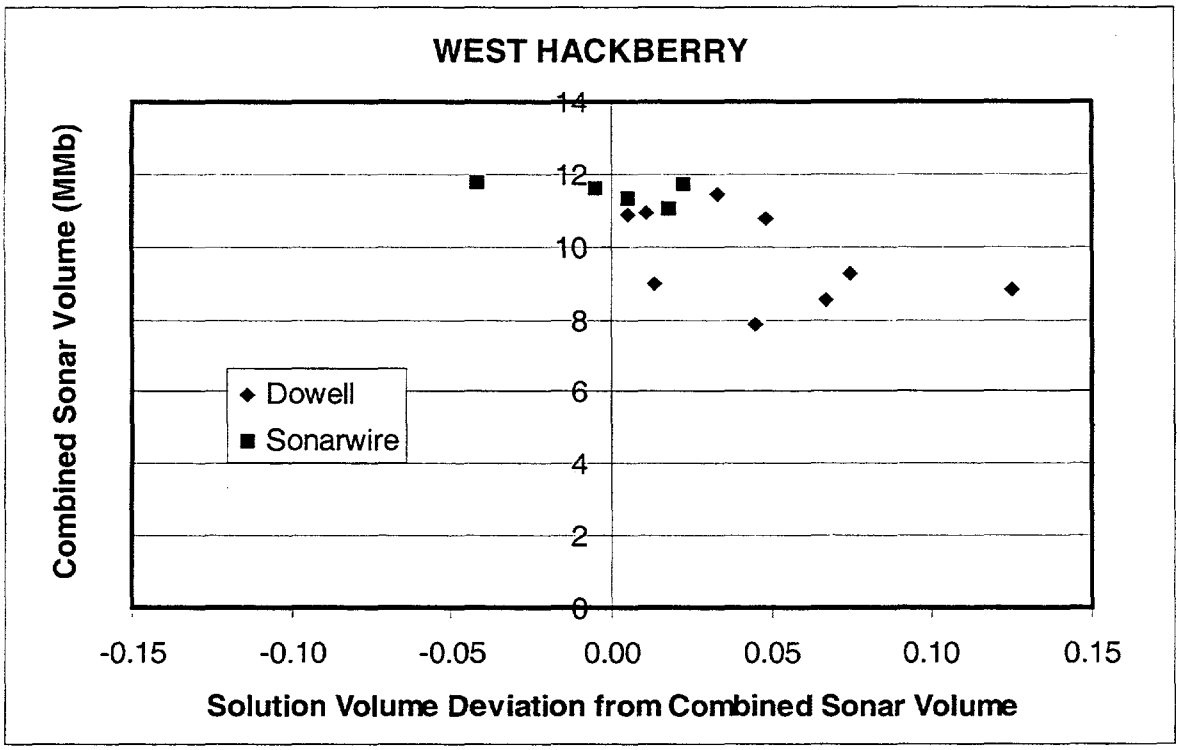

Figure 8. Solution Volume Deviation from Combined Sonar Volume, West Hackberry.

(*m'*) of 0.96, somewhat less than the 5% for the uncombined data presented in Figure 5. On the other hand, the Sonarwire results conform well to the perfect relationship line, or to a trend line with a slope of one, which is also shown on Figure 7.

The West Hackberry data presented above (Figures 5 and 7) are very consistent with the Big Hill results presented earlier (Figure 1). Even though it was initially thought that the concurrent filling of the caverns during construction would compromise the information, apparently the compromise, if any, was actually insignificant. The scatter and biases of calculated solution volume and sonar survey volume data from the two sites was comparable. By their nature, one would expect the combining of two volumes, one with more uncertainty (sonar) and one with less uncertainty (metered oil) that the overall uncertainty would be reduced. As a consequence, even though they are very consistent with the uncombined data, these results must be used with some reservation.

4.2.2 Equivalent Sonar Volumes and Oil Inventories

There is also a reasonable collection of oil inventories and equivalent sonar volumes reported for West Hackberry. These are give in Table V. As is apparent, all of the caverns of the site are represented. But as in the earlier discussions only the SPR constructed caverns will be compared because of the well documented history of these caverns.

However, these data must be examined very carefully because it is apparent that the equivalent volumes of many of the caverns are questionable. It is unlikely that the equivalent volumes would ever so systematically match exactly, to the barrel, the volume of the inventory. It would certainly be the best of situations if this were true. However, because of the questionable aspects of the data, even those data that are not identical perhaps could be questioned.

Table V. Equivalent Sonar Volumes in Brine and Oil Inventories (10/99), West Hackberry.

Cav.No.	Oil Inv. (MMb)	Sonar Vol. (MMb)	Sonar Discrep. (MMb)	% Diff.	Remarks
Sweet Caverns					
WH7	12.137444	12.137444	+00.000000	+0.00	Questionable #
WH101	09.651241	09.651241	+00.000000	+0.00	Questionable #
WH102*	09.671898	09.655389	-00.016509	-0.17	
WH104	09.929362	09.929362	+00.000000	+0.00	Questionable #
WH105	10.098319	10.098319	+00.000000	+0.00	Questionable
WH107*	10.535390	10.550560	+00.015170	+0.14	
WH108	09.128025	09.128025	+00.000000	+0.00	Questionable #
WH110	10.146629	10.146629	+00.000000	+0.00	Questionable #
WH113*	04.515762	04.447462	-00.066300	-1.49	
WH116	09.462087	09.462067	-00.000020	+0.00	Questionable #
			Vol. Ave.	-0.07	(-0.27% for 3)
Sour Caverns					
WH6	06.724143	06.881802	+00.157659	+2.35	
WH8	09.619514	09.725219	+00.105705	+1.10	
WH9	08.931352	08.955135	+00.023783	+0.27	
WH11	07.992363	08.064117	+00.071754	+0.89	
WH106	09.141028	09.140280	+00.000748	+0.01	Questionable #
WH109*	06.092619	06.051069	-00.041550	-0.67	
WH111*	08.164205	08.177244	+00.013039	+0.16	
WH112	07.638313	07.638313	+00.000000	+0.00	Questionable #
WH114*	08.493561	08.497777	+00.004216	+0.05	
WH115*	06.786631	06.764332	-00.022299	-0.33	
WH117*	09.851468	09.826111	-00.025357	-0.26	
			Vol. Ave.	+0.32	(+0.39 for 11)

Data from Project Oil Inventory Summaries. An exact equivalence to the barrel is very unlikely, so these data are considered questionable. Questionable data are not plotted.

* These data are used to determine the average value of difference shown in Remarks column.

For the purposes here, it is assumed that those data pairs which are identical are not actual data, but merely an unintentional duplication where the actual sonar survey volume data could not be obtained. The data pairs that are not identical are assumed to be actual data and correct. Only those data that appear to be actual data will be discussed and used. In Table V, the discrepancies in the sonar values are quite small, except for the converted commercial caverns, which can be more than 1%. If the volume average discrepancy of the caverns that are not questionable is taken, the average discrepancy for the both the sweet and sour crude caverns is less than 1%, with the facility volume average of only 0.22%. This average discrepancy is very acceptable. Again using only data from SPR constructed caverns, these data are plotted in Figure 9. Here, the diamonds are sweet crude and squares are the sour crude. The line on the figure is the perfect correlation line and not a trend line. Obviously there is excellent agreement with the perfect correlation line, as shown. The scatter is much less than 1% for these West Hackberry results.

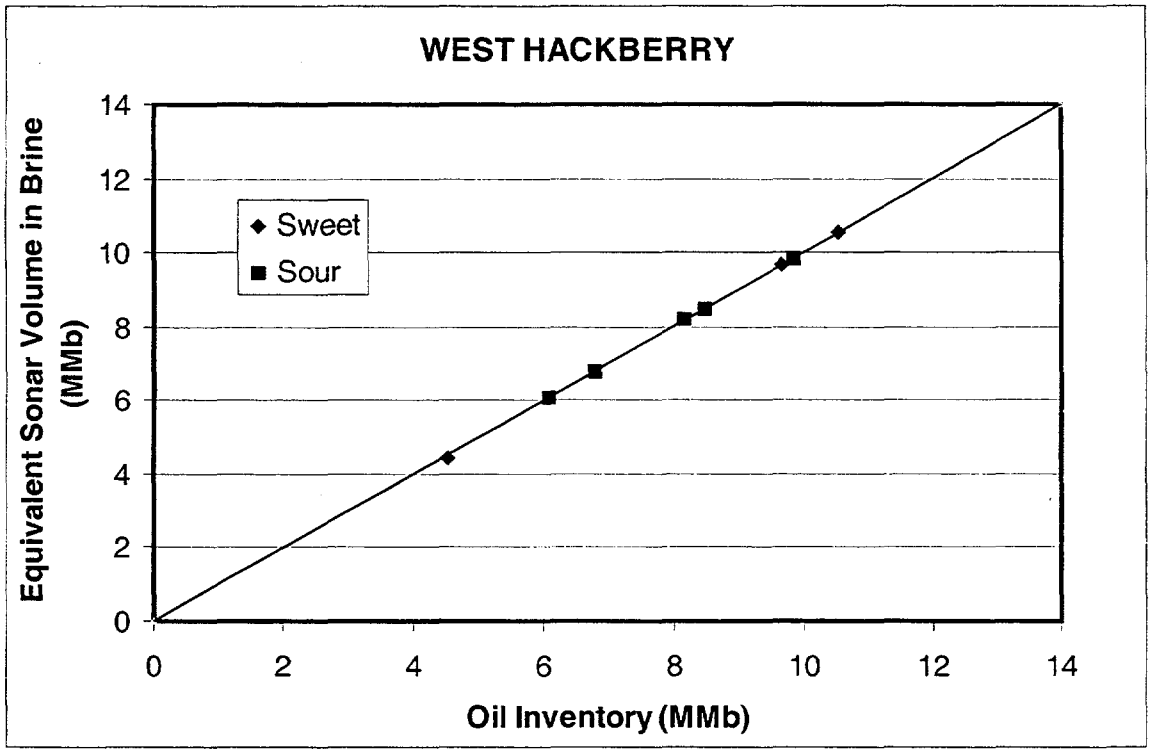

Figure 9. Equivalent Sonar Volume in Brine vs. Oil Inventory, West Hackberry.

As noted previously, the West Hackberry sonar surveys were chronologically much earlier than the Big Hill surveys. This is important because at the time of the West Hackberry surveys the detail in these early surveys was much less, in general, because there was greater spacing between stations and fewer azimuth angles surveyed. Although there is no specific notes in the SPR sonar survey records, it is likely that the transducers and detection systems were also less sophisticated at that time. Both the detail and the older technology may have caused the surveys to have less accuracy. Even with these potential problems, the results where the equivalent sonar volumes can be compared to the oil inventories are to be considered exceptional. These results (Figure 9) from West Hackberry are even in somewhat better agreement than those presented previously for Big Hill (Figure 3).

4.2.3 Sonar Volumes in Oil and Oil Inventories

In the more recent years, where improvements in technology have permitted sonar surveys through oil, initial attempts to survey caverns through oil were made. As noted, some of these were as early as 1986, although most were taken in 1997. Data of this type still are still quite limited. Only two surveys through oil have been made for the West Hackberry caverns (WH105 and WH116). Table VI tabulates these data for West Hackberry. As is detailed in Table IV, the discrepancy in WH117 is nearly 12%, while the discrepancy in WH105 is a more acceptable 4%.

The two data points are plotted in Figure 10. As is apparent, the agreement to the perfect relationship line is not that good. Although it is difficult to know the technical details, it is probable that these initial attempts were still somewhat limited by the techniques. Consequently, the correlation between the sonar volumes as determined through oil and the metered oil inventories are less than hoped for. When these results (Figure 10) are compared to similar data

Table VI. Equivalent Sonar Volumes in Brine and in Oil and Oil Inventories, West Hackberry.

Cav.No.	Co.* (Oper.)	Date	Sol.Vol. (MMb)	Ratio (w/(s+o))	Sonar Vol. (MMb)	Oil Vol. (MMb)	Remarks#
WH105 Oil/Mea	SW(U)	05/86	11.377363w	1.005mix	01.374451s 10.299700so	09.949386o	so/o 1.035
WH109	SW(M)	03/97	11.987278w	1.022mix	05.592140s 06.140606so	?	
WH114	SW(M)	05/97			09.162772so		
WH116 Oil/Mea	SW(U)	04/86	11.276217w	1.035mix	03.457000s 08.315000so	07.431818o	so/o 1.119

* All of these sonar surveys were by Sonarwire, where the technician was either McCool (U = the elder) or McCool (M = the younger).

The following indicators are used, so is sonar in oil, s is sonar in brine, and o is oil meter measurement.

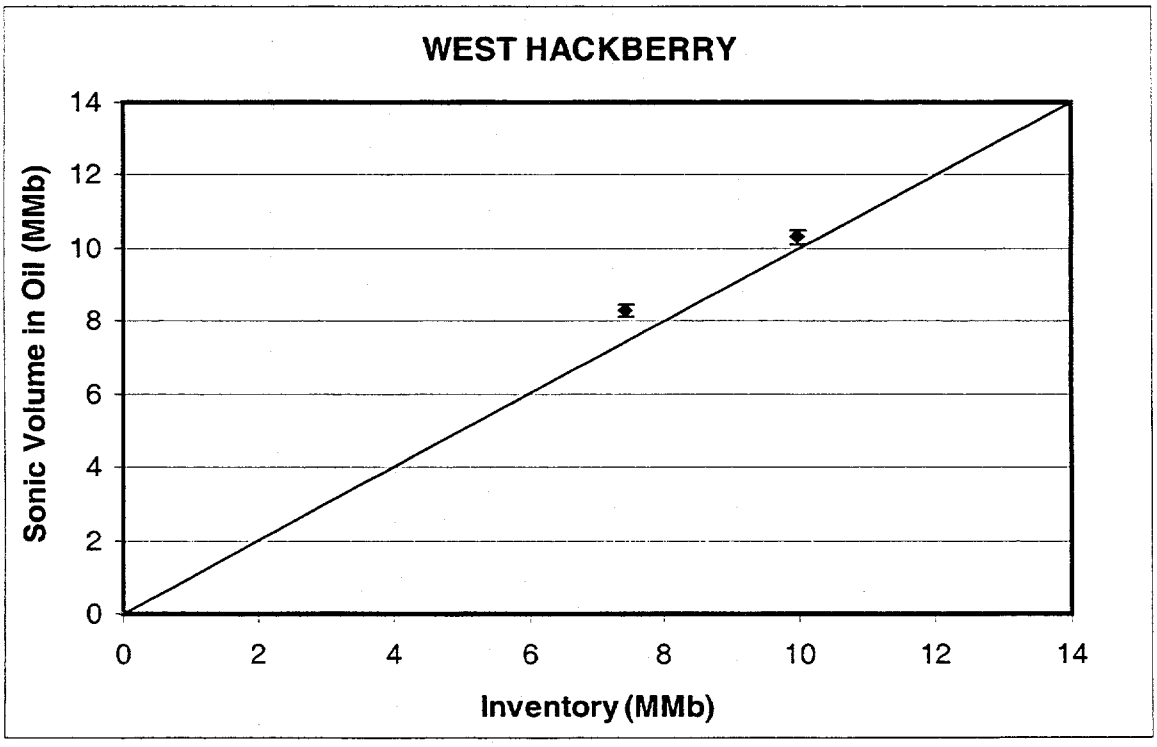

Figure 10. Equivalent Sonar Volume in Oil vs. Oil Inventory, West Hackberry.

from Big Hill (Figure 4), it is apparent that the Big Hill correlation is superior. In contrast, the West Hackberry data show considerable discrepancy from the perfect fit line. The discrepancy is such that the sonar survey volumes, where the greatest uncertainty would be expected, apparently overestimate the oil inventory volume. The deduced uncertainty of +/-2% is shown by the error bars on the data in the graph. If it is assumed that the oil inventories were measured by custody transfer meters, the +/-0.25% error bars would be contained within the data points. However, it may be more likely that the individual cavern inventories were obtained from individual cavern meters at the site. Moreover, it is likely that some split-streaming occurred. Because of the questionable data for some caverns, at this point, there is no way to determine how the mean discrepancy of caverns for the two caverns relates to the total facility oil inventory and sonar volume.

In general, uncertainty levels of the West Hackberry sonar data in oil are large, with 12% being unreasonable. Moreover, there appears to be no explanation for the discrepancies observed.

4.2.4 Summary Remarks for West Hackberry

Considering that the West Hackberry cavern construction and sonar surveys were relatively early in the history of the SPR, the agreement between the calculated solutioning volumes and the sonar results (Figure 5 and 7) reflect the discrepancies expected. Each of the different collections of results appear to have a bias, which is potentially due to uncertainties in the sonic velocities. Around these biases, the scatter is more acceptable. The results that are in closest agreement to the perfect correlation relationship are those from combined sonar volumes (Figure 7). While this may be the consequence of the inherent smaller uncertainty in the mixed volume, it may also be a consequence of an improvement of the sonar techniques, since these surveys were taken later in the project history. Actually, the West Hackberry results are very comparable to the Big Hill results. Interestingly, the magnitudes and direction of the biases for the different operators are the same in both West Hackberry and Big Hill databases.

For those comparisons of the oil inventories to the equivalent sonar volumes through brine, there is considerable question about correctness of the data. Much of the information cannot be real. However, when those data thought to be actual data are considered (Figure 9), the discrepancies are very acceptable.

Limited data are available for sonar volumes determined directly through the oil (Figure 10). Very large discrepancies were found, but the reason for the large discrepancies is not known. However, one could look to marked changes in technology, or the primitive state of these transducers, as a possible reason for the greater discrepancy in these results.

4.3 Bayou Choctaw (BC)

The SPR has only one purpose-constructed cavern at Bayou Choctaw, BC101. Actually, the SPR did construct another cavern, BC102, as a part of a trade deal to obtain some existing commercial caverns in this salt dome. Both of these caverns were constructed quite early in the project, about equivalent to the time of the West Hackberry caverns. These were both two well caverns.

Because of these two caverns were constructed according to SPR requirements, they are very consistent in geometry and construction with the caverns of Big Hill. All construction was completed on BC101 before it was filled with oil. BC102, of course, was never filled with oil prior to being traded. The other SPR caverns at Big Hill are former commercial caverns

purchased by the government. Even though Bayou Choctaw is now represented by only one cavern, and limited data from another, analysis is treated in the same manner as the other sites.

4.3.1 Solution Volumes and Sonar Volumes

As with the earlier presentations, the calculated solution volumes are compared to the sonar volumes determined through brine. Even though BC102 is not a SPR cavern, available results are also used here. Although only two caverns were involved, three different companies performed the sonar surveys: Dowell, MicroGage, and Sonarwire. The data from Bayou Choctaw are tabulated in Table VII. Dowell did the earliest of the surveys, while the other two operators overlapped in time. Perhaps even more interesting is that some of surveys involving Sonarwire and MicroGage were made in the same month and are duplicates, as shown in Table VII.

Calculated solution volume and sonar volume data for Bayou Choctaw are plotted in Figure 11 Here, the diamonds are Dowell (DW), the squares are Sonarwire (SW), and the triangles are MicroGage (MG) data. As seen in the figure, the trend line has a slope of 0.94, which represents the Sonarwire and the MicroGage data adequately. However, the Dowell data might suggest a much smaller slope. While the Bayou Choctaw data indicate a slightly greater uncertainty than the Big Hill data or the West Hackberry data, the uncertainty remains within acceptable limits. The error bars on the data points represent the assumed +/-3% in solution volume and +/-2% in sonar volume. It is not really surprising that the earlier survey results are the least accurate because the accumulated solution volumes in these early surveys are small. It may be also that the sonar techniques at this stage of the project were less refined.

Table VII. Calculated Solution, Sonar, and Oil Volumes, Bayou Choctaw.

Cav.No.	Co.* (Oper.)	Date	Sol.Vol. (MMb)	Ratio (w/(s+o))	Sonar Vol. (MMb)	Oil Vol. (MMb)	Remarks
BC101	SW(M)	07/95			08.430s	04.277o	
	SW(M)	03/93			07.704s	04.882o	
	SW(M)	01/90	11.409w	1.055	10.817s		**
	MG(C)	01/90	11.409w	1.075	10.616s		3.21%insol. **
	MG(B)	03/89	07.225w	1.003	07.205s		3.13%insol.
		09/88			04.296s		
	SW(U)	04/88	02.206w	1.083	02.036s		
	DW(V)	10/87	00.311w	1.200	00.260s		Duplicate (?)**
	DW(V)	10/87	00.311w	1.200	00.260s		Duplicate (?)**
BC102	SW(M)	10/84	06.053w	1.108	05.462s		
	DW(F)	09/83	02.754w	1.201	02.294s		

* Companies are: MG = Micro Gage (a Boeing Company), DW = Dowell (Sonar and Well Testing Services), SW = Sonarwire.
Technicians are: U = Unknown Operator is McCool (the elder), B = Broussard, C = Childress, F = Free, M = McCool (younger), V = Van Metre.

** Duplicate surveys. Results of different operators on 01/90 were within 2% of each other. The duplicates on 10/87 by the same operator are suspect however because the results are identical. Here w indicates solutioning, s indicates sonar, and o indicates oil volumes.

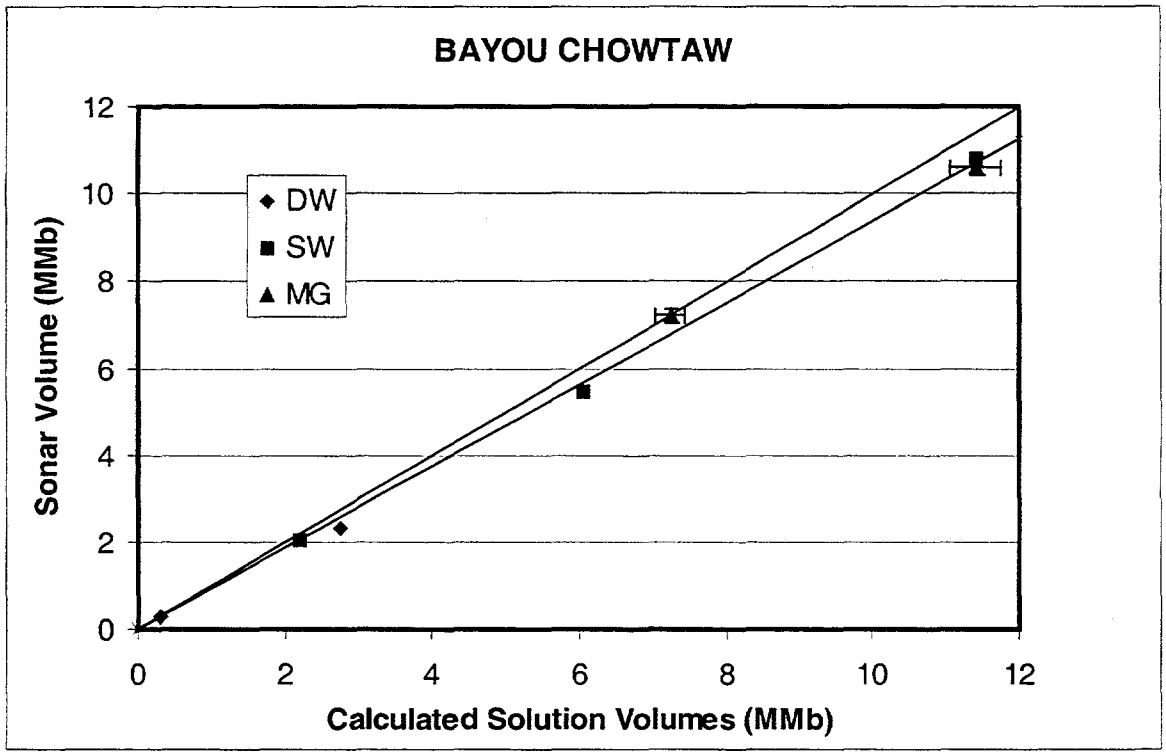

Figure 11. Solution Volume vs. Sonar Volume, Bayou Choctaw.

These Sonarwire and MicroGage, and perhaps Dowell, results all seem to have essentially the same bias, in the same direction, independent of operator. This differs from the previous results for Big Hill and West Hackberry where the MicroGage data apparently had a bias of a different sign, although of about the same magnitude, as the data from the other operators. One of the observations in interpretation these data is that the bias values are not consistent in magnitude. This is similar to the results found for Big Hill.

When the graph of the deviation of the calculated solution volume is compared to the sonar survey volume, perhaps a little more information becomes apparent. These results are shown in Figure 12, where three operators are involved: Dowell (DW) with diamond symbols, Sonarwire (SW) with the square symbols, and MicroGage (MG) with the triangle symbols. It is tempting to suggest that there are really two different biases applicable to these data. However, this must be tempered with a word of caution: clearly the range of scatter found in previous databases could easily cover the range of scatter shown in the figure. It should be also noted, that the DW data are for quite small total volumes. Nevertheless, it appears that the DW data form one bias group, while the SW and MG form another bias group. Again, this may just be fortuitous.

Two independent surveys were made in the same time frame by Sonarwire and MicroGage (01/90), when the cavern was at 10 MMb. The two sonar volumes were within 2% of each other. This seems to confirm that two operators can obtain similar results. However, Dowell performed two surveys, within the same month (10/87), on BC101, when the total volume of the cavern was less than a million barrels. The surveys produced identical results, with volumes the same to the barrel. This agreement seems unlikely and suggests the possibly of merely a duplicate report.

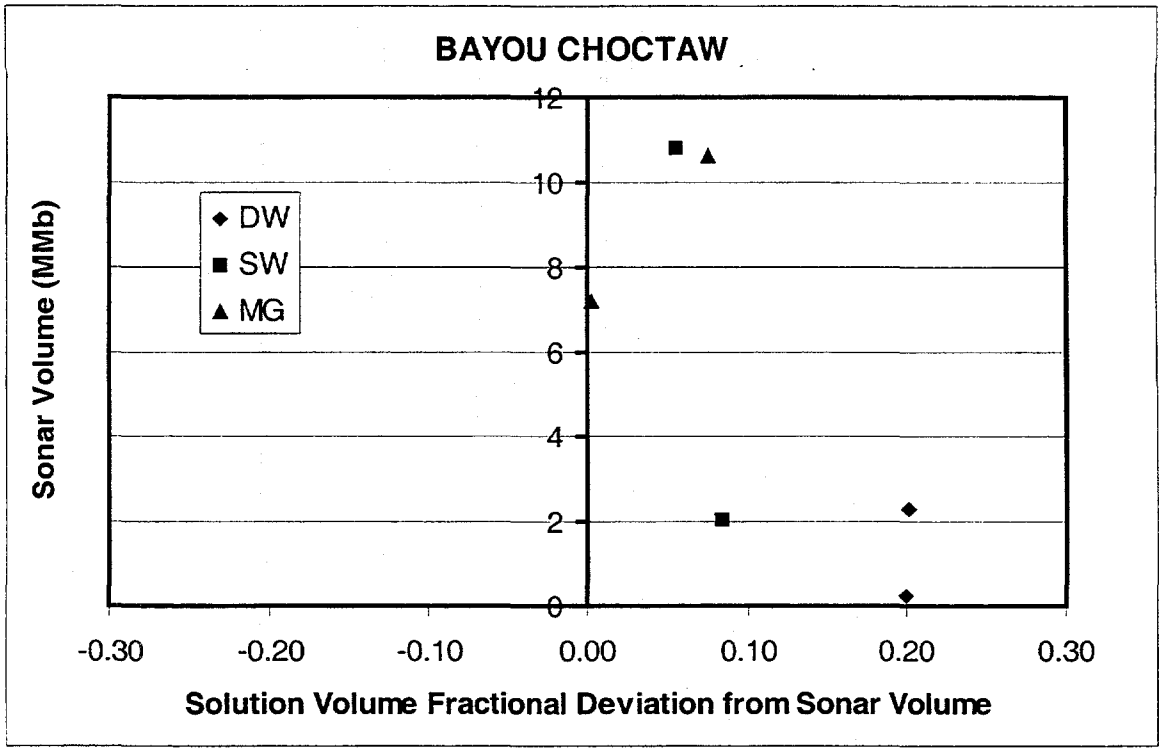

Figure 12. Solution Volume Deviation from Sonar Volume, Bayou Choctaw.

In summary, the rather limited data for Bayou Choctaw support the general trend for the solution volume to be somewhat greater than the sonar volumes. Bias appears to be about 6%, essentially that found for the West Hackberry and the Big Hill databases. In addition, although it could be considered as normal scatter, the data of different operators may suggest different biases, as had been found previously in other databases.

4.3.2 Equivalent Sonar Volumes and Oil Inventories

There is a single datum for the SPR constructed cavern (BC101) on the relationship between the equivalent sonar volume and the oil inventory. This datum was supplied by Osborne [1999]. Unfortunately, even though the date of the survey is given, the actual sonar survey was not available at the time of this analysis. As a consequence, the history or the operator is not really known. It is believe from the date that the operator must have been Sonarwire. This result (BC101) is given in Table VIII and is plotted in Figure 13, together with the perfect relationship trend line. The discrepancy in this result is just 1%, comparable to the deviations seen for the Big Hill and West Hackberry results. It is reasonably clear that this discrepancy is well within the accepted uncertainty of the sonar surveys. The sign of the discrepancy is such that it would have the sonar volume greater than the oil inventory, but within the uncertainty.

Also found in Table VIII are similar data for the commercial caverns of Bayou Choctaw. While the data from the commercial caverns of any site have not been plotting or discussing in detail, these results are especially interesting. In looking at the ratios of equivalent sonar volumes to the oil inventory volumes, it becomes clear that the oil appears to have a volume slightly greater than the sonar survey indicates is available. Except within the accepted uncertainty, this is impossible, of course.

Table VIII. Special Sonar Survey Volumes and Oil Inventories, Bayou Choctaw.

Cav.No.	Co.* (Oper.)	Date	Sol.Vol. (MMb)	Ratio	Sonar Vol. (MMb)	Oil Vol. (MMb)	Remarks#
Sour							
BC15		05/99			15.542700s	15.495300o	s/o 1.003
BC17		06/99			10.380300s	11.501500o	s/o 0.903
BC19		05/99			11.083600s	11.895100o	s/o 0.932
BC101		03/99			11.367300s	11.511800o	s/o 0.987
Sweet							
BC18		08/99			14.428200s	13.728900o	s/o 1.049
BC20		08/99			07.497600s	07.407600o	s/o 1.012

* Sonar surveys not available to author at the time of analysis, s is sonar in brine, and o is oil meter measurement..

\# Data from Osborne [1999].

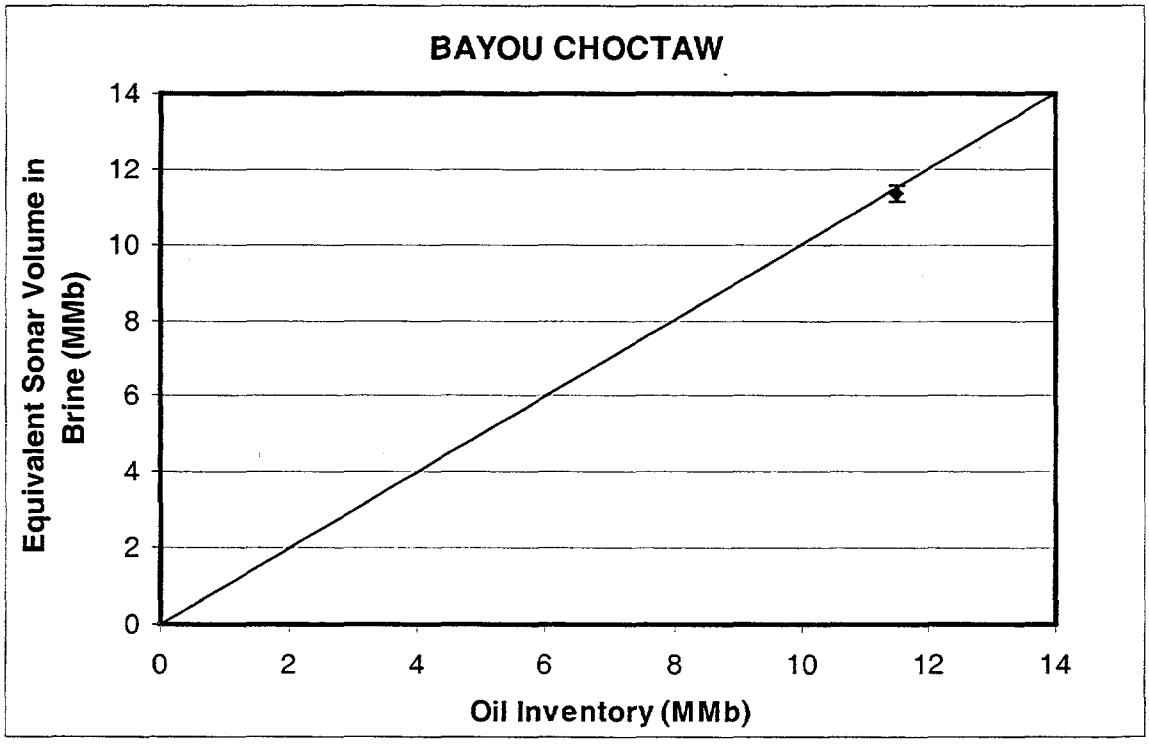

Figure 13. Equivalent Sonar Volume vs. Oil Inventory, Bayou Choctaw (BC101).

Moreover, when all of the data for Bayou Choctaw are plotted, as in Figure 14, it is apparent the behavior is quite complicated. In fact, the sweet crude caverns appear to be consistent, with measured sonar volumes only slightly greater than the oil inventory. The sour crude caverns suggest a discrepancy where the oil inventory is often substantially greater than the sonar survey volume. Because there are two measurements involved, the metered oil volume and the sonar survey volume, both must be examined [Munson, 2000]. First, for the potential problems with the metered volume, it is believed that when the caverns were filled, the total oil of a given type was measured by a custody transfer meter at the St. James Terminal. When it reached the site the oil was then transferred to individual caverns storing that type of crude oil through a manifold system, using split-streaming. The oil placed in a given cavern was measured by the individual cavern meters. These meters are of lesser accuracy than the custody transfer meter and can introduce more uncertainty into the inventory data. As a result, any given cavern of the group storing that type of crude, or involved in the split-streaming, could indicate a larger oil inventory than the sonar volume. However, the sum or total oil inventory of these caverns, because it is determined by the custody transfer meter, must be slightly greater than or equal to the sonar volumes involved. From the data it is seen that this is true for the sweet storage caverns. The sour caverns, on the other hand, produce a total discrepancy ratio of 0.960, or 4%. This certainly suggests that the discrepancy is probably not caused by the individual cavern oil meters.

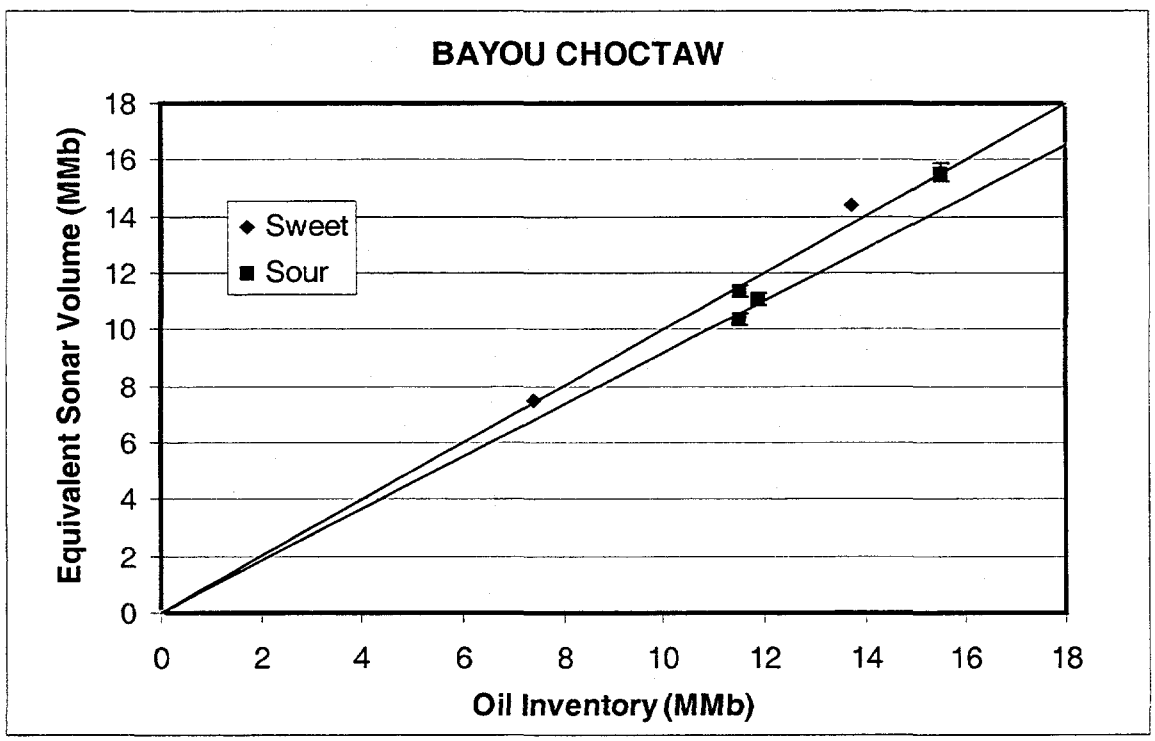

Figure 14. Equivalent Sonar Volume vs. Oil Inventory, Bayou Choctaw (All Caverns).

Next, the possible errors in the sonar volumes are examined. Here there are two quantities involved: the measurement of the oil/brine interface depth and the sonar survey calculation of volume. Possible error in the depth measurement is typically less than two feet, which in a normal SPR cavern amounts to an uncertainty of about 10,000 barrels in volume. Since this footage error is roughly fixed, the percentage uncertainty obviously changes as the amount of oil

varies. For a typical 10 MMb storage, a two foot uncertainty gives just 0.10%. Thus, an extremely large reporting or measuring error would be required in the interface depth.

Consequently, it can be concluded that the sonar volume as being the most probable source of the discrepancy in the Bayou Choctaw sour crude volume data. As the trend line in Figure 14 suggests, the two sonar volume data points with the greatest discrepancy lie on a line with a slope of 0.917, significantly biased from the perfect correlation line. In fact, the possibility was suggested [Munson, 2000] of the sonic velocities being in error for these data.

4.3.3 Summary Remarks for Bayou Choctaw

The very limited data for Bayou Choctaw permit only a few observations. It appears that the solution and sonar data are consistent with both the Big Hill and West Hackberry data, with some differences in the observed biases for the different operators. Instead of using only the single SPR constructed cavern for equivalent volume comparisons, the SPR purchased commercial caverns were also examined. Here, the discrepancies observed between the inventories and the equivalent sonar volumes seem to indicate that the sonar data must be biased to produce a physically unrealistic situation for the sour crude storage.

4.4 Bryan Mound (BM)

The Bryan Mound caverns are somewhat unusual, but in the opposite sense from the Big Hill caverns, because these caverns were the first to be constructed, used three wells for solutioning, and were filled concurrently with construction. The three-well configuration was thought necessary to give the proper hydraulic flows to permit larger quantities of water, and eventually oil, to be moved through the caverns. This configuration also allowed solutioning to continue even during storage of incoming oil through the third well. These factors have combined to make the volume characterization of the Bryan Mound caverns quite difficult. The use of three wells not only made the solutioning quite irregular, but tended to produce individual, non-coalesced, solution voids over all or part of the cavern. This was especially severe in the early stages of solutioning. Solutioning proceeded initially with the development of a sump, typically using two wells. At some point, the sumps of the two wells coalesced to form a single void. At this point, the upper portions of the wells were, however, still distinct and isolated from each other. When the follow on stages of reverse solutioning took place, it was necessary to develop the top of the caverns first to provide the necessary storage volume. As the top storage volume reached the intended size, the solutioning process was moved further down in the cavern. However, as the intended cavern size was reached, parts of the cavern intermediate between the coalesced sump void and the upper necessary oil storage void remained as isolated, non-coalesced wells. Thus, the initial sonar surveys were incapable of detecting all of the cavern volume, and even during the late stages of construction, portions of the cavern were hidden from sonar surveys in any well. Some of the problem was eliminated by the ability to construct joint survey results. Lack of refinement of the early sonar surveys also resulted in a large uncertainty in the volumes assigned to survey and oil volume, so when these volumes are mixed the combined results were widely scattered. Perhaps the most difficult part of interpretation of these early volume measures is that the procedures appear to be ill-defined. Often, all of the pertinent information was not included in the engineers report at the time of the survey. Even some of the more recent Bryan Mound data suffers from discrepancies in reporting. This means that the comparative numbers for solutioning and equivalent sonar volumes at the reporting time are not available.

Because of the complex history of the construction of the Bryan Mound caverns, all of the late time sonar surveys were in caverns with considerable amounts of stored oil. These results are all

Table IX. Calculated Solution, Sonar, and Oil Volumes, Bryan Mound.

Cav.No.	Co.* (Oper.)	Date	Sol.Vol. (MMb)	Ratio (w/(s+o))	Sonar Vol. (MMb)	Oil Vol. (MMb)	Remarks
BM101A	SW(M)	08/96			13.200s		
	DW(V)	09/84	11.245w	1.012mix	06.553s	04.560o	20.96% insol.**
	DW(W)	02/84	10.705w	1.121mix	02.804s	06.747o	07.30% insol.**
	DW(T)	06/83	07.419w	1.066	06.957s		07.13% insol.
	DW(V)	11/82	02.664w				Non-coalesced.
BM102C	DW(V)	07/83	05.117w	1.135	04.507s		Survey 2 wells
	DW(W)	03/83	02.384w	0.752	03.170s		Survey 2 wells
BM103B	SW(M)	03/97			12.502s		
	DW(W)	12/83	10.246w	1.144mix	06.629s	02.320o	07.80% insol.**
	DW(S)	03/83	05.307w	1.035	05.126s		08.32% insol.
	DW(V)	10/82	02.666w	1.072	02.486s		
**							
	DW(V)	08/81	01.934w	0.959	02.015s		Non-coalesced
BM105	DW(V)	04/82			06.118s		
	DW(W)	06/83	11.187w	1.083mix	04.101s	06.230o	**
BM106	DW(V)	12/80			02.031s		
BM107B	SW(M)	06/97			12.354s		
	DW(W)	01/81			01.640s		
BM108							
BM109	SW(M)	12/96			12.497s		A well only
	SW(M)	11/96			10.175s		C well only
	DW(S)	10/81			02.244s		Survey 2 wells
	DW(S)	12/80			00.775s		Survey 2 wells
BM110							
BM111A	SW(M)	09/97			12.605s		
	DW(W)	04/84	06.116w	1.074	05.693s		09.47% insol.
	DW(F)	10/83	02.715w	1.119	02.427s		12.20% insol.
	DW(T)	06/83	00.604w	1.038	00.582s		Survey 2 wells
BM112C	DW(F)	02/84	06.193w	1.101	05.627s		07.84%insol.
	DW(T)	06/83	02.771w	1.117	02.481s		C well only
	DW(T)	09/82	00.194w	0.850	00.229s		Non-coalesced
BM113A	SW(M)	10/95			06.952s		A well only
	SW(U)	01/87	07.105w	1.057	06.720s		A well (Dupl.)
	SW(U)	12/86	07.105w	1.031	06.891s		A well (Dupl.) (06.805 ave. +/- 1.26%)
	DW(V)	09/85	06.332w	1.142	05.540s		05.52% insol.
	DW(S)	05/85	03.188w	1.132	02.815s		06.50% insol.
	DW(F)	09/84	00.368w	1.355?	00.272s		B well only
BM114	SW(M)	02/96			09.020s		A well only
	SW(U)	10/86	08.023w	0.976mix	05.605s	02.616o	06.36% ins. **
	DW(V)	07/85	04.746w	1.055	04.498s		A well only
BM115	SW(U)	08/86	11.196w	1.078mix	06.968s	03.416o	03.97% ins. **
	DW(F)	09/85	07.500w	0.920	05.726s	02.427o	08.17% insol.
	DW(S)	04/85	05.906w	1.113	05.308s		04.44% insol.

Table IX. (Cont.). Calculated Solution, Sonar, and Oil Volumes, Bryan Mound.

Cav.No.	Co.* (Oper.)	Date	Sol.Vol. (MMb)	Ratio (w/(s+o))	Sonar Vol. (MMb)	Oil Vol. (MMb)	Remarks
	DW(F)	10/84	02.175w	1.102	01.973s		11.93% insol.
	DW(S)	07/84	00.284w	1.190	00.239s		B well only
BM116	SW(U)	11/86			10.475s		A well only
	SW(U)	08/86	11.196w			03.400o	A well only
	DW(S)	03/85	05.984w	1.017	05.886s		07.00% insol.
	DW(S)	10/84	02.997w	1.085	02.764s		08.67% insol.
	DW(W)	05/84	00.415w	0.700?	00.292s		Non-coalesced

* Companies are: SW = Sonarwire, DW = Dowell (also Sonar and Well Testing Services). Technicians are: B = Broussard, C = Childress, F = Free, M = McCool (younger), T = Thomas, U = Unknown Operator (here it is the elder McCool), W = Ward.

** Mixed (combined) volume where the oil (o) makes up a considerable fraction of the total volume, so that the solution (w) /sonar (s) volume ratio is compromised.

combined volumes, as will be noted. Only the very early reported sonar surveys volumes were determined with small volumes of blanket oil. Usually, the blanket oil was in the necks of each of the three wells, so that often when only one well was surveyed the total quantity of blanket oil could not be determined. This difficult in accounting for all of the sonar volume in the cavern continued, because even the amount of volume in each of the cavern necks, and in the isolated well sections at intermediate depth, were not usually surveyed. As a result, a large uncertainty can be introduced into the comparative evaluations of the volumes that has nothing to do with the uncertainties of the various measurement methods, and interpretation may require caution.

4.4.1 Solution Volumes and Sonar Volumes

All of the available calculated solution volumes, sonar volumes and measured oil volumes are given in Table IX. There were essentially two contractors involved in the surveys of the Bryan Mound caverns: Dowell (and associated companies) and Sonarwire. The uncombined data are presented first, as shown in Figure15. The Dowell (DW) data are the diamonds, whereas Sonarwire (SW) data are the squares. In the table, there is no special notation used for the uncombined data. This is because these data, unlike those for the preceding caverns, are not thought to be of high quality. Usually, uncombined data occur only for the smaller solution volumes, typically less than 60% of the anticipated final cavern volume. Also, the data may represent cavern conditions when the separation of the well voids is not certain. Since the triple asterisk is a mark of quality, it is probably not justified by the Bryan Mound database.

As was done with other data of this form, the deviation of the calculated solution volume from the sonar volume, taken as a reference, was determined. These results are given in Figure 16, and are both instructional and confirm the trends expected. It is clear that the results at small cavern volumes exhibit considerable uncertainty. As noted earlier, volume errors because of unknown blanket oil quantities and obscured volumes will influence the apparent deviations strongly. But, as the cavern volumes increase the uncertainties narrow markedly. However, it is clear that the results are biased toward a positive discrepancy. The best trend line which can be constructed is shown in Figure 15. This trend line indicates the deviation from perfect agreement is significant,

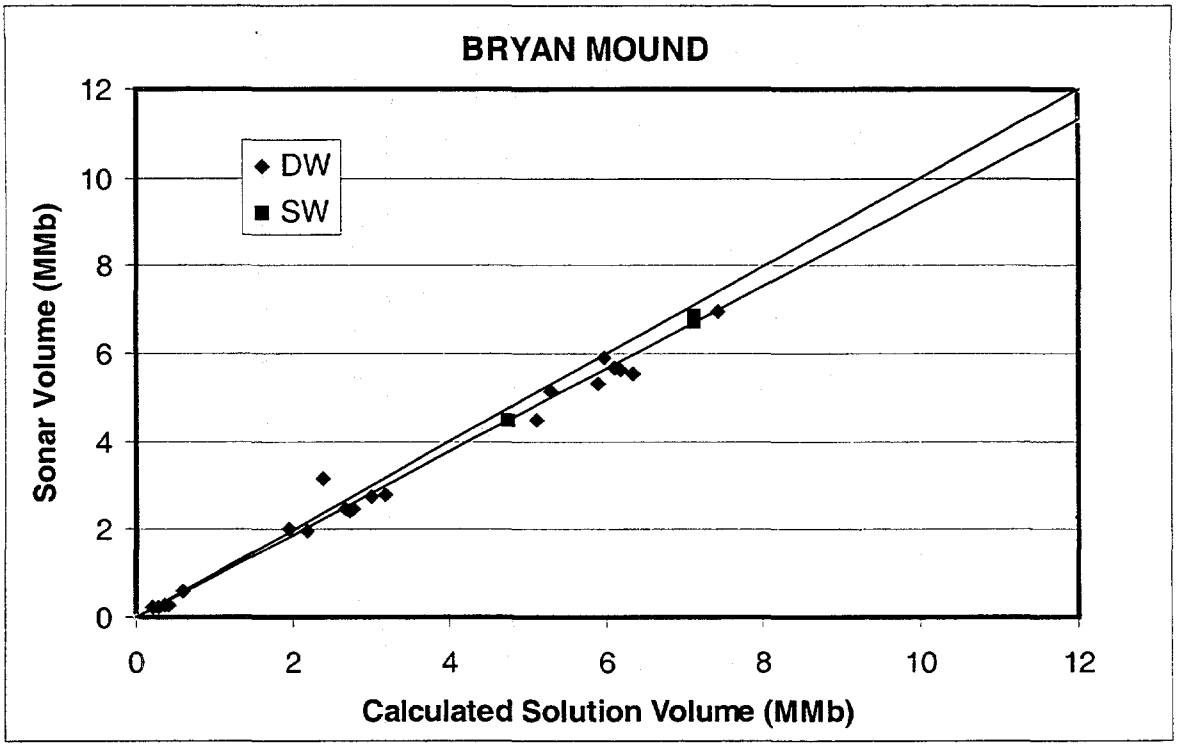

Figure 15. Solution Volume vs. Sonar Volume, Bryan Mound.

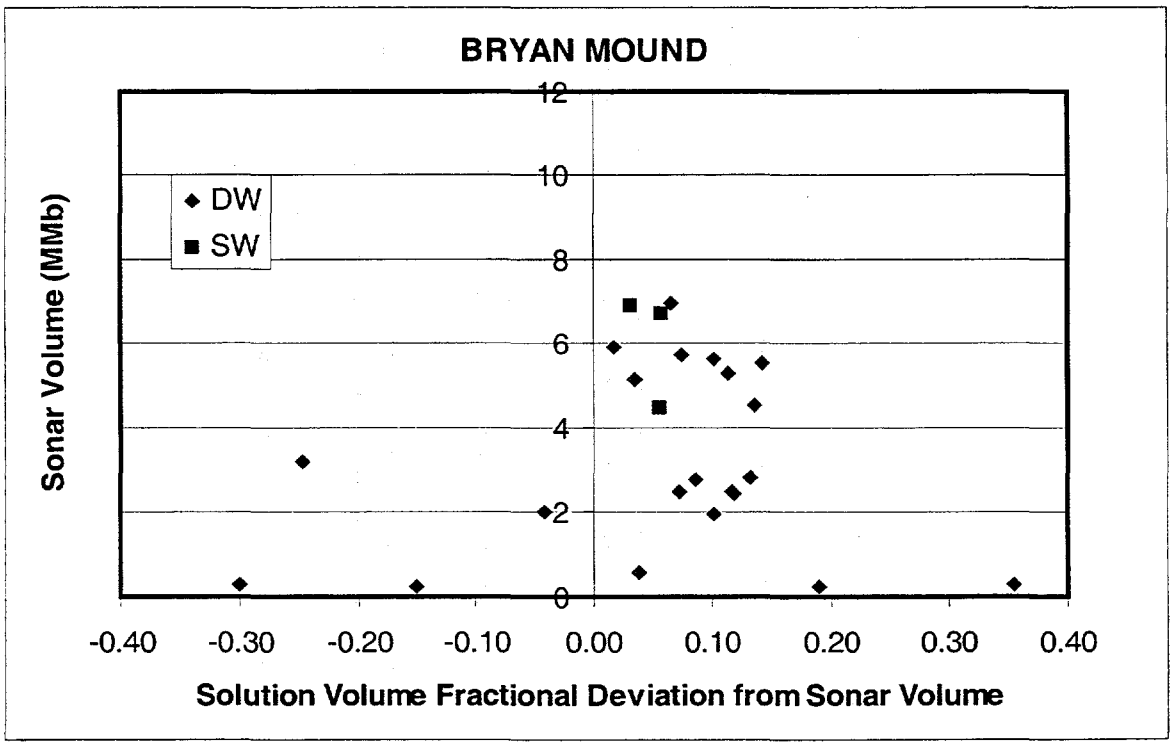

Figure 16. Solution Volume Deviation from Sonar Volume, Bryan Mound.

in this case a slope (*m'*) of 0.942, or about a 6% bias toward the sonar underestimation of the solution volume. Actually, this deviation is in the direction expected as a result of our belief in the tendency of the sonar reflections to preferentially select the nearest surface. The bias is somewhat greater than that found for Big Hill, a result which could be caused by the lower refinement in the earlier sonar techniques used at Bryan Mound.

Although it is not apparent how much detail can be read into the data of Figure 16, it appears that the bias of the Sonarwire data is less than the bias of the Dowell data. A bias of about 4% seems to best describe the Sonarwire results, which then indicates a bias of about 9% for the Dowell data. Such differences between operators would be entirely logical, but difficult to explain.

One thing that is apparent is the relatively large scatter of the data. In comparative terms, the scatter of the Bryan Mound data exceeds that observed for the other SPR sites. This occurs particularly at the small cavern solution volumes as demonstrated in Figure 16. At the larger cavern volumes, however, the scatter becomes comparable, and perhaps less, than that observed for other sites. Appearance of scatter is a very interesting effect because it is essentially demagnified in the presentation of Figure 15, which makes these data appear to be a good fit to the trend line. However, the diminution of the scatter, and the uncertainty, with increase in the total cavern volume is thought to be a real effect, reflecting the different responses of the bias and fixed uncertainties in the governing equations. Even though the Bryan Mound data are the earliest obtained in the program, they seem to be very comparable to the later data. However, this, as will be seen, applies only to the uncombined data.

Many of the available data involve combined sonar volumes. As is customary, these will be treated separately. These data are plotted in Figure 17. There appears to be very large scatter.

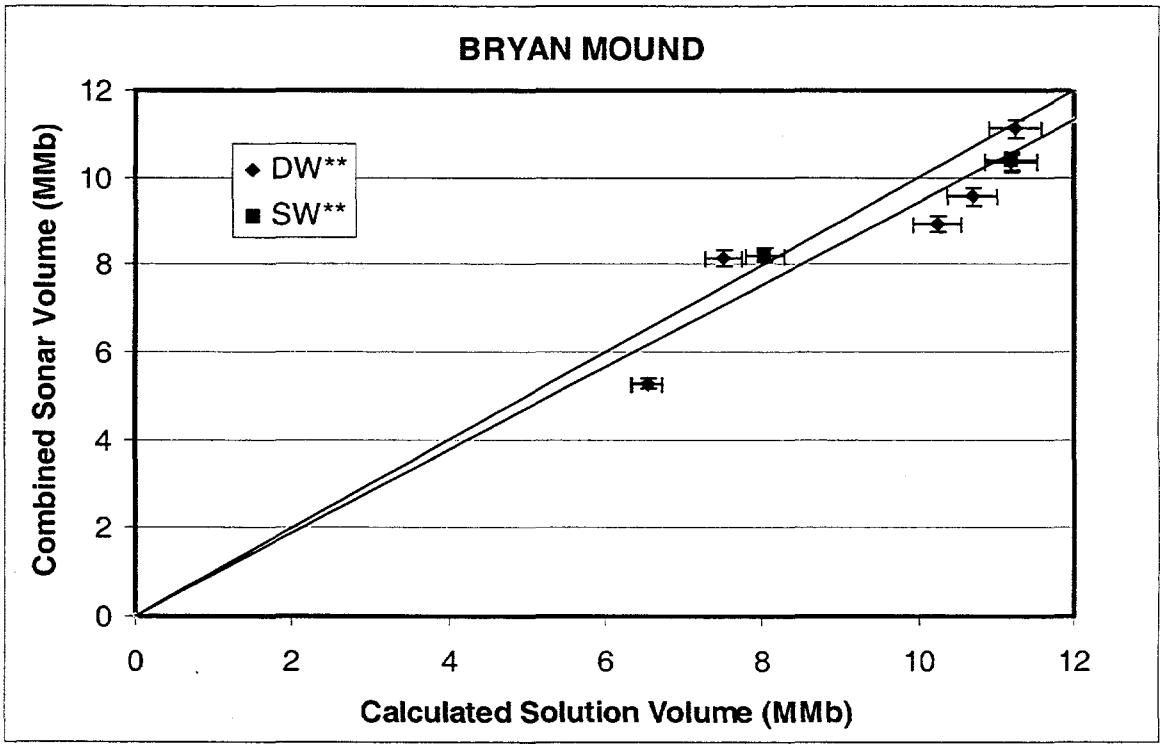

Figure 17. Solution Volume vs. Combined Sonar Volume, Bryan Mound.

Exactly why these results are so much more scattered compared to the results of the uncombined sonar volumes is unknown. In fact, the scatter would be expected to be no worse, and perhaps even less, than the uncombined volume data (Figure 15). The trend line in Figure 17 has a slope of 0.942, or about 6% bias, a value assumed from the earlier uncombined data, and not these data.

It is clear from these combined volume Bryan Mound results that major discrepancies can occur. The uncertainties deduced earlier in this report for this type of data, of sonar +/-2% and solutioning +/-3%, as shown imposed on the data points, illustrate the significant problem. In fact, uncertainties in the Bryan Mound combined data are so large as to call the data into question. As stated previously, it is not possible to assign the distinct contributions of the various measurements to the overall uncertainties, but there are some logical arguments that can be made. Unusual differences in the uncertainty between the various Bryan Mound data sets probably are not the result of the dissolution constant. Nor, in this case, are they believed to be the result of the sonar techniques. In fact, it could be argued that the dissolution constant for the calculated solution volume was probably maintained at the same value throughout the construction program. As a consequence, it should have about the same uncertainty as found for the uncombined results. And, for that matter, the value found for all of the other sites. There also appears no reason to suppose that the sonar techniques changed so radically that these combined data should have any greater uncertainty than the data from other sites. Potentially, the principal factor responsible for the increased scatter of the Bryan Mound combined results would seem to be increased errors in just the accounting process. From engineering reports for the Bryan Mound caverns, a number of relatively arbitrary adjustments were made to the solution volume to correct what appeared to be major inconsistencies at the time. Obviously questionable data were avoided in this work, when identified; however, whether or not this practice could always be identified is unknown.

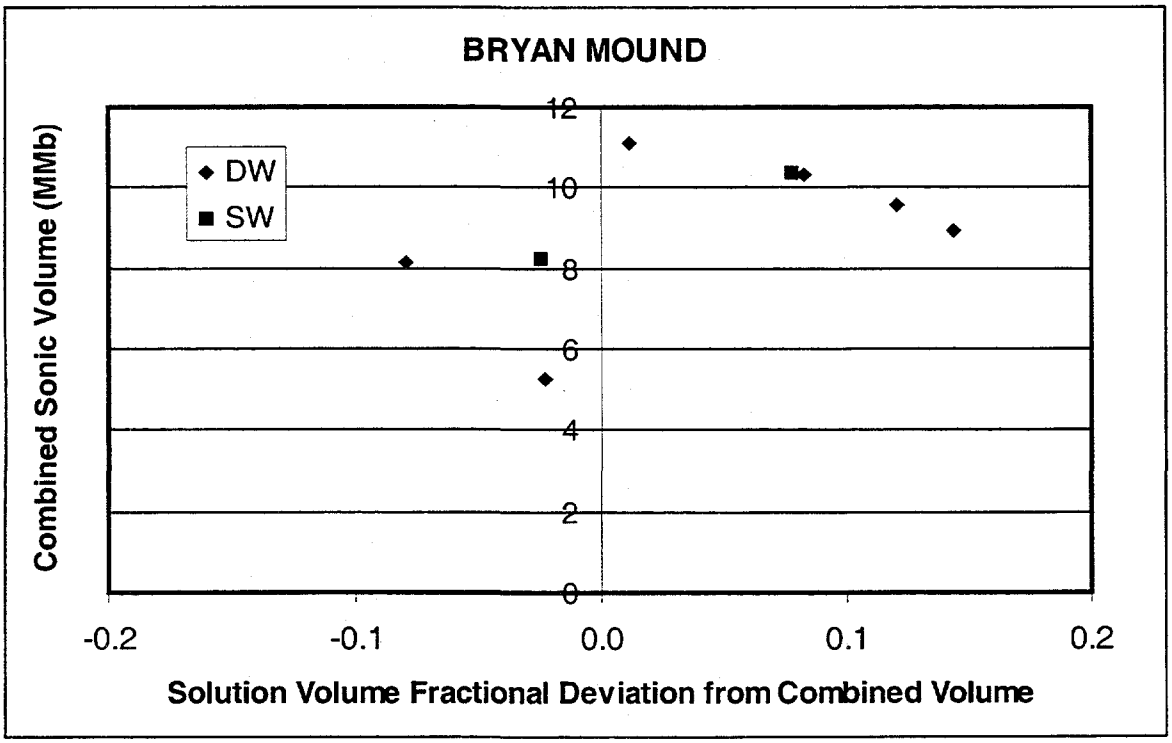

Figure 18. Solution Volume Deviation from Combined Sonar Volume, Bryan Mound.

In general, the comparisons of the calculated solution volumes and the sonar survey results for Bryan Mound are not as consistent as for the other sites. The scatter is especially large, as demonstrated for the deviations in Figure 18 for the combined sonar results. While the scatter for the uncombined sonar volume comparisons diminishes at the larger total volumes, the scatter even at large volumes is especially large for the combined sonar volumes, which seems contrary to what one would expect. To some extent the large discrepancies for Bryan Mound are probably the result of the concurrent solutioning and oil filling, problems in accounting correctly for the volumes of non-coalesced void around the wells, and arbitrary adjustments. In particular, use of three wells during cavern construction could be considered as the major contributor to confusion in the various volumes. A survey from any given well possibly could not reveal the hidden volumes in the remaining wells, with the attendant introduction of accounting errors in the volumes. Accounting errors are relatively arbitrary and have not been considered previously.

4.4.2 Equivalent Sonar Volumes and Oil Inventories

Bryan Mound caverns are nearly all filled with oil, and in most instances, the equivalent sonar volumes can be correctly assigned. The results for the SPR constructed caverns are given in Table X. As in the earlier Big Hill data, the Bryan Mound information has been grouped according to the type of crude oil stored. The data for the SPR built caverns as well as the SPR purchased former commercial caverns are given. The inventory data for all caverns are plotted against the equivalent sonar volumes in Figure 19. In this case, the different operators have not specifically identified, although such data could probably be obtained. The diamonds are for the caverns with sour crude and the squares are the caverns with sweet crude. Note that the reference quantity is the oil inventory, so a positive percentage means the sonar volume is less than the inventory.

It appears that a number of the data points fall within acceptable uncertainty to the perfect correlation relationship. However, a significant number indicate that the inventory volume exceeds the equivalent sonar volume. The trend line shown is about 4% from the perfect relationship. Even though one would suppose that such a deviation is not possible, this is not the only situation where it occurs. Based on the earlier theoretical argument which suggests a consistent trend of the calculated solution volume to exceed slightly the sonar volume, the same argument can be applied to the comparison of oil volume and sonar volume. One might expect the sonar volume to be slightly less than the inventory volume because of preferential reflection from the closer surfaces, as explained previously. However, it is difficult to apply this reasoning to all of the data because some show the two volumes to be in essential agreement. Perhaps this is the scatter canceling the bias.

Presence of what appears to be a distinct bias for some of the data may be significant. Certainly the occurrence of bias is consistent with the comparison of the calculated solution volume and sonar volume of the data presented earlier in this report.

The comparison of the equivalent sonar volumes and the oil inventories is of some concern, suggesting that many of the sonar volumes are less than the oil inventory. In part, the problem is undoubtedly related to the inability to clearly separate bias and scatter. Whether or not this can eventually be resolved remains a question.

4.4.3 Summary Remarks for Bryan Mound

Of all of the facilities, the uncertainties for Bryan Mound were expected to be the greatest. This facility was the first to be developed for the SPR and presented several significant problems for

Table X. Equivalent Sonar Volumes in Brine and Oil Inventories (10/99), Bryan Mound[#].

Cav.No.	Oil Inv. (MMb)	Sonar Vol. (MMb)	Sonar Discrep. (MMb)	% Diff.	Remarks
Sweet					
BM2	06.701000	06.661000	-00.040000	-0.60	
BM4	21.778000	20.770900	-01.007000	-4.62	
BM113	06.294000	06.276600	-00.017400	-0.28	
BM114	07.723000	07.705900	-00.017100	-0.22	
BM115	09.076000	08.475400	-00.600600	-6.62	
BM116	10.592000	10.119530	-00.472500	-4.46	
BM106	?				Brine Filled
			Vol. Ave.	-3.59	
Sour					
BM1	07.248000	06.593489	+00.6545000	-9.03	
BM5	35.747000				No Sonar
BM101	12.087000	12.349630	+00.262600	+2.17	
BM102	10.819000	10.944930	+00.135900	+1.16	
BM103	09.719000	09.258900	-00.460100	-4.73	
BM104	11.177000	10.665200	-00.511800	-4.58	
BM105	11.060000	11.192600	+00.132600	+1.20	
BM107	10.213000	09.755400	-00.457600	-4.48	
BM108	11.355000	11.473800	+00.118800	+1.05	
BM109	08.936000	08.810900	-00.125100	-1.40	
BM110	10.454000				No Sonar
BM111	05.698000	05.863300	+00.165000	+2.90	
BM112	05.492000	05.120200	-00.371800	-6.77	
			Vol. Ave.	-1.71	

[#] Data of Osborne [1999].

determining the cavern volumes. In the solutioning process, there were three wells involved, which permitted individual solution voids to be created around each well. With continued solutioning, coalescence of the individual well voids occurred, but not uniformly through the height of the cavern. The problem which eventually evolved was that the chimney of each well could be isolated, with volumes that were difficult to survey. This problem continued with depth into the cavern, where individual surveys of a given well could not detect isolated volumes associated with an adjacent well. Although reconstruction of the individual well sonar surveys were possible to give the combined volumes, the uncertainty in the sonar volumes remained large. This uncertainty may very well be an accounting error as opposed to a survey instrument or technique uncertainty.

The correction for the uncertainty introduced because of the geometric and construction complexity of the Bryan Mound caverns is, at least in part, a very careful reconstruction of the various well voids. Thus, it was possible in some sense to obtain very good comparisons of the equivalent sonar volumes and the oil inventories. As with other facilities, it appears that individual sonar surveys can be biased. This was also again found in the comparisons of equivalent sonar volumes and oil inventories. Part of the bias may be the natural tendency for the

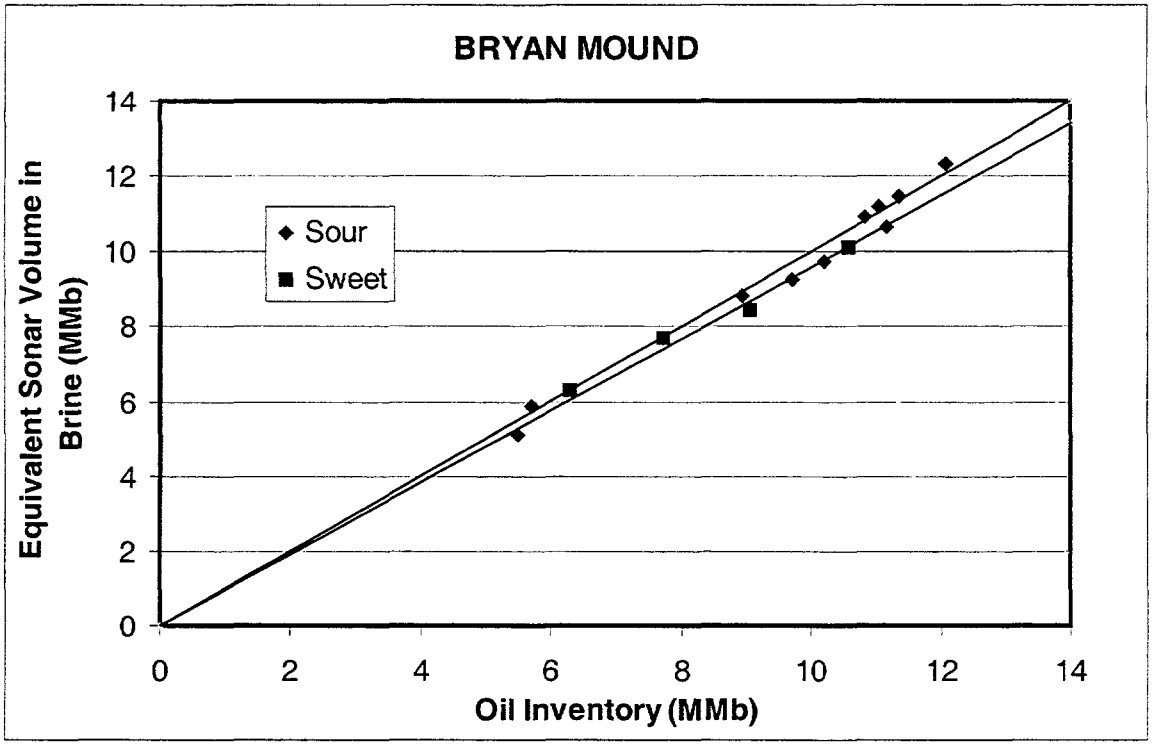

Figure 19. Equivalent Sonar Volume vs. Oil Inventory, Bryan Mound.

sonar survey to underdetermine the actual volume, but part may also be a true instrument bias. Each of these must be eventually accounted for in the analysis.

5 STATISTICAL ANALYSIS

Clearly, the volume measurement databases used for the comparisons present an opportunity for quantitative statistical analysis. The intent is to determine the distribution and standard deviation for the uncertainty. In order to accomplish this, the theoretical aspect of the study must be recalled. It suggests that the deviation of the data is really composed of two parts, a bias because of a systematic error in the measurement system and a random error produced by the uncertainty of the measurement system. Even if the cause of the bias is unknown, the observational evidence that it exists in each subset of data by operator is strong. Normally, where a uniform bias is common to all the data, a statistical analysis can be made and the bias appears as a skew of the distribution. However, in the subsets of these data, the biases can all be different. Statistical analysis of such sets, if analyzed directly, would cause multiple skewed peaks in the distribution, provided the databases were large. With these small databases, the effect would be to broaden the distribution artificially. As a consequence, the raw deviation results given previously will be adjusted by removing the bias before being analyzed statistically. Biases were determined by the appearance and relationship of the data compared to the perfect correlation. Even though the biases may not be determined exactly, they are probably accurate enough. Biases as determined to this point are summarized in Table XI. Table XI separates the databases according to the category of data, just as previously, and by SPR site, and by operator or crude type.

On the basis of the analysis, there appear to be essentially two primary causes of the biases in these data. First, a systematic error in the measurement of the sonic velocity is possible, and second, the tendency for the sonar reflection to occur predominantly from the nearest surface of a rough cavern wall could lead to a systematic error. The first error possibility leads to a proportionality bias and the direction of the bias could have either sign. The second possibility, while systematic, would decrease with cavern radius, and the direction of the bias would always be to underestimate the actual volume. It is believed that no systematic bias would occur in the solution volume determination and all errors would be essentially random.

The data can be adjusted by appropriate addition (or subtraction) of the bias. This results in a deviation which is thought to be the result of only the measurement scatter or uncertainty.

Once the data are adjusted to eliminate the bias, then it is possible to assign each datum to one of the specific bins into which the fractional deviation range has been divided. In this case the bins have either a fractional width of 0.002 (0.2%) or 0.001 (0.1%). These bin sizes seemed about optimum. Any smaller bin size would not add further detail and any larger bin size would detract from the detail. From the bin quantities, a cumulative distribution was determined.

As the categories of Table XI indicate, the analysis first treats the most populous database for the comparisons between the calculated solution volumes and the uncombined sonar volumes. The somewhat smaller database for the comparison between the calculated solution volumes and the combined (sonar plus oil inventory) is then analyzed. And then, the comparison of equivalent sonar volumes through brine and the oil inventories are analyzed statistically, even though it is a very small database. Finally, the comparison of the equivalent sonar volume through oil and the oil inventories are discussed; but, here, the database is so small statistical analysis is not possible.

5.1 Solution and Uncombined Sonar Data Statistics

The deviations between the calculated solution volume and the uncombined sonar volumes are treated first. The adjusted deviations for each of the SPR storage sites are shown graphically in Figures 20 through 24.

Table XI. Summary of Bias Adjustments and Remaining Scatter.

Category Type	Facility	Company	Bias (%) $100(1-m')$	Resid.Scat. (%)[#] $100(\Delta\varepsilon_{min/max})$	No. Points	Remarks
Solution						
Uncombined (Sonar)						
	Big Hill	Dowell	+13.0		1	Single Datum
		Sonarwire***	+2.5	-5.0 to +6.0	17	Best Data
		MicroGage	-2.1	-14.0 to +14.0	27	
		Sonarwire	+2.5	-9.0 to +9.0	4	Small Volume
	West Hackberry	Dowell	+5.0	-19.0 to +15.0	30	
		Sonarwire	+5.0	-2.0 to +10.0	3	
		MicroGage	-9.0		1	Single Datum
		Other	+4.0		1	Single Datum
	Bayou Choctaw	Dowell	+20.0		2	
		Sonarwire	+6.0	-1.0 to +5.0	2	
		MicroGage	+6.0	-6.0 to +3.0	2	
	Bryan Mound	Dowell	+9.0	-40.0 to +26.0	21	Small Volume
		Sonarwire	+5.0	-2.0 to +1.0	3	
Solution						
Combined (Sonar + Oil)						
	West Hackberry	Dowell	+4.0	-4.0 to +9.0	9	
		Sonarwire	0.0	-4.0 to +2.0	4	
	Bryan Mound	Dowell	+6.0?	-14.0 to +14.0	6	
		Sonarwire	+6.0?	-8.0 to +2.0	2	
Equivalent Sonar						
	Big Hill	Sweet	+0.00(-0.37)[##]	-2.0 to +1.8	3	
		Sour	+0.00(+0.97)	-3.0 to +6.0	7	Plus Com.[@]
	West Hackberry	Sweet	+0.00(+0.51)	+0.0 to +1.5	3	
		Sour	+0.00(+0.39)	-2.5 to +1.0	5	Plus Com.[@]
	Bayou Choctaw	Sweet	+0.00	-5.5 to -1.0	2	Plus Com.[@]
		Sour	+0.00&+8.00	+1.0 to +3.0	4	Plus Com.[@]
	Bryan Mound	Sweet	+0.00&+7.00	-2.0 to +1.0	4	
		Sour	+0.00&+7.00	-3.0 to +3.0	10	
Sonar in Oil						
	Big Hill		+1.00(?)	-2.0 to +1.0	3	Three Cav.
	West Hackberry		+6.45(?)	-3.0 to +5.5	2	Two Cav.

[#] After removal of the bias, the residual scatter the ranges from -min to +max% values.

***Data, these points are completed caverns with uncombined volumes and are thought to be the highest quality data.

[##] The numbers in parenthesis were possibly suggested by the data but were not used in the analysis. The mixed adjustment values are both shown.

[@] The commercial caverns at these facilities were included in these results.

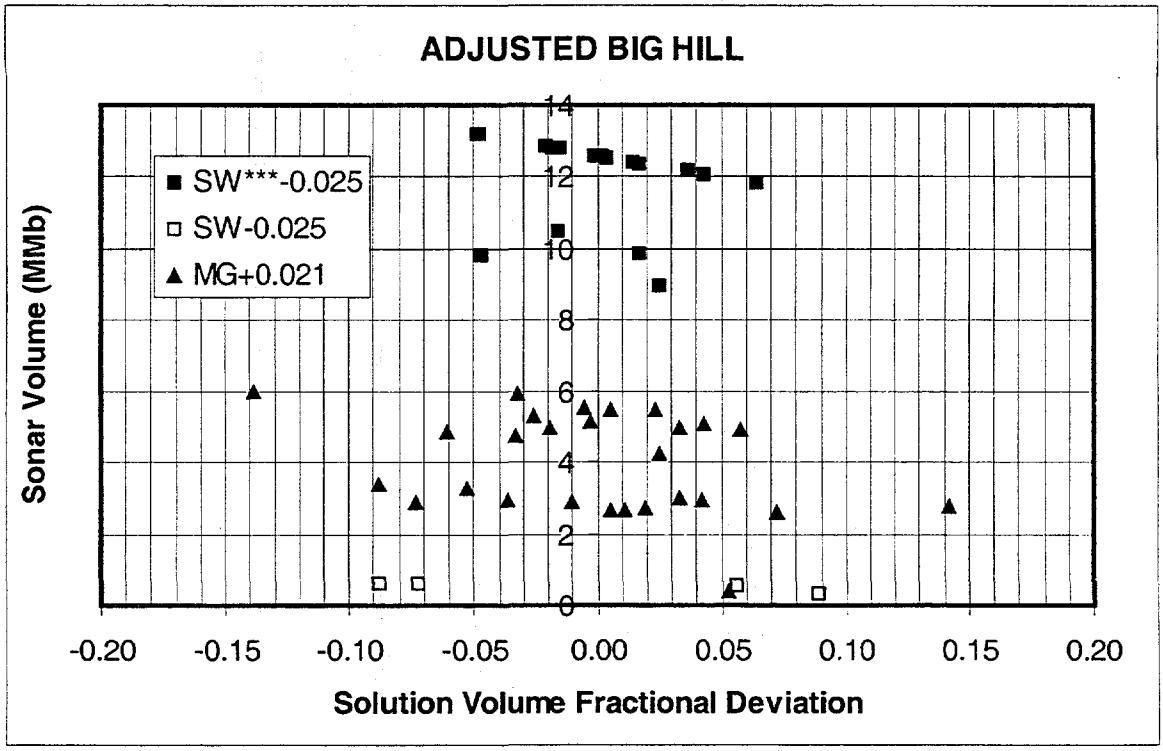

Figure 20. Adjusted Deviations of Solution from Uncombined Sonar Data, Big Hill.

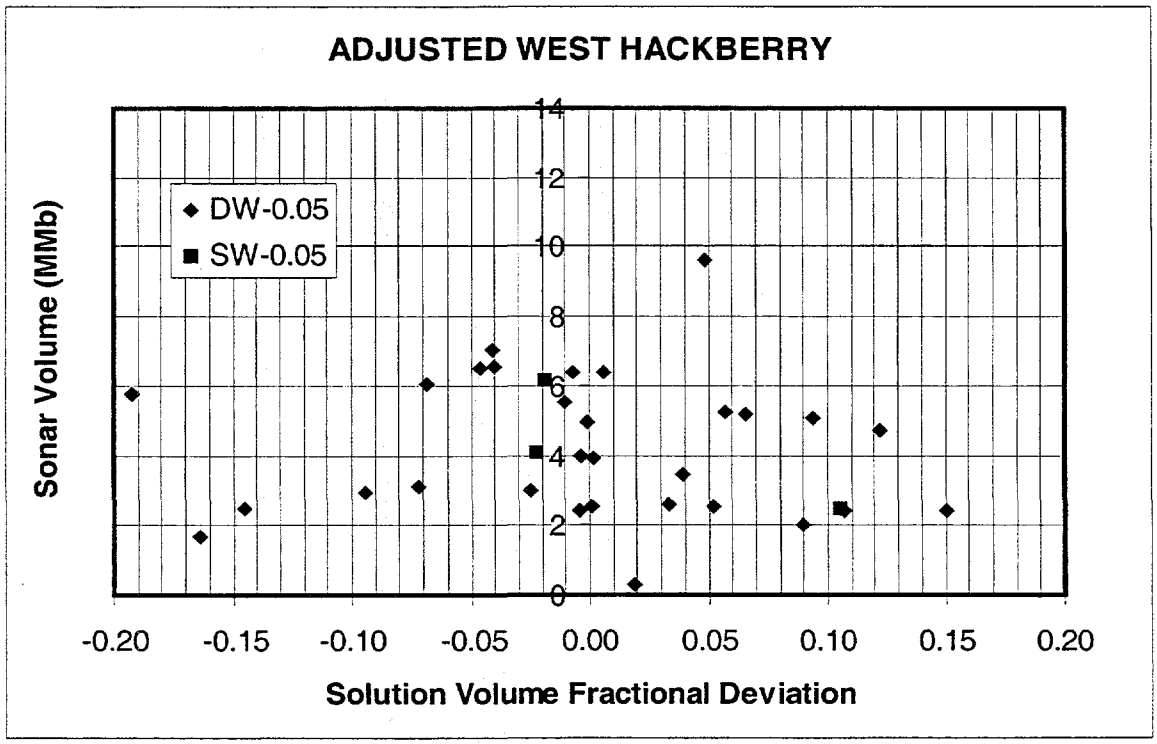

Figure 21. Adjusted Deviations of Solution from Uncombined Sonar Data, West Hackberry.

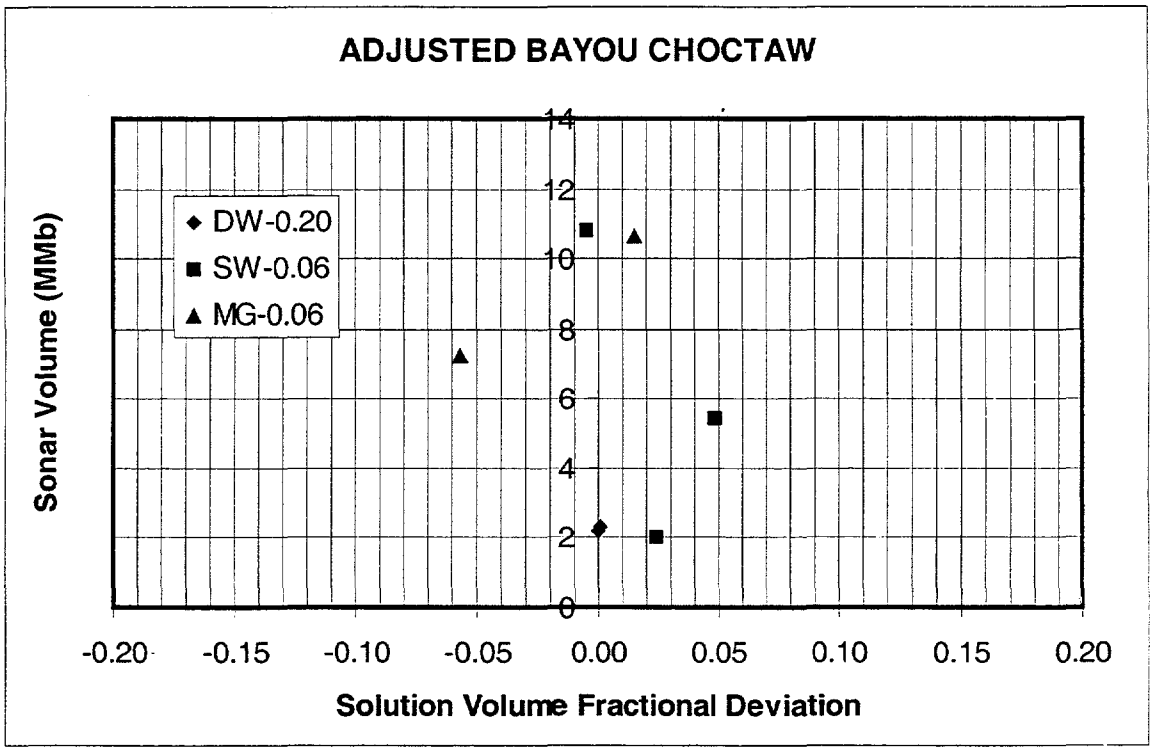

Figure 22. Adjusted Deviations of Solution from Uncombined Sonar Data, Bayou Choctaw.

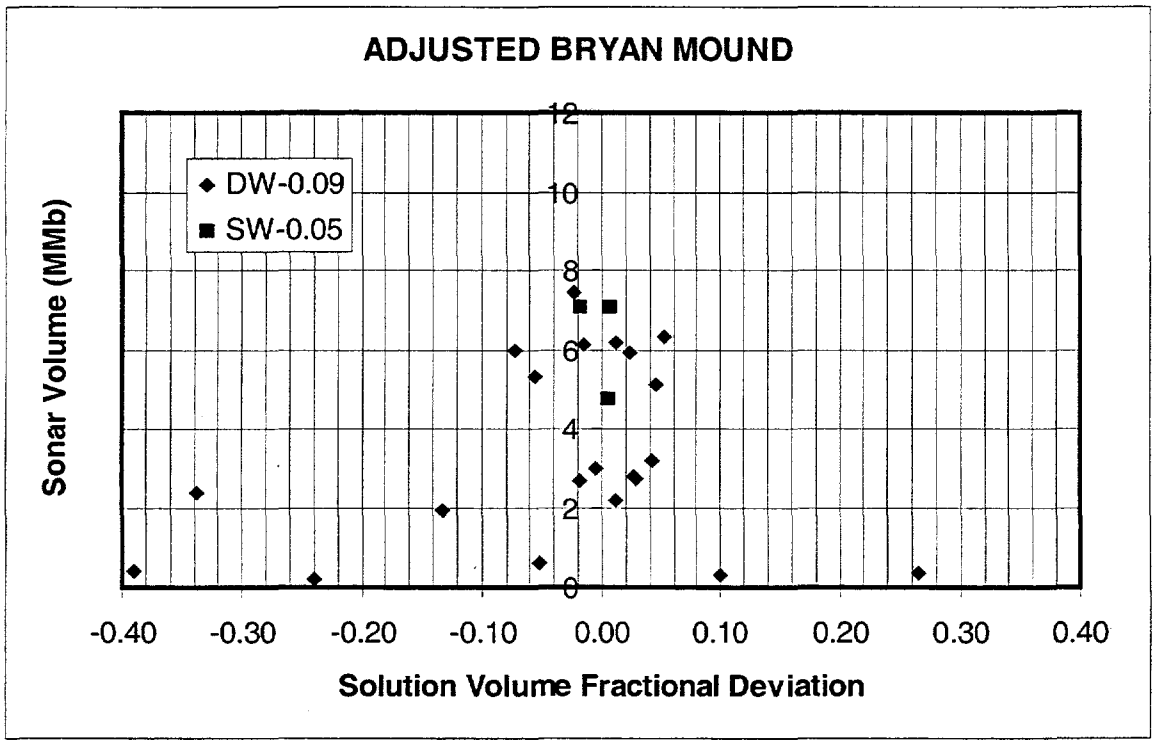

Figure 23. Adjusted Deviations of Solution from Uncombined Sonar Data, Bryan Mound.

In the figures and in the table, the range of the scatter appears to be somewhat greater for the small volumes. This perhaps suggests that small volumes unaccounted for in the uncombined sonar volumes and early input water volumes make more significant contributions to these data. The somewhat greater scatter of these data will widen the probability distribution function, especially in the tails of the function. The SPR site with the greatest scatter, as previously noted, is Bryan Mound.

According to the procedure described previously, from these adjusted deviation results, the numbers of caverns in each fractional 0.002, or 0.2%, wide bin were counted. While individual numbers of caverns could have been plotted according to the appropriate bin, they can also be plotted as a cumulative number of caverns. Such a plot for the uncombined sonar data is given in Figure 24. Also shown is a plot of the normal, or Gaussian, distribution. While initially the distribution is unknown, one would expect these measurements to give a normal distribution. The probability data conform to the normal distribution exceptionally well. This would indicate that the uncertainty in the measurements of solution volume and sonar volume is random.

Also shown on Figure 24 is the range of one standard deviation, or 1-sigma. The standard deviation is +/- 0.0578, or just about +/- 6%, which is consistent with the accumulated sum of the individual uncertainties, according to Equation 5. As cited previously during the comparisons, these uncertainties are somewhat less than the +/5% in the sonar volumes and the +/-5% in the solution volumes as usually assumed by the operators. The +/-2% and +/-3% values are very supportive of those deduced earlier by just looking at the data. The mean of the distribution is +0.90%, or reasonably close to zero. What is extremely satisfying is that the results of the statistical analysis are exactly what would be expected, and very reasonable. Certainly, this suggests that one can be confident of these cavern volume measurement techniques.

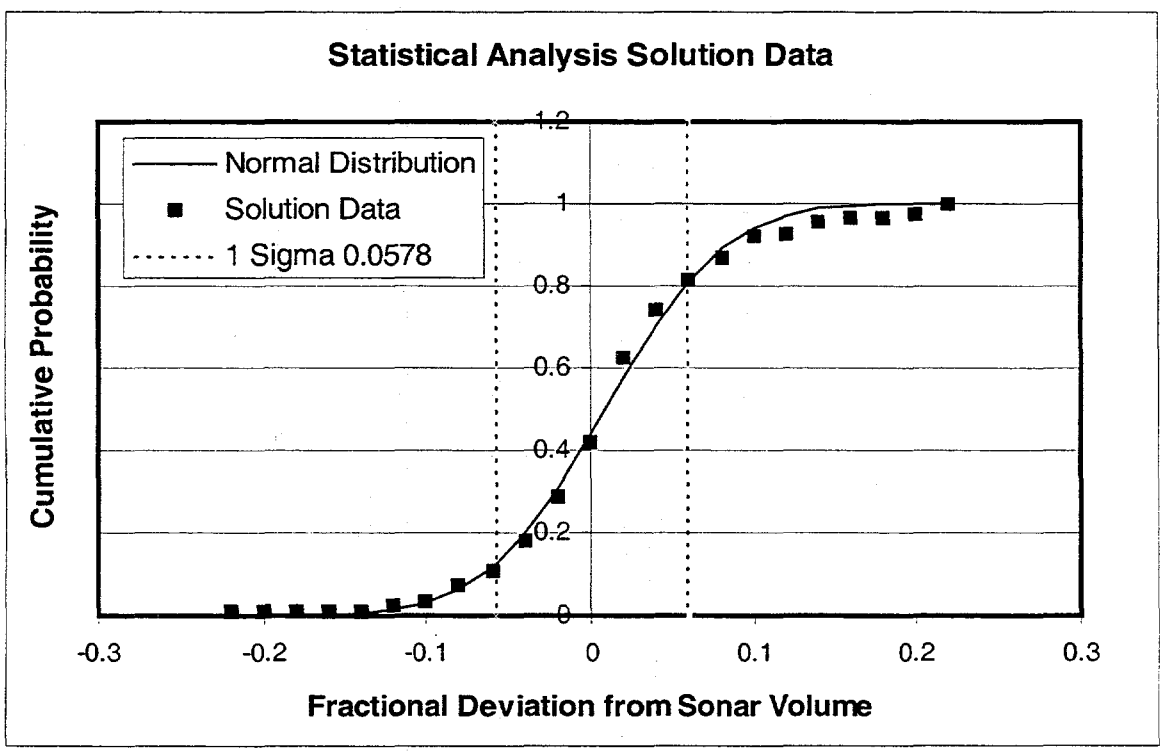

Figure 24. Cumulative Distribution for All Solution and Uncombined Sonar Data.

5.2 Solution and Combined Sonar Data Statistics

Two of the SPR sites, West Hackberry and Bryan Mound, have data in which the comparison of the calculated solution volumes is possible only against a combined sonar volume. Combined sonar volume actually is only partially obtained from the sonar survey, the remainder is obtained by addition of the oil inventory volume. As noted previously, the resulting sonar volume then contains some combined effect of the uncertainties in the sonar survey and the oil inventory. Because the uncertainty in the oil inventory is much smaller than that of the sonar survey, the resultant uncertainty of the combined volume would be expected to be less than if the entire volume was determined by the sonar survey.

Analysis of the combined sonar data proceeded in the same manner as described above. First the data were adjusted to remove the biases according to the values in Table XI. These adjusted data for the discrepancy of the calculated solution volumes from the combined sonar volumes are shown in Figures 25 and 26. As noted in earlier discussions, the data for the two sites really involved only caverns that were near completion, or the final design volume, where concurrent filling with oil occurred. Because the solution scheme for West Hackberry was based on the two well cavern design, the accounting was apparently quite good. As a consequence, the West Hackberry data are very tightly grouped, with little scatter. However, the Bryan Mound data show considerable scatter, which in earlier discussions was partially attributed to the difficulty in accounting for the various volumes in these three well caverns. Since it is not possible to separate the uncertainties of the measurements from the accounting problems, it is necessary to recognize that part of the scatter may not be experimental. However, the analysis can proceed regardless of the source of scatter.

In the analysis, as before, the number of caverns in each of the 0.2% width data bins was used to determine a cumulative distribution, which is plotted in Figure 27. Also shown in the figure is

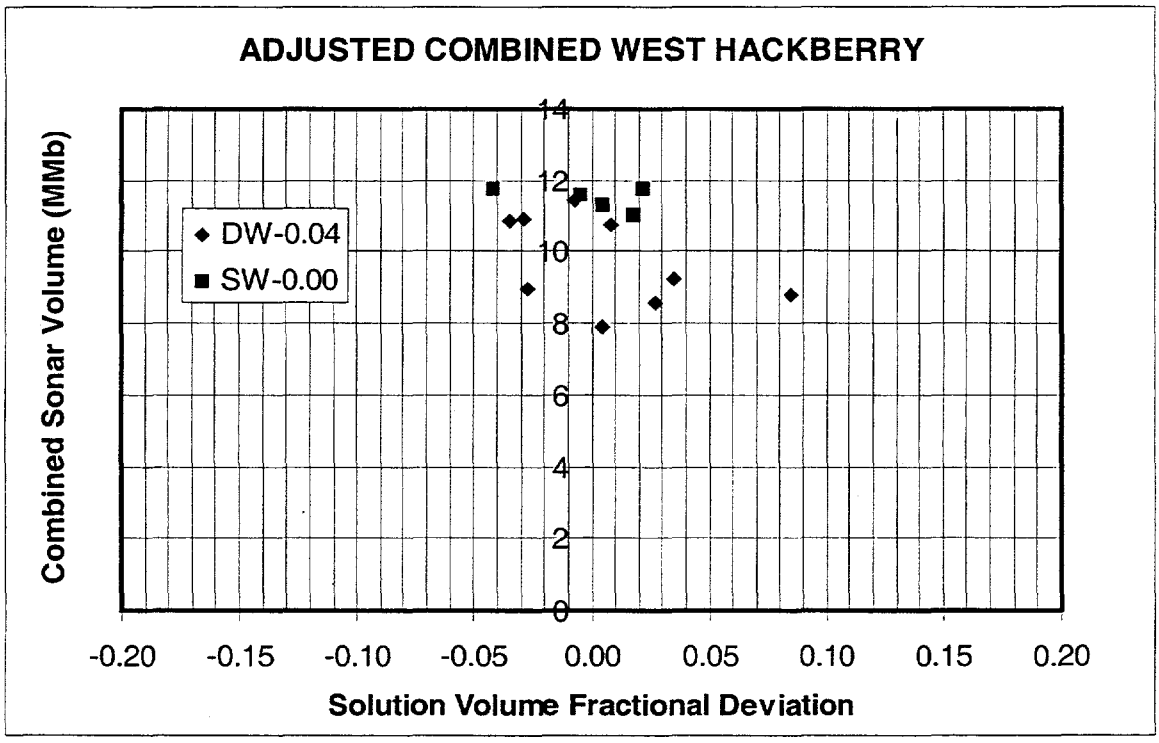

Figure 25. Adjusted Deviations of Solution from Combined Sonar Data, West Hackberry.

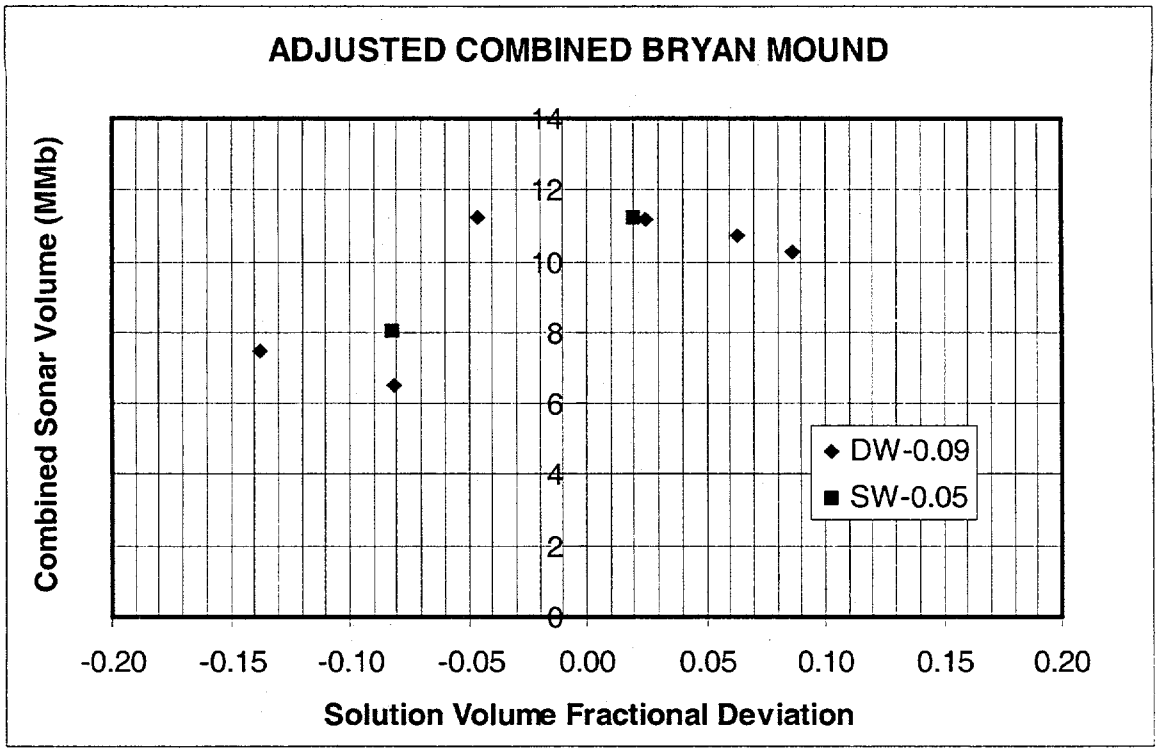

Figure 26. Adjusted Deviation of Solution from Combined Sonar Data, Bryan Mound.

the normal probability distribution. As in the case of the uncombined sonar data, the combined sonar data conform very well to the normal distribution. The fact the data conform to a normal distribution strongly suggests that the biases used to adjust the data are nearly correct. Here, the distribution is somewhat narrower than that determined for the uncombined data. For the combined data a standard deviation of +/-0.0472 was found, or slightly less than 5%. A narrower standard distribution is certainly consistent with the earlier opinion that the uncertainty in the combined sonar volume should be less than in the previously discussed uncombined volumes.

Even though the database is quite small, the difference between the normal distribution and the data distribution shows a systematic trend. As noted earlier, the Bryan Mound data exhibit markedly greater scatter, which in Figure 27 appears as exaggerated, but relatively unimportant, tails in the distribution. When these data are fit by the normal distribution, they have the effect of broadening the normal distribution. Thus, the experimental data in the center of the distribution actually have a higher slope, indicating the narrower distribution of the West Hackberry results. Here the mean was determined to be just –1.20%, consistent with the somewhat steeper central portion of the data distribution.

5.3 Equivalent Sonar and Oil Inventory Data Statistics

Perhaps one of the more significant comparisons is between the oil inventory and the truncated portion of the sonar survey above the oil/brine interface. The significance resides in the fact the oil inventory seems to be quite accurate, with the uncertainty of the cavern meters minimized. This implies that only the very small +/-0.25% uncertainty of the custody transfer meters evident in these comparisons. These equivalent surveys are relative common because they took place through the brine prior to the filling with oil, and are therefore relatively easy to perform. A

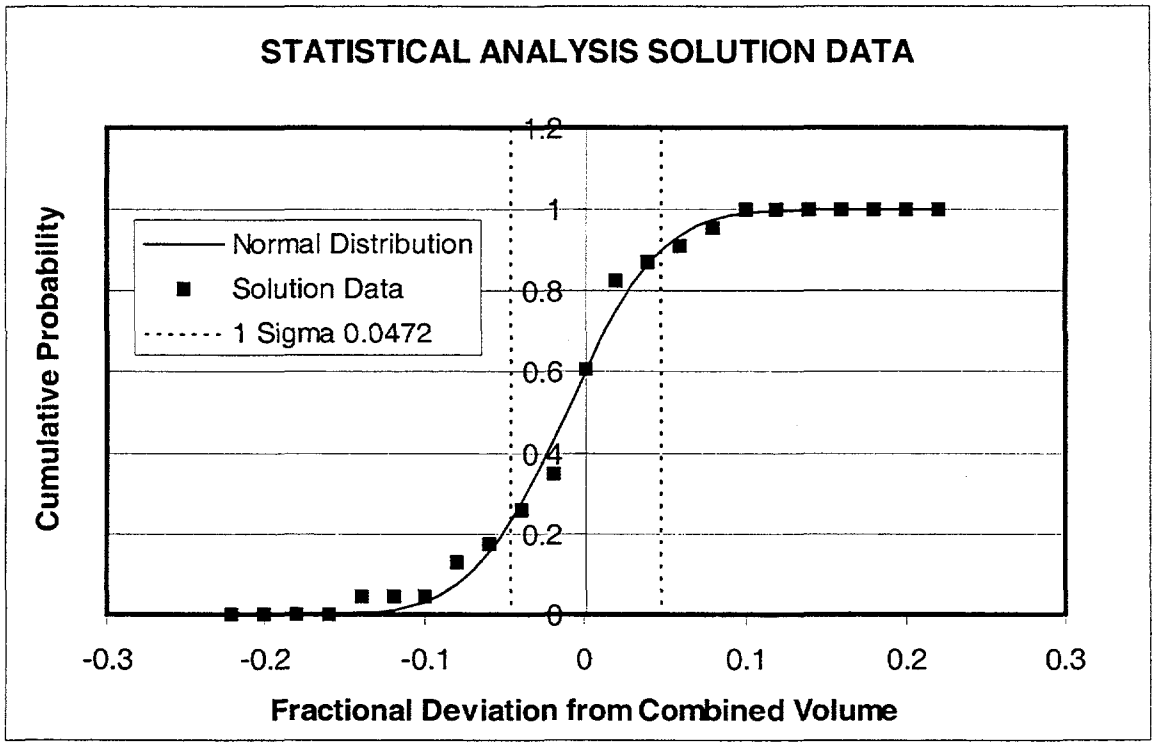

Figure 27. Cumulative Distribution for All Solution and Combined Sonar Data.

certain amount of care is required in determining the appropriate equivalent sonar volume. Some data which were questionable were not included in the analysis. The analysis proceeded in essentially the same manner as the analysis of the solution volumes just presented.

There is some difference in the databases involved. Whereas in the previous comparisons the specific operators could be identified because the data were taken directly from the sonar surveys, in the comparison of the equivalent sonar volumes the databases are secondary products. These secondary records were summary data used within the project. Typically, in the database the original survey data were not identified specifically by operator, although in theory they could be traced. Consequently, the principal categories were taken as sweet or sour crude, as governed by the inventory. Each category would be related to a unique manifold at a given site.

The deviations were determined between the oil inventory and the equivalent sonar volume, with the equivalent sonar volume being taken as the reference. These data were previously given , for Big Hill in Table II and Figure 3, West Hackberry in Table V and Figure 9, Bayou Choctaw in Table VIII and Figure 14, and Bryan Mound in Table X and Figure 19. All of the data is used, including both the SPR constructed caverns and the SPR purchased former commercial caverns, except for those questionable data of West Hackberry noted previously. Again, it is necessary to reduce the data by removing the biases, however, the biases here can not be identified with operator. Rather, the biases are recognized only by the groupings of data. In a sense, this makes the biases more arbitrary. Unadjusted deviation data for Big Hill are given in Figure 28, and for West Hackberry in Figure 29. These data are relatively clean with less than 1% apparent bias for either site. The situation for the remaining two sites is more complicated. The data for Bayou Choctaw and Bryan Mound seem to form distinct groups with fixed but different biases for each group, but without regard to crude type. Consequently, the unadjusted data for these sites were

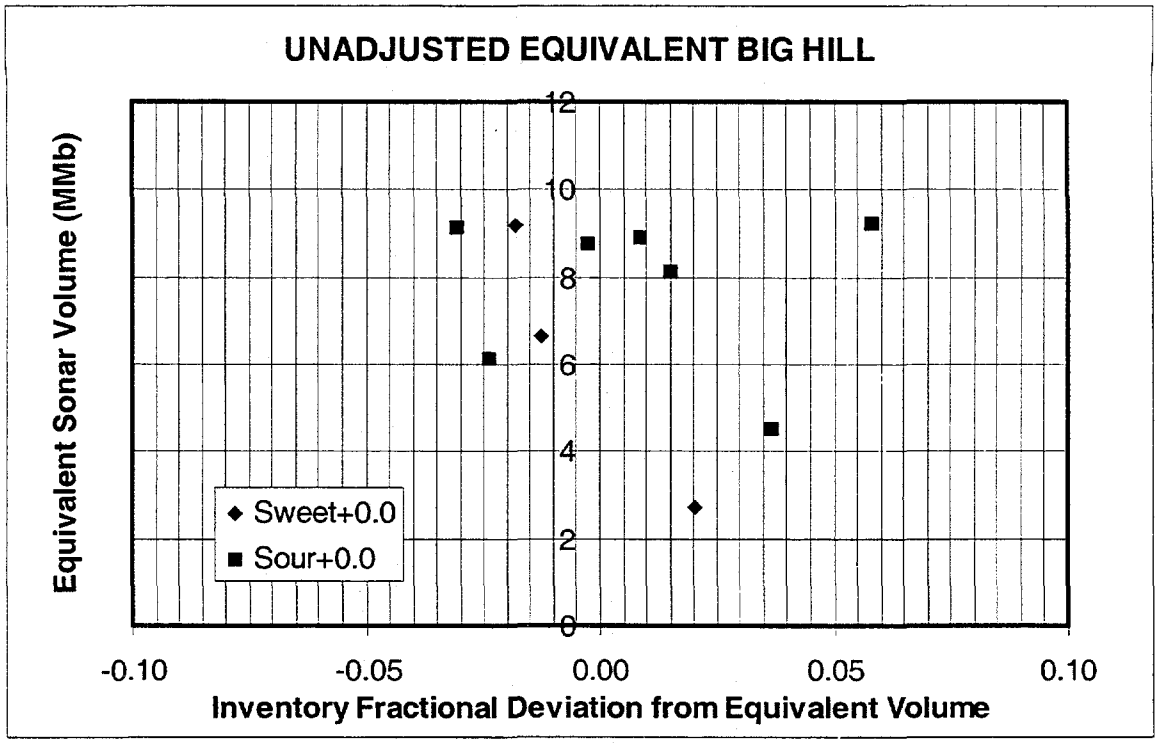

Figure 28. Unadjusted Deviation of Equivalent Sonar from Oil Inventory, Big Hill.

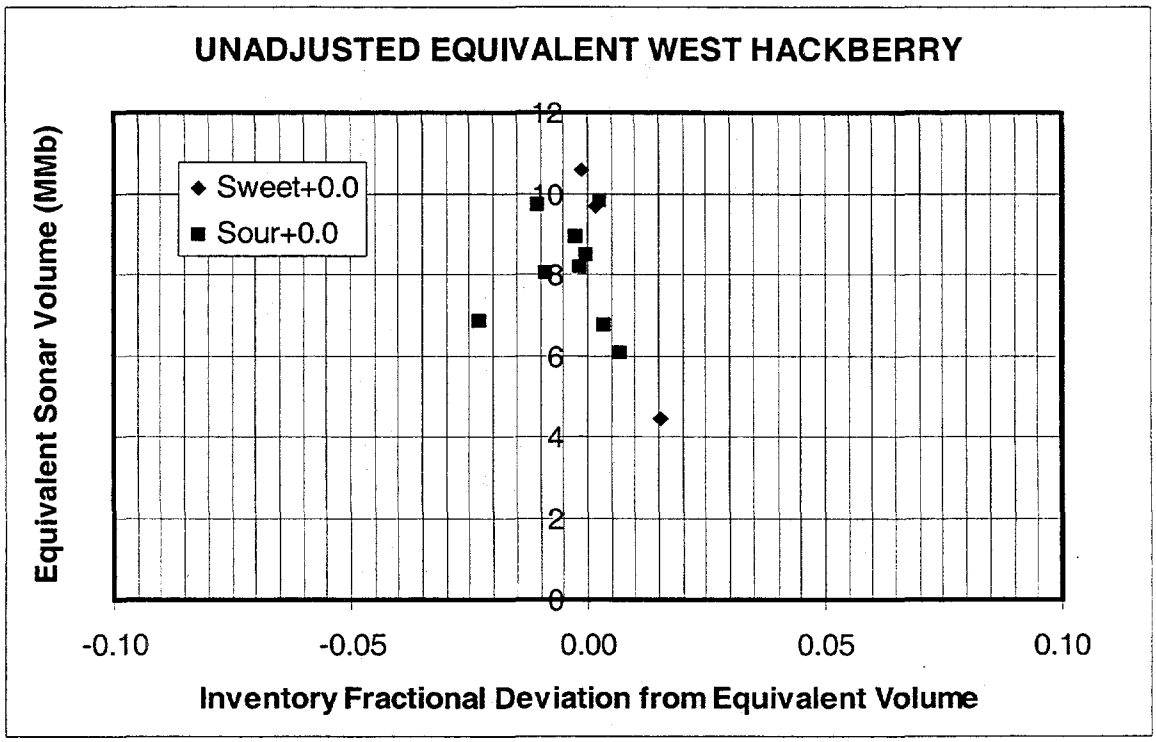

Figure 29. Unadjusted Deviation of Equivalent Sonar from Oil Inventory, West Hackberry.

plotted, and then the appropriate adjustments are determined by group. The amounts of the adjustments are suggested by the initial plots and trend lines of the initial data comparisons. The unadjusted data for Bayou Choctaw are given in Figure 30, and comparable unadjusted data for the Bryan Mound facility are given in Figure 31. The adjusted data for Bayou Choctaw and Bryan Mound were then plotted. The adjusted data for Bayou Choctaw is in Figure 32 and for Bryan Mound in Figure 33. Actual adjustment amounts are noted in the legends of the figures. Where adjustments of data with two different biases are made, the resultant data are called mixed bias. Essentially, one group of data required no adjustment and the other group required roughly 7% to 8%. Both the adjusted and the unadjusted data are used in the statistical analysis.

Two options need to be explored: first that some of the uncertainty observed in the Bayou Choctaw and Bryan Mound data is the result of different biases in the data, plus scatter, and second that the uncertainty is from scatter alone. For the first instance, the unadjusted data shown in Figures 28 and 29 are used with the mixed adjusted data shown in Figures 32and 33 The cumulative distribution was determined for bin widths of 0.001 or 0.1%. This bin width is less than that used previously for the solution data because it is apparent that the equivalent volume data are more tightly grouped. The statistical analysis of these results is shown in Figure 34. As shown in the figure, the cumulative distribution compares very well to the normal distribution. The cumulative distribution has a standard deviation of 0.0169 and a mean of -0.0083.

Under the assumption that the bias adjustments are acceptable, the standard deviation becomes +/- 1.69%. Actually, as previously noted, the uncertainty determined from the comparisons of the sonar and oil inventory data is the sum of the individual uncertainties in the measurement techniques. However, because the uncertainty in the oil inventories is believed to be very small, the standard deviation is effectively just the uncertainty in the sonar survey data.. Consequently,

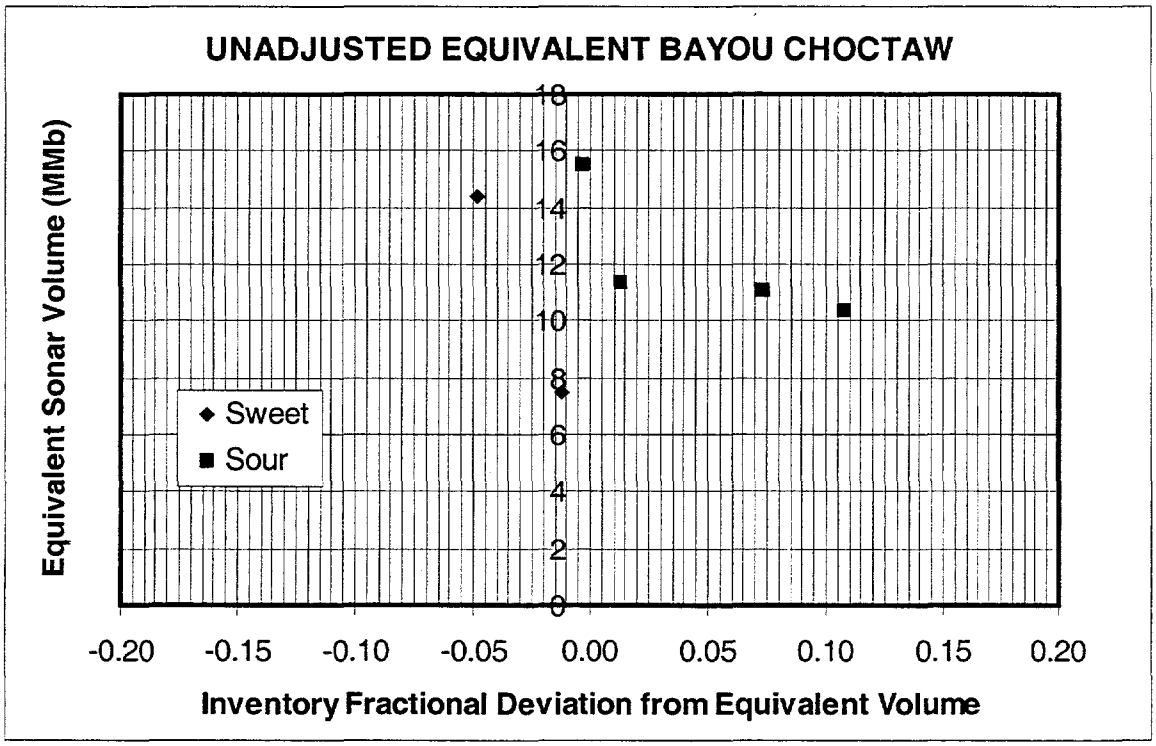

Figure 30. Unadjusted Deviation of Equivalent Sonar from Oil Inventory, Bayou Choctaw.

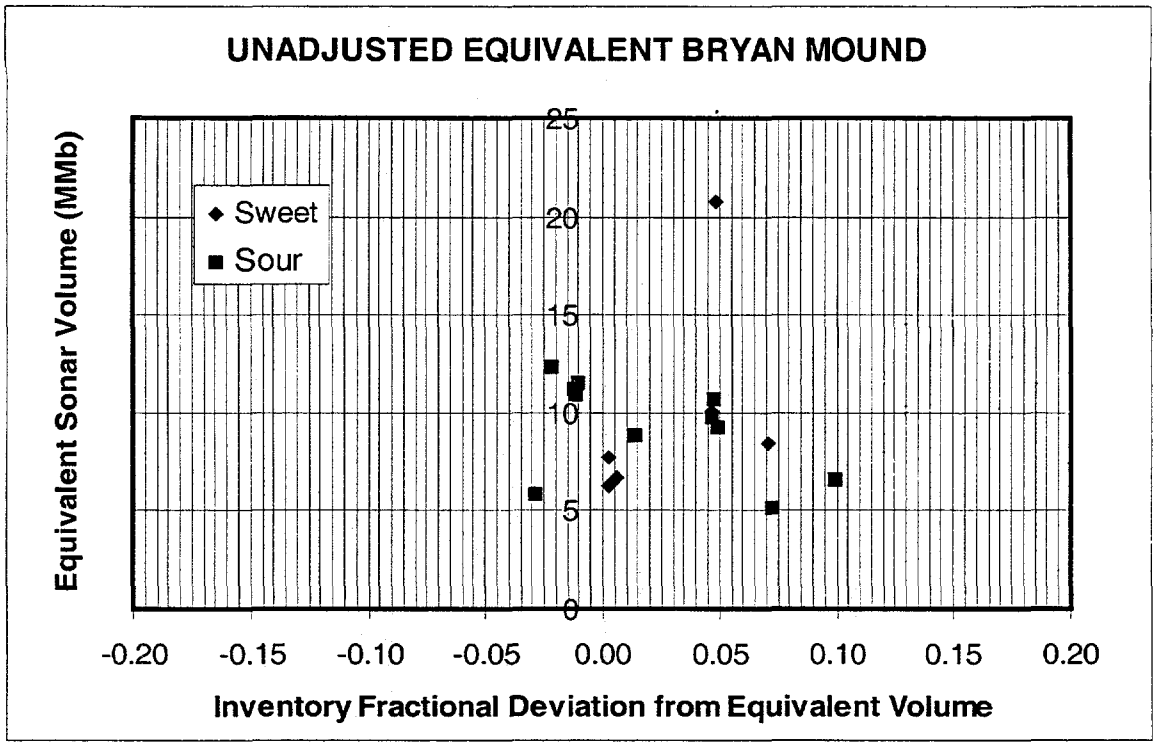

Figure 31. Unadjusted Deviation of Equivalent Sonar from Oil Inventory, Bryan Mound.

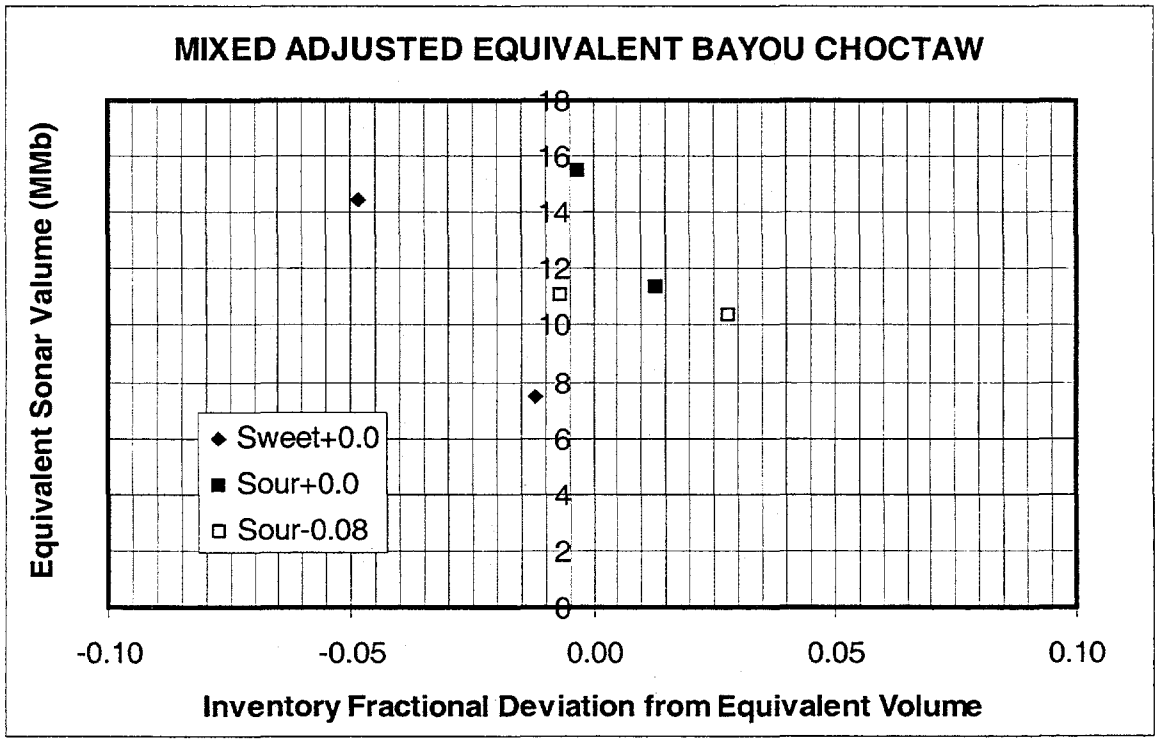

Figure 32. Mixed Adjusted Deviation of Equivalent Sonar from Oil Inventory, Bayou Choctaw.

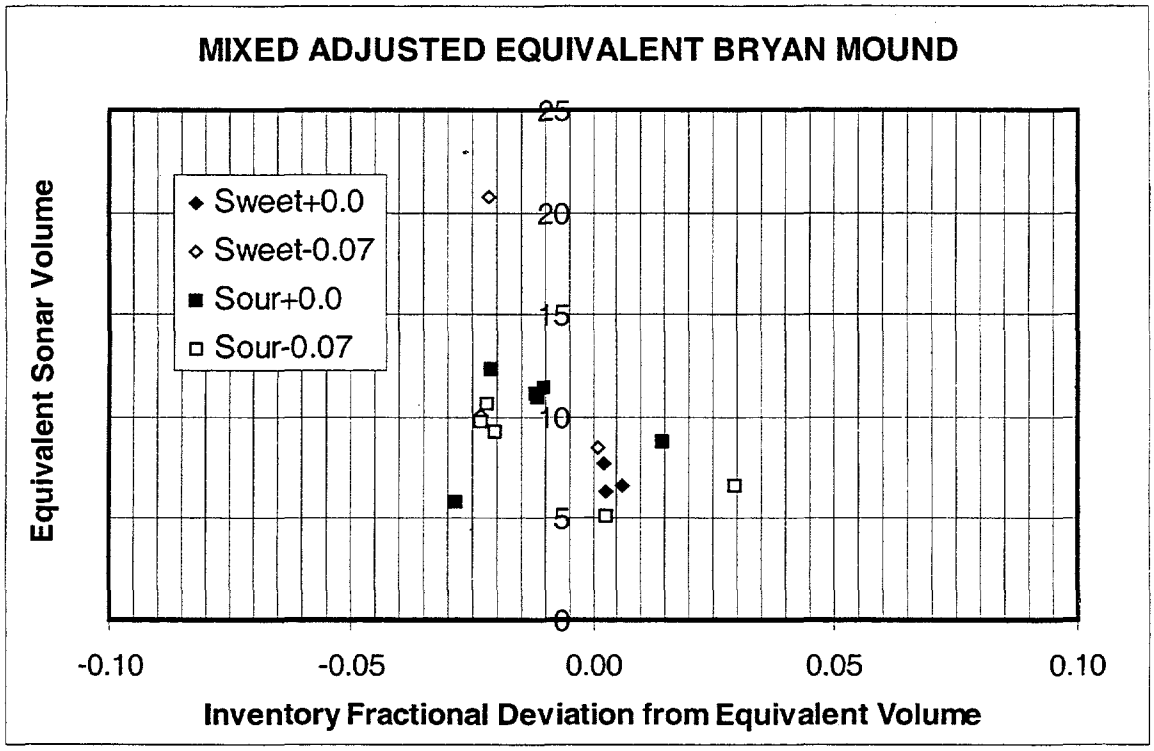

Figure 33. Mixed Adjusted Deviation of Equivalent Sonar from Oil Inventory, Bryan Mound.

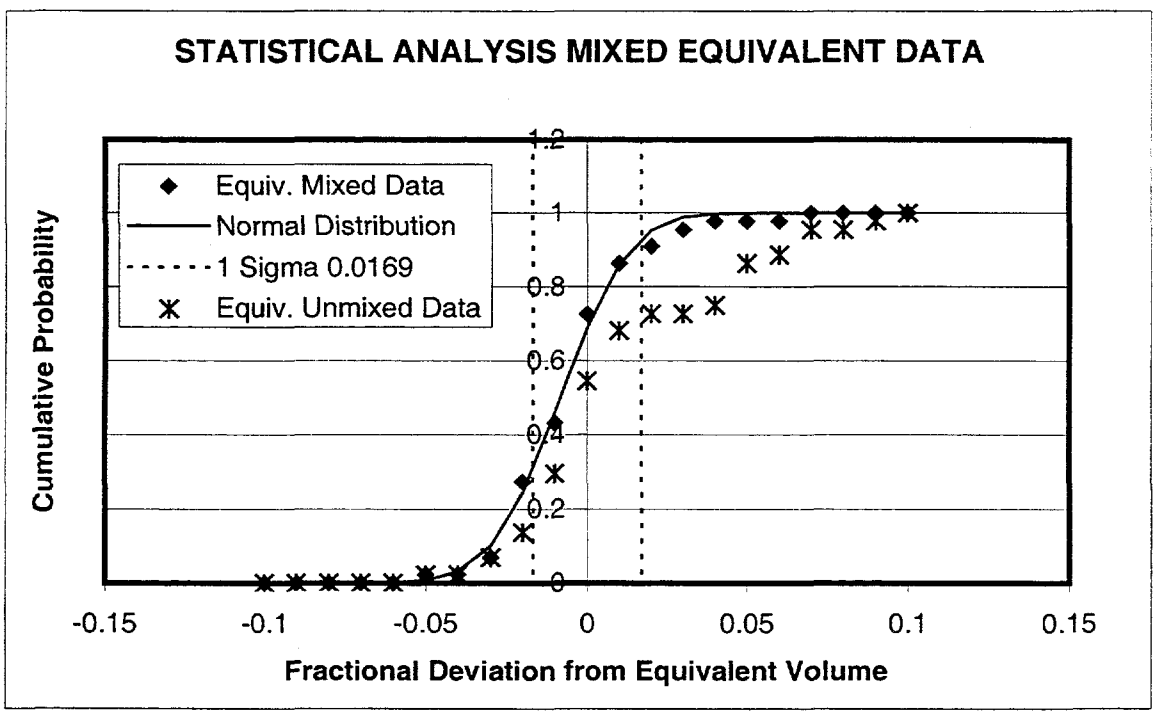

Figure 34. Cumulative Distribution for All Equivalent Sonar and Oil Inventory Data.

the statistical analysis appears to be in fundamental agreement with the commonly deduced uncertainty of +/-2% in the sonar survey data, which is comparable to the +/- 1.69% of the first standard deviation. Certainly, this is a gratifying result, which is supported moreover by the earlier results of the uncertainties in the calculated solution comparisons to the sonar data.

Even though there is confidence in the use of mixed biases for the adjustment of the data, the impact of this must be examined. To this end, the unadjusted data for all of the sites was treated as described to obtain a cumulative probability distribution. These data are shown in Figures 28 through 31. The cumulative distribution of these data is also shown in Figure 34. As compared to the normal distribution, the unadjusted distribution becomes broader, and the mean also shifts to higher positive values. Significant asymmetry changes take place in the character of the positive side distribution tail. This type of asymmetry in the data curve suggests the possibility of an additional, but skewed, normal distribution. This equivalent to saying that some of the data are biased, as initially assumed. However, even the distribution of the unadjusted data would still give quite a reasonable standard deviation, almost within the commonly held acceptable limits of sonar uncertainties.

5.4 Statistical Analysis of Surveys through Oil

With only five surveys, there are insufficient data from the through-oil surveys to perform a statistical analysis. However, it must be remembered that these surveys are quite difficult to perform, primarily because of the transmission properties of the crude oil. This obviously taxes the resolution of the survey. In addition, the modifications to the tools and techniques required to obtain these surveys were significant. This certainly caused problems. Deviations are relatively large, certainly much larger than the possible expectation for such a direct method of comparison. For the three measurements in Big Hill caverns, the sonar through oil to oil inventory ratios were 0.937, 1.019, and 1.010, for deviations from –6% to +2%. Results for the two measurements in West Hackberry are even less understandable, with the ratios of the sonar through oil to the oil inventory of 1.035 and 1.119, or deviations of +4% to +12%. Here, for all of the data, the average deviation is +2.4%.

While it is obvious that the through-oil surveys have significant problems, it is not possible to define the nature of these problems. It seems only continued experience and the acquisition of a larger database will shed light on the problems. In general, if the resolution and accuracy of the through-oil surveys could be improved, they would be the most useful tool to the project.

6. SUMMARY

There are several meaningful observations that can be made from the above data analysis. The summary is presented in the same order as the analysis, with the results first of the calculated solution volume comparisons to the uncombined sonar volumes and then progressing to the oil inventory comparisons to the equivalent sonar volumes. However, most emphasis is placed on the more relevant bias and statistical results, as follows:

(1) One of the most important findings of this study was that the measurements appear to contain two distinct kinds of error, a systematic deviation (bias) from the perfect correlation and a scatter (uncertainty) caused by experimental error. As a result, it is possible to make assumptions about contributions of these factors in any given data set.

(2) In the comparison of the calculated solution volumes to the sonar survey volumes, there are two groups of data: the uncombined sonar data involving only small amount of blanket oil included in the total sonar volume, and combined data involving significant amounts of fill oil included in the total sonar volume. When the uncombined data are adjusted for the assumed biases and analyzed statistically, the uncertainty conforms well to a normal distribution. The distribution has a standard deviation of +/-5.78% with a mean of +0.90%. With the standard deviation being a sum of the uncertainties, this suggests a possible +/-2% uncertainty in the sonar volume and a +/-3% in the solution volumes. These numbers are both somewhat less than the commonly accepted +/-5% for sonar by the survey companies and the +/-5% uncertainty commonly quoted for solution volumes by the contractors. The standard deviation for the combined sonar volumes, because they combine the uncertainties of the sonar with the more precise oil volumes, are somewhat less than that of the uncombined sonar data, as would be expected.

(3) The probability distribution for the equivalent sonar volumes compared to the oil inventory volumes indicates an uncertainty with a normal distribution with a standard deviation of +/-1.69%, and a mean value of –0.83%. Because of the small calibrated uncertainty in the custody transfer measurement, most of the uncertainty in these databases is thought to be a consequence of the uncertainty in the sonar measurements. The standard deviation value is very consistent with the uncertainty of about +/-2% deduced from the comparison of the solution volumes and the sonar volumes, discussed above.

In addition to the major findings give immediately above, there are a number of other lesser points that should be mentioned, as follows

(1) Based on the significant differences in the biases produced by the databases of the different sonar survey operators, it appears that the biases depend upon survey company, and perhaps on the specific survey tool.

(2) The uncombined databases from Big Hill and Bayou Choctaw, where cavern construction was completed prior to oil filling, offer the highest quality databases. The Big Hill database from Sonarwire surveys exhibited probable biases of +2.5%. Comparable databases from MicroGage surveys, however, produced a –2.1% bias. The fact that two operators obtained opposite biases may indicate potential differences in sonic velocity values as determined for the different tools. Equally, high quality data from West Hackberry surveys obtained during the early stages of construction essentially confirms the above observations. The Sonarwire database exhibited a +5.0% bias, identical to the Dowell bias of +5.0%. Here again, the MicroGage data were contrary with a –9.0% bias.

While Bayou Choctaw consisted of only two caverns (eventually just one retained by SPR), the apparent biases for the Sonarwire and MicroGage databases were identical at +6.0%. Bryan Mound, from which the databases one would supposed to be of less quality, appeared to actually be quite acceptable.

(3) The equivalent sonar volumes and oil inventory databases of Big Hill and West Hackberry sites do not appear to have any bias, which leaves just random scatter. However, this seems to be an unusual case. Similar databases for Bayou Choctaw and Bryan Mound contained effects attributed to bias. But, a single bias value did not apply to the data from a given site. Adjustments for bias had to be applied on a group basis, where the group included both caverns with sweet and sour crude, which eliminates association of the bias with the internal site manifold distribution uncertainties. An acceptable value of the bias appeared to be +7% to +8%.

The results of this study, in general, indicate that measurement methods are really quite good, and in fact support or improve those values of uncertainty customarily associated by the technical community with each type of volume measurement. The reality of measurement bias should be kept in mind, with the possibility that the bias is an experimental factor that perhaps can be eliminated. One major recommendation is that in the future it is important the measurements be compared to each other in the context of the perfect correlation relationship.

There is one clear recommendation that comes from this study. An independent calibration of the sonic velocity measurement device associated with each sonar tool could potentially make a very significant improvement in the technique and the sonar survey results.

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8 APPENDIX - INDEPENDENT OBSERVATIONS ON INSOLUBLES

During the considerable extraction effort to obtain the data given above, additional data were also reclaimed. Specifically, it was possible to determine in a crude fashion the content of insolubles in the salt dissolved during the construction of some caverns. Because sonar surveys coincided with the end of each solutioning stage, the amount of additional solutioning could be calculated and the new bottom elevation could be measured. Thus, it was possible to determine the volume of the accumulated insoluble material. For a given stage of solutioning, the previous sonar survey gives the diameter of the cavern at the top of the sump, as well as the depth to this point (cavern total depth). During the solutioning stage, the new solution volume can be calculated from the known amount of inflow raw water and outflow brine concentrations, as previously noted. When the given solutioning stage had been completed, all of the insoluble material released by the solutioning is assumed to have fallen into the sump; i.e., none of the insolubles were carried out in the brine stream. For most of the data presented here, the cavern volumes were reasonably large so one would suppose the fluid velocities were small and that most of the insolubles would settle to the bottom. Subsequently, a new cavern total depth is obtained. Then, the volume of the insoluble material in the sump can be calculated, and hence, the percentage of the insolubles in the volume of salt dissolved during a given stage. The calculation based on the values described, is an "apparent" or raw volume. The volume is apparent because the sump material may include significant porosity. This apparent volume is that given earlier in Tables I, III, VII, and IX.

In the calculation it is necessary to convert the solution volume (in barrels) for a given stage into cubic feet of salt, where the conversion is taken as 5.62 cubic feet per barrel. Although in theory the solid volume equivalent to the apparent volume can be calculated, there is a difficulty in determining the exact porosity of the material. When the insoluble material falls to the sump, it is probably an assemblage of unconsolidated particles. Unfortunately, however, the exact packing density is unknown. Further, with time the sump material probably compacts to form a more dense mass. Only the two extremes of this process can be known. Loosely deposited material typically can produce only about 55% of its fully compacted density. On the other hand fully compacted material will have the full density, or 100%. Even though it is doubtful that full compaction occurs, it is known that self-compaction of wet insolubles, probably polyhalites and anhydrites together with clay particles, can be reasonably rapid. This is evidenced by deposits in brine ponds and material piles exposed to the weather. Whether or not the apparent volume of insolubles gives the insoluble content of the cavern salt also depends upon how much of the insoluble content is transported out of the cavern in the brine stream.

The apparent volumes of insolubles have been calculated for those caverns where the records are available. These volumes are given in Tables XII -XV. Apparent volume, which is the number calculated from the solutioning, sonar and depth data, is the raw data. It must be multiplied by whatever one assumes for the compaction density ratio. For the study here, it is assumed that the sump material at the time the accumulation depth is measured is 55% of the fully compacted density. Because there is little time delay between solutioning and the survey, little compaction is believed to have taken place.

Apparent uncompacted insoluble percentage values for each stage are multiplied by a weighting factor taken as the calculated solution volume generated during that stage over the sum of all of the stage volumes. This gives the cavern insoluble content, or at least that portion of the cavern sampled. These apparent content percentages are then multiplied by the assumed volume fraction of solids in the uncompacted volume to give the equivalent <u>solid</u> insoluble content. The process is repeated further using the total calculated solution volumes of the stages involved to obtain an volume average insoluble content for the salt dome, or at least the SPR portion of the dome.

Table XII. Insoluble Contents from Stage Solutions and Sump Build-Up, Big Hill.

Cav. No. (Events)	Stage	Apparent Insoluble Content* Stage %	Vol. (MMb)	Tot. %	Calc. Solid % Tot. % x 0.55	Remarks
BH101	1	09.66	8.2			
	2	07.69	1.8	09.31	05.12	
BH102	1	11.20	7.8			
	2	12.80	2.0	11.53	06.34	
BH103	1	08.46	3.5			
	2	03.52	6.4	05.35	02.94	Some Stage Variation
	3	05.53	4.5			
BH104	1	10.20	8.0	10.20	05.61	
BH105	1	06.65	8.5			
	2	12.00	1.7	07.54	04.15	Some Stage Variation
BH106	1	11.20	2.3			
	2	09.44	5.3			
	3	10.20	2.3	10.03	05.52	
BH107	1	14.70	8.6			
	2	12.40	1.5	14.36	07.90	
BH108	1	08.76	7.9			
	2	15.70	2.4	10.38	05.71	Some Stage Variation
BH109	1	06.99	7.9			
	2	10.60	2.3	07.80	04.29	
BH110	1	06.52	8.5	06.52	02.36	
BH111	1	09.28	7.6			
	2	10.30	2.2	09.51	05.23	
BH112	1	08.60	7.9			
	2	13.80	1.9	09.61	05.28	
BH113	1	10.60	2.6			
	2	08.96	4.8			
	3	04.52	5.1	07.80	04.29	Some Stage Variation
BH114(1)	1	08.40	4.0			
	2	09.85	2.9	09.01	04.95	
		Facility Insoluble Content Ave. Vol. %.			04.97	

* Stage % in volume percent is for the partial Vol. (MMb) involved in that stage, and Tot.% is the cavern insoluble content calculated using the Stage % weighted by stage/cavern volumes.

The cavern volume average insoluble content is obtained by weighting the individual solutioning stage results for the cavern, and summing over all of the stages. The weight factor is just the fraction represented by the stage compared to the total solution volume (either barrels or cubic feet can be used). The facility volume is obtained in the same manner. The weighting is the cavern volume over the total facility volume taken times the cavern insoluble content.

The results for Big Hill as shown in Table XII are very complete. Here the volume average insoluble material content for the domal salt of the facility was found to be 4.97%. This seems a

very reasonable number. It must be remembered that this number represents all of the insoluble materials, including impurity particles of clay and silica minerals and polyhalite and anhydrite phases. Only a small portion of the total is thought to be non-coherent inclusions of clay and silica minerals. The scatter about the 4.97% average is from +2.9% to –2.6%.

The results for West Hackberry in Table XIII are nearly complete except for three caverns where the records did not permit calculation of the insoluble content. Whether or not a more detailed search for these records would be fruitful is unknown. Data from the individual stages of cavern development appear to be quite uniform. An average value for the salt dome region of the SPR caverns is 3.94%, again a very reasonable value. Scatter is +1.7% and –1.6% around the average.

Even though there were two caverns constructed at Bayou Choctaw, only the SPR cavern has sufficient information to calculate the insoluble content. This result is shown in Table XIV. The

Table XIII. Insoluble Contents from Stage Solutions and Sump Build-Up, West Hackberry.

Cav. No. (Events)	Stage	Apparent Insoluble Content* Stage %	Vol. (MMb)	Tot. %	Calc. Solid % Tot. % x 0.55	Remarks
WH101	1	08.50	4.8	08.50	04.68	
WH102(1)	1	10.33	2.9	10.33	05.68	
WH103(3)	1	10.78	1.9			
	2	09.35	4.5	09.77	05.38	
WH104	1	08.99	1.6			
	2	06.19	4.1	06.98	03.84	
WH105	1	03.24	2.3			
	2	05.73	4.2	04.85	02.67	
WH106						No Data
WH107(1)	1	09.74	3.0	09.74	05.36	
WH108(2)	1	08.53	2.5			
	2	06.59	3.0	07.47	04.11	
WH109(2)						No Data
WH110(1)						No Data
WH111	1	05.39	6.5			
	2	06.88	1.3	05.64	03.10	
WH112	1	06.46	3.8			
	2	09.35	2.5	07.61	04.18	
WH113	1	07.70	6.1	07.70	04.24	
WH114	1	06.39	4.7	06.39	03.51	
WH115	1	06.34	4.4	06.34	03.49	
WH116	1	04.61	0.9			
	2	04.14	3.0	04.25	02.34	
WH117	1	07.71	6.0			
	2	05.00	2.2	6.98	03.84	
		Facility Insoluble Content Ave. Vol. %			03.94	

* Stage % in volume percent is for the partial Vol. (MMb) involved in that stage, and Tot.% is the cavern insoluble content calculated using the Stage % weighted by stage/cavern volumes.

Table XIV. Insoluble Contents from Stage Solutions and Sump Build-Up, Bayou Choctaw.

Cav. No. (Events)	Stage	Apparent Insoluble Content* Stage %	Vol. (MMb)	Tot. %	Calc. Solid % Tot. % x 0.55	Remarks
BC101(2)	1	03.21	3.4			
	2	03.13	2.9	03.17	01.74	Single Cavern
		Facility Insoluble Content Ave. Vol. %			01.74	

* Stage % in volume percent is for the partial Vol. (MMb) involved in that stage, and Tot.% is the cavern insoluble content calculated using the Stage % weighted by stage/cavern volumes.

stages are very consistent and the cavern average is relatively small, being only 1.74%. At this point there is no independent information that suggests the Bayou Choctaw salt is of higher purity than the other domes. However, even though the volume percentage of insolubles in Bayou Choctaw appears to be markedly less than the other facilities, the value is still considered to be a reasonable value.

As one would expect, the Bryan Mound results are somewhat fragmentary. However, where the data permit, the insoluble contents have been calculated and are given in Table XV. Only eight of the sixteen caverns had sufficient data. The volume average of these eight was found to be 4.13%. This value for the domal average of the site is very consistent with the other SPR domal values. Scatter is +1.6% and –0.8% about the average.

For Bryan Mound, there are some earlier calculations [Munson et al., 1998] of the insoluble content of a number of the caverns. While the general calculational approach is the same, the details differ. In these earlier calculations, the volume of the sump was obtained by assuming a conical sump evolution from the initial total depth of the solutioning well, upward to the cavern bottom diameter obtained upon completion of solutioning. Insoluble contents determined in this manner are also given in Table XV. Even with the possibility for greater error because of the assumption of the sump geometry, the insoluble quantities determined in the earlier manner are comparable to those of this work. For the four caverns where the two determinations are directly comparable, they agree within a factor of two. The earlier results for the seven caverns based on the total sump-volume calculation would appear to average about 4.30%, compared to 4.13% from this work.

The comparable total solution volume upon variation in the percentage insolubles for some stages were different by a factor of two, as noted in the tables. In some respects, it is quite surprising that the crude calculations of the insoluble contents of the caverns are reproducible and have as little scatter as they do. Also, they are actually well within what one would expect from other independent estimates based on recovered core and direct in-mine observations. Typically these estimates range up to a few percent, but seldom exceed ten percent. Although no illustration is given, there appears to be no systematic relationship between the insoluble contents and the cavern location in the dome. Whether this is the result of the scatter, homogeneity of the dome, or the use of the total insoluble content rather than impurity particle content, is unknown.

Some additional observations must be made. There is no evidence that the creep rate of the salt in the dome around the caverns is affected by the insoluble content. A relatively wide range of

Table XV. Insoluble Contents from Stage Solutions and Sump Build-Up, Bryan Mound.

Cav. No. (Events)	Stage	Apparent Insoluble Content* Stage %	Vol. (MMb)	Tot. %	Calc. Solid % Tot. % x 0.55	Remarks
BM101(2)	1	20.96	0.5			05.5% insol.#
	2	07.30	3.3			
	3	07.13	4.8	08.99	04.40	Some Stage Variation
BM102(2)						01.0% insol.#
BM103(5)	1	07.80	4.9			04.9% insol.#
	2	08.32	2.7	07.98	04.39	
BM104						No Data
BM105						05.3% insol.#
BM106(10)						No Data
BM107(9)						No Data
BM108(5)						04.2% insol.#
BM109(7)						No Data
BM110						No Data
BM111(1)	1	09.47	3.4			03.4% insol.#
	2	12.20	2.1	10.51	05.78	
BM112(5)	1	07.84	3.5	07.84	04.31	03.2% insol.#
BM113(2)	1	05.52	3.2			
	2	06.50	2.8	05.98	03.29	
BM114	1	06.36	3.3	06.36	03.50	
BM115	1	03.97	3.7			
	2	08.17	1.6			
	3	04.44	3.7			
	4	11.93	1.9	06.01	03.31	Some Stage Variation
BM116(1)	1	07.00	3.0			
	2	08.67	2.5	07.75	04.27	
		Facility Insoluble Content Ave. Vol. %			04.13	04.30% insol.#

* Stage % in volume percent is for the partial Vol. (MMb) involved in that stage, and Tot.% is the cavern insoluble content calculated using the Stage % weighted by stage/cavern volumes.
# Insoluble percentage calculations from Munson et al. [1998].

creep rates [Linn, 1998], as determined by the volume closures of the caverns, is found, from a high value of 0.227 %/year down to 0.014%/year. On theoretical grounds, the insoluble content is expected to have little influence on the creep response of salt.

The other question that arises concerns the relationship, if any, between the number of hanging string events [Munson et al., 1998] and the insoluble content of the salt. Each cavern contains a number of long strings of casing or tubing that are suspended vertically from the surface collar of the well into the cavern. These hanging strings permit transfer of fluids into and out of the cavern. A hanging string event is where a portion of the string is lost. Some of the events are believed to be the result of chunks of salt falling from the walls of the cavern and impacting the hanging string. The number of these events (the figure in parenthesis following the cavern

number) are given in the tables for each cavern. The caverns with most hanging sting events, BM106 and BM107, unfortunately, have no solutioning data available for the determination of the insoluble amounts. Nevertheless, the bulk of the evidence supports the idea that the most hanging string events occur in caverns with more than 3% insolubles. The number of events is greatest for contents above 4%. The maximum cavern solid insoluble content never exceeds 6%. Bayou Choctaw is of course the exception, with two events and a insoluble content of only 1.74%. With the available evidence it is really difficult to assign any significant correlation between the insoluble contents and the development of hanging string events. As previously noted [Munson et al., 1998], Bryan Mound exhibits the most events. To the contrary, West Hackberry and Big Hill caverns have relatively few events, even with about the same insoluble contents as the Bryan Mound dome. Consequently, it appears that the insoluble content alone is insufficient to determine the propensity of a cavern to sustain a hanging string event.

There is still much that is unknown about the interior conditions of the SPR caverns. The insoluble contents determined here do not separate the possible different insoluble components of the natural salt deposits of the domes. Two of the components are second phase components, polyhalite and anhydrite, which probably form coherent platelets on specific crystallographic planes of the halite. The other insoluble component is probably a collection of non-evaporite impurities, such as clay and silicate particles. These particles are not coherent with the halite lattice. Such impurities are common as products of land erosion carried into the body of water from which the evaporite is deposited. Evidence of these impurities in domal salts is found in core recovered from the domes and in underground mine openings in the domes. In general, the particulate matter is perhaps only one or two percentage points of the total insoluble content.

In summary, based on an assumed initial sump material with 0.55 relative volume porosity, the average, equivalent solid density, insoluble content of the SPR domal salts is 4.97% for Big Hill, 3.94% for West Hackberry, 1.74% for Bayou Choctaw, and 4.13% for Bryan Mound. These solid percentages include the second phase anhydrite and polyhalite as well as the non-evaporite particulate matter. Although there is no way to separate these insolubles, the total amounts are consistent with other estimates of salt dome compositions.

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