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RELATIVE EVALUATION OF STORAGE CAVERN VOLUME MEASUREMENTS

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ABSTRACT

Over the course of the construction and operation of the Strategic Petroleum Reserve (SPR) crude oil storage caverns, three types of measurements of the cavern volumes have been maintained: calculated solution volumes based on dissolution of salt by raw water, calculated sonar volumes based on the sonar surveys of the cavern dimensions, and cavern volumes occupied by metered oil inventories. Because these are frequently made almost concurrently, the measures are of the same, but unknown, cavern volume and it is possible to make a comparative evaluation of the volumes. In this way it may be possible to understand and determine the uncertainties involved in these measures. A very simple theory shows that any measure can contain a bias produced by a systematic error and a scatter produced by a random error. By equating volumes determined by different measurement types it is possible to distinguish biases from random scatter. As a result, a comparative evaluation of solution volumes against sonar volumes suggests that a bias of a few percent exists, and this bias seems to depend upon the specific survey company. Because the bias can be removed from the raw results, the remaining random uncertainty data can be analyzed statistically. The random scatter, which is a sum of the scatter of the sonic survey and the solutioning process is very nearly a normal distribution and has a standard deviation of 5.78%, which appears to be reasonable. This statistical uncertainty suggests a +/-2% uncertainty in the sonar measurements and a +/3% uncertainty in the solutioning data. These two values are less than the +/-5% that is customarily associated with these two measures by the survey companies and construction contractors. Evaluation of the equivalent sonar volumes when compared to the oil inventories also show bias and scatter. When analyzed statistically, the random uncertainty in the equivalent sonar volumes compared to the oil inventory also gives essentially a normal distribution with a standard deviation of 1.69%. These results suggest that the deduced +/2% scatter in the sonar survey dominates the uncertainty, with the very small oil inventory uncertainty governed by the highly accurate oil custody transfer meter.

INTRODUCTION

In addition to addressing cavern stability safety issues, salt cavern storage operations normally require some measure of the cavern volume, be it for inventory, operation, or regulatory purposes. In fact, some volume measures, to different degrees, are probably maintained in all storage caverns in salt. Certainly, this is the case for the Strategic Petroleum Reserve (SPR) caverns storing crude oil in facilities located in the Gulf Coast salt domes. In these caverns, historically

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there have been maintained three independent measures of cavern volume: (1) a calculated solution volume based on the solutioning by raw water during construction and any subsequent movement of oil by water displacement, (2) a calculated sonar volume based on the surveyed dimensions of the cavern, and (3) a direct metering of oil to give the volume of that portion of the cavern filled with the oil. The latter method also requires a measure of the oil/brine interface. Solutioning and sonar volumes are calculated from the measurements through equations that involve specific constants and parameters. In the case of the sonar measurements, one free parameter is a determination of the sonic velocity of the fluid in the cavern. Oil metering is a more direct measure, involving a calibration of the meter. The most accurate measure is through a custody transfer meter, which is independently calibrated though collection of a known oil volume with time. While custody transfer meters are accurate to within +/-0.25%, these meters are normally located only at oil terminals remote from the storage site boundaries. Once inside the site boundaries, the oil is often split-streamed and placed into caverns through less accurate cavern meters.

Evaluation of the three types of measurements may be complicated by various factors. These factors range from the comparatively large uncertainties possible in some of the individual measurements to operationally dictated time offsets between the different measurements. While some of the timing difficulties can be resolved from the records, the necessary details are often not specifically documented. An additional factor, unrelated to measurements and complicating the comparisons is introduced through accounting problems. Especially in some caverns where undiscovered, isolated solution voids can occur and partial volumes obtained at disparate times can be difficult to add correctly. In some instances, especially during cavern construction, attempts were made to adjust apparent discrepancies in the absence of actual information and this error was carried forward.

Clearly, the various measurements are subject to errors which are relatively difficult to evaluate independently. Interestingly, although the cavern volume is unknown, within the time interval over which these independent measurements are taken, it is essentially constant. This permits relative comparisons of the different measurements to be made. Furthermore, it is possible to apply a simple theoretical basis to the comparisons. The theory is based on the hypothetical "perfect correlation" between measurements taken of the same volume. Deviations from the perfect correlation can be framed in terms of a systematic error, or bias, and a random error, or uncertainty.

The intent of the study is to make a relative evaluation of the volume data obtained for the SPR Phase II and III caverns which were constructed specifically for the project in major facilities at the Big Hill and Bryan Mound salt domes in Texas, and the West Hackberry and Bayou Choctaw domes in Louisiana. These caverns are approximately uniform in size and shape, being roughly right circular cylinders about 2000 ft in height and 200 ft in diameter, and under about 2000 ft of overburden and salt. The geometric shapes, while in a sense well controlled, exhibit solutioning irregularities. Caverns this size on the order of 10 MMb in volume. The essential volume data have been compiled from SPR project records by Munson [2000]. General descriptions of the domal site characteristics and SPR caverns can be found in Hart et al. [1981], Magorian and Neal [1988] and Neal et al. [1993a] for Big Hill; Hogan (ed.) [1980] and Neal et al. [1994] for Bryan Mound; Magorian et al. [1991] for West Hackberry; and Neal et al. [1993b] for Bayou Choctaw.

In presenting the work, the three types of measurements are discussed, with emphasis on the nature of the data reduction equations. Then the simple theory is developed based on the perfect correlation and errors which characterize the relative comparisons of measurements. Although there are differences in the data types because of differences in the construction and filling of the

caverns, representative data are used to demonstrate the comparison of the solution volumes to the sonar volumes. Then the equivalent sonar volumes are compared to the metered oil volumes. A statistical analysis follows based on recognizing the existence of a data bias which can be extracted to yield the random uncertainty, or scatter, in the data. The work concludes with a summary and suggestions for the sources of error and where potential improvements in technique are possible.

MEASUREMENTS

Calculated solution volume is based on very elementary measurements of the volume of raw water introduced during the construction of the cavern or during any subsequent fluid transfers by raw water. In addition to the amount of water, the salinity of the inlet water and the outlet brine must be known. From these quantities, the volume of the cavern, V_t, can be calculated, via the following:

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

where ρ is the density of pure salt, C_b and C_w are the specific gravities of the output brine and raw water, respectively, and V_w is the volume of raw water input. V_i is the volume of insolubles and k the fraction of insolubles lost to the output brine flow. Accumulation of insolubles in the brine ponds is evidence that some of the insolubles are swept out in the brine stream. However, this is normally a small amount, because of the large cavern volumes, and hence long settling times. As a result, k is thought to be nearly zero. As is apparent, only an accurately known physical density constant and readily calibrated gravimetric measures are involved in this data reduction equation. Any marked errors in the solution volume will probably arise from the metering of the raw water. And, in fact, during construction, sometimes the raw water meters were inoperative and the amount of water was therefore estimated. It is believed that the metering errors are essentially random, with their average significance diminishing as the total raw water volume increases. The construction operators usually assign an uncertainty of +/-5% to the calculated solution volumes. While not based on analysis, this rather large uncertainty was largely attributed to the probable errors in raw water metering.

Sonar measurements are attractive because they offer a direct, and quite detailed, method of determining cavern geometry, as well as the volume. They can be extremely useful by providing knowledge of the cavern geometry during solutioning and in guiding appropriate relocation of water insertion hanging strings to achieve the desired geometry results. The fundamental concept of the sonar survey measurement is that a sonic pulse from a known transmitter/receiver location travels through the fluid media and reflects from the cavern wall. Detection of the reflected wave at the transmitter/receiver permits a determination of the transit time of the pulse. Although the mechanical and electronic intricacies of the sonar tool and its operation are beyond the scope of this report, considerable development has been expended in order to obtain an accurate pulse transit time. Nevertheless, the governing equation for data reduction is very simple, with the distance between the reflecting surface and the transmitter given by:

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

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 sonic gage with an accurately known path length mounted on the main sonar survey tool. While the velocity determination 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. For example, the velocity of sound in the fluid may depend upon spatial variations in density and temperature. Also, other factors such as the interpretation of pulse arrival time can produce uncertainty. Indeed, the sonic velocity gage itself may have an experimental uncertainty. Distance measurements are made systematic in discrete increments over the height and circumference of the cavern, which in turn permits a calculation of the volume.

Oil metering is used to measure the amount of oil in a cavern. Cavern volume is also measured, at least in the part, by the quantity of oil that it contains. This volume is truncated by the oil/brine interface which can be determined within about 2 ft by standard wireline logs. Because of the need to maintain 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. These limits are in the 90-95% range. Operational considerations may result in even less. Measuring of the physical inventory of crude oil is a crucial operation for the SPR. The principal measurement of oil quantity is through a custody transfer meter. The stated uncertainty, as agreed to by parties to the transfer, is +/-0.25%. This meter is routinely flow calibrated using the measured time to collect a known volume. However, the custody transfer meter is normally remote from the site boundaries. Within the site boundaries, there is a manifold for oil distribution to the caverns through individual cavern meters. Individual cavern meters are thought to be relatively inaccurate, with uncertainties of +/-5%. The oil metering is a direct measure, and no data reduction equation is required.

THEORY OF PERFECT CORRELATION

Interestingly, correlation of volume quantities has a very simple theoretical basis. Over relatively brief intervals of time, the different types measurements can be obtained. During these intervals, the actual cavern volume, even though it is unknown, is essentially constant. Consequently, the different types of measurements taken within the same brief interval are measuring this quasi-constant volume. The various measured quantities, however, can and do differ from the actual value. This deviation can be expressed in terms of a systematic error and a random error according to the following:

$$V_a = m\left(V_x + \left(\pm \Delta \varepsilon\right)\right) \qquad 3$$

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

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

$$V_{x1} = V_{x2}m' + \left(\pm\Delta\varepsilon_2\right) + \left(\mp\Delta\varepsilon_1\right) \qquad\qquad 4$$

where the m' is the combined systematic error of m_2 / m_1. The reformed equation still contains a bias which is the product of the two measurement biases. Moreover, the uncertainties from the random errors when taken over a large database will simply form a new distribution. An interesting feature of this simple theory is when the systematic error factor is one and the random uncertainties are zero, the correlation is perfect. This perfect correlation line will appear in many of the presentations and discussions which follow. In addition, trend lines, which are straight lines emanating from the origin and passing through a given dataset, will also appear in many of the graphical representations and in the discussions.

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

RELATIVE EVALUATIONS

Each of the four SPR sites was developed in a somewhat different manner during construction. Big Hill (BH) was developed late in the cavern construction phase of the program and was the "cleanest" site in that these two-well caverns were solutioned to completion before being filled with oil. This was also the case for Bayou Choctaw (BC). Both West Hackberry (WH) and Bryan Mound (BM) were developed early in the program when the need to rapidly store oil required concurrent cavern solutioning and filling. In addition, the Bryan Mound caverns, constructed first, used three wells, which in the end allowed portions of solutioning void to remain uncoalesced around individual wells.

Construction involved several stages of solutioning, with repositioning of the input water location, prior to the completion of the cavern. The initial stage was direct solutioning of the cavern sump. The sump development stage was followed by several stages, perhaps three, of reverse solutioning, to develop the top and mid portions of the cavern. Typically, at the end of each stage, a sonar survey was taken. Even after oil filling of the cavern, any subsequent movement of oil using raw water displacement also typically involved a final sonar survey. Consequently, each cavern will have several relative measures of volume taken over its history. Additionally, a previous sonar survey of a portion of the cavern filled with oil provides another relative measure of that cavern volume filled with oil. The raw volume data [Munson, 2000] consisted of calculated solution volumes, calculated sonar survey volumes, and oil inventory volumes. While this provides a rather large database, operational variations often result in complicated data. Where the cavern was completed prior to filling, only the solution volume and sonar volume are involved and the results are uncomplicated with only two measurement uncertainties. However, where cavern filling was concurrent with solutioning, it was necessary to add the oil inventory and the sonar volume of the new portion of the cavern created. In this case, uncertainties of all three measurement methods become intermixed, rather than just two

uncertainties. Data involving only two uncertainties have been separated out to form an underlined uncombined database, whereas the other date form a combined database. The oil inventory comparisons form another distinct database. While the databases from the SPR sites are actually quite large and cannot be dealt with in the limited space allowed here, all of the comparisons and analyses can be found in Munson [2000]. Here, only selected examples of those data from the extremes in cavern construction, Big Hill and Bryan Mound, will be presented. Thus, both uncombined and combined comparisons will be discussed briefly. Oil inventory volume and equivalent sonar volume will be compared, but just for the Bryan Mound site. Nevertheless, the examples used here are thought to be representative of all of the cavern sites.

Solution Volumes and Sonar Volumes

Throughout the Phase II and III cavern development, the general data reduction to obtain the calculated solution volumes were probably consistent and involved the same construction contractor. The data reduction used Eq. 1, in which there are few parameters or calibrations that can be significantly changed. As a result, the solution volumes are thought to form a consistent database throughout the development of the caverns. The sonar survey data, on the other hand, were obtained through a number of different survey companies, sometimes in different, and sometimes overlapping, time frames. Each of these companies would logically use different survey tools and, in some instances, a given company could have more than one survey tool. The structure of the data reduction process, using Eq. 2, requires the determination of the sonic velocity parameter. This parameter is obtained through a separate velocity measurement made concurrently in the fluid being surveyed; however, it is not a true calibration against an independent standard. As a result, it is possible that each individual survey tool could be expected to differ slightly.

The presentation of the comparison of the calculated solution volumes to the sonar volumes begins with the data for the *Big Hill* caverns. All of the sonar results are for uncombined sonar data, where the sonar volume either ignores or includes the very small amounts of blanket oil in the cavern at the time. Blanket oil was a small amount of oil placed in the cavern during construction to prevent solutioning of the cavern roof. Data-sets denoted by an asterisk in the figure legends are considered high quality, with complete cavern sonar surveys and only small amounts of blanket oil included in the volume. Often existing records did not note the presence of blanket oil. These data-sets, without an asterisk, are still considered of very high quality, but the quantity of blanket oil is unknown and assumed to be small. These results are interesting because they were obtained by three different survey companies, as denoted by the data-sets: BH1* (and BH1), BH2, and BH3. In Figure 1, two data-sets are shown, BH1* from surveys taken near the completion of the caverns and BH2 data taken from surveys at the beginning of cavern construction. The rather odd vertical alignment of the BH1* data results from using a target volume for solutioning the caverns. The error bars shown on some of the data points are +/-3% in solution volume and +/2% in sonar volume. It appears that errors of this magnitude would essentially bring the data of a given data-set into agreement. Errors of +/-5% are customarily associated with these two measurement types by the various contractor and survey companies, but these values are somewhat greater than the uncertainties deduced from Figure 1.

Also shown in Figure 1 are two trend lines that begin at the origin and pass through the data of the individual data-sets. Not shown, however, is the perfect correlation line that would begin at the origin and have a slope of one. Each of the data-sets can be assigned a value of *m'* (BH1* is 0.975 and BH2 is 1.021) that indicates their systematic deviation from a perfect correlation. In examining the results in Figure 1, it is possible to make some important observations. It is known the construction contractor remained the same during the period of cavern construction, and

BIG HILL

- ■ BH1* m'=0.975
- ▲ BH2 m'=1.021

Y-axis: Sonar Volume (MMb)

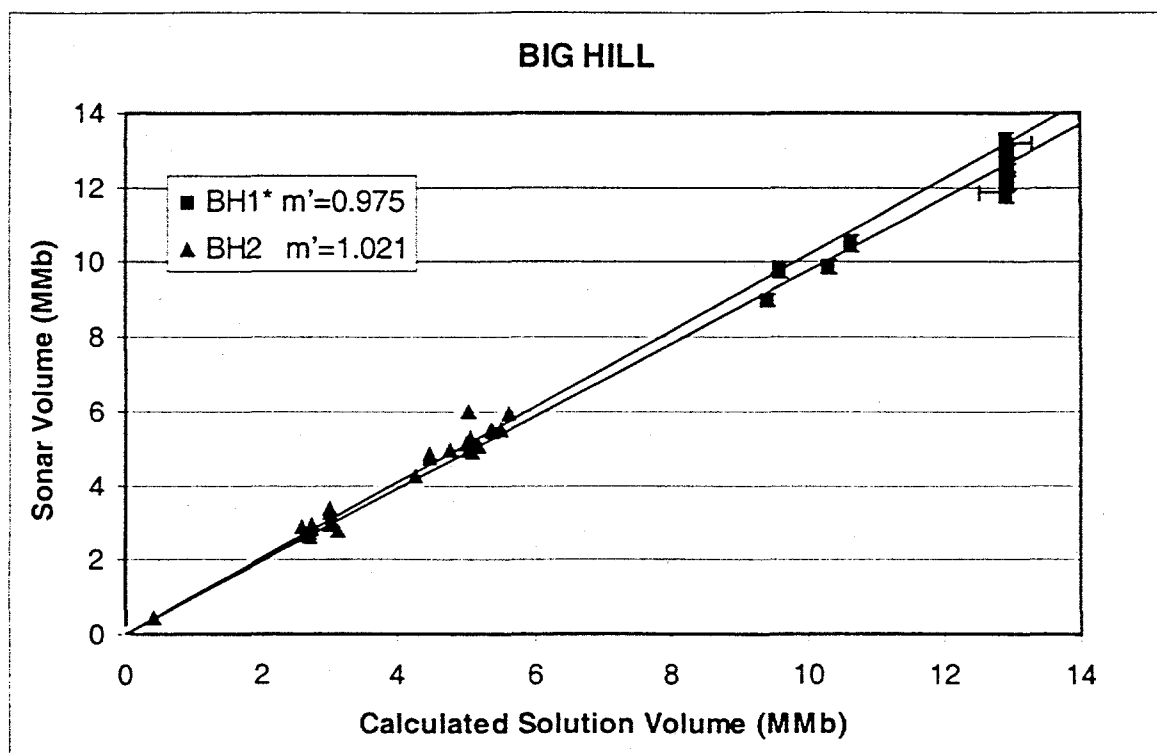X-axis: Calculated Solution Volume (MMb)

Figure 1. Solution Volume vs. Sonar Volume for Big Hill Caverns.

therefore it can be assumed that the procedures of the data reduction and the constants in Eq. 2 did not change during this period. The solution volume is, of course, independent of any physical distance measure. Thus, if there were any bias in the solution volumes, it would be constant during the construction period. However, two different biases are observed. As a consequence, at least one, and perhaps both, of the biases observed in these two data-sets must be the result of differences in the determination of the sonar volume. Two possible sources for bias in the sonic volume can be postulated. First, the reflection of the sonar wave from the rough surface of the cavern wall would tend to "average" the roughness to give an smaller apparent radius. This, in turn, would give a slightly smaller apparent cavern volume. Consequently, the sonar volume could be expected to always be somewhat less than the solution volume. Second, in data reduction using Eq. 2, the sonic velocity appears. This is a speed measured in the fluid concurrently with the sonar survey using a small measurement cavity attached to the survey tool. While it appears that this sonic velocity measurement is a calibration of the tool, it is normally an uncalibrated parameter. Concurrent measurement of the sonic velocity is used to compensate for changes caused by fluid density and temperature variations. As is apparent, the biases, which are opposite sign, seem to depend only upon the data-set, which can be equated with a given survey company, or more likely, the survey tool used.

While the biases in the data are readily apparent, equally clear is the uncertainty or scatter in the data. This uncertainty can be treated independently of the bias. The fractional deviation of the data is taken to be the difference between the solution and sonar volumes divided by the sonar volume. We could plot these fractional deviation values directly against sonar volume; however, it is more instructive to subtract the bias, leaving only the uncertainty, before making such a plot. Big Hill data treated in this manner are shown in Figure 2. Here all of the BH data-sets, except for the single BH3 datum, are plotted. Data-set BH1, while the same survey company as BH1*,
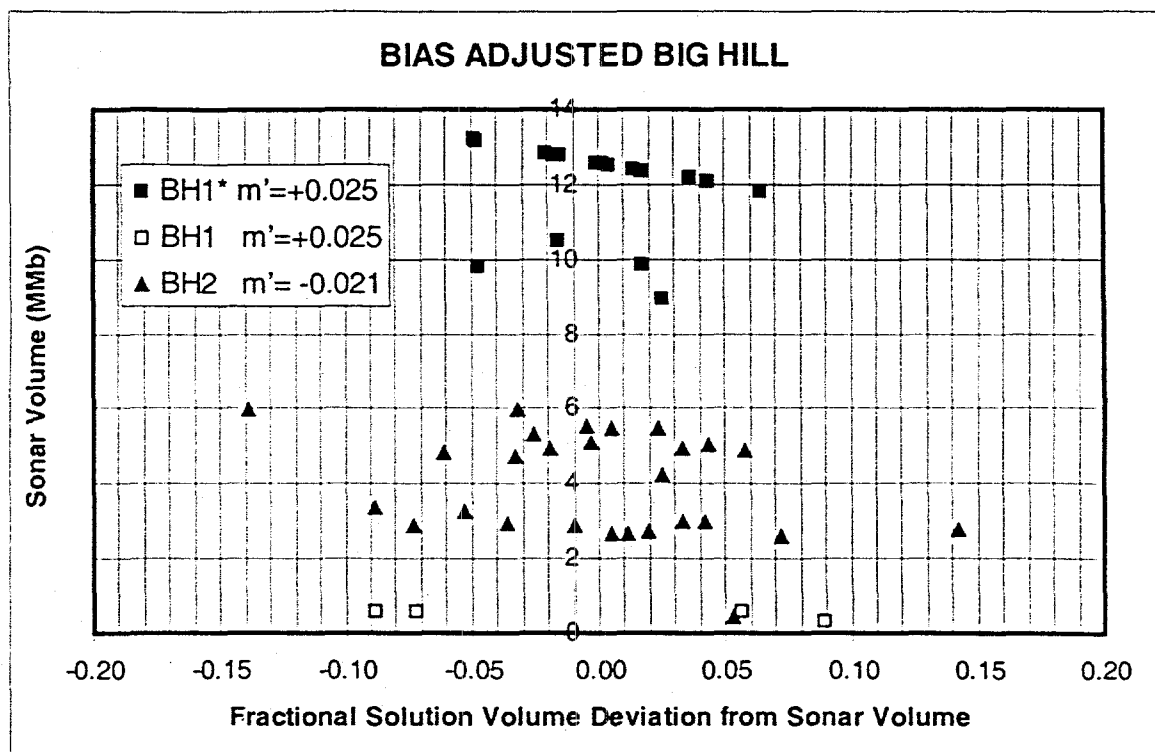
Figure 2. Bias Adjusted Fractional Solution Volume Deviation from Sonar Volume.

consists of sonar volumes obtained early in the construction where the total cavern volumes were small and the amount of blanket oil was unknown. Even then, the same bias value was used for both BH1* and BH1. The inability to account for the blanket oil volume introduces some additional error into the comparison of the BH1 data-set.

Bayou Choctaw, which closely matches Big Hill in the details of construction and filling, gives results that are consistent with the Big Hill data. These results are available in Munson [2000].

As mentioned previously, the *Bryan Mound* data are thought to be more complicated because of the requirement for concurrent cavern filling during construction, as well as the use of three wells. The three well configuration permitted greater flow volumes for solutioning and the use of one of the wells for simultaneous oil filling. This resulted in the isolation of uncoalesced solution voids at several locations in the caverns which could not be surveyed from a single well. To find the sonar volume required combining surveys. In addition, the blanket oil and brine volumes of some of the wells remained unknown, causing difficulty in proper accounting. The greatest complication is that some caverns, especially at the later stages of construction, contained large quantities of oil inventory. In this case, the resulting sonar volume was a sum of the sonar and oil inventory volumes, a complex quantity with the measurement uncertainties of the oil inventory and the sonar intermixed. Because the uncertainties in these two cases are fundamentally different, one involved three different measurements while the other involved only two measurements, the results caused generation of two groups of data: uncombined and combined sonic volumes. These two groups of data will be treated separately.

In the sonar surveys only two individual companies were involved, but because of uncombined and combined volumes, four data-sets resulted. The uncombined data-sets are BM1 and BM3;

UNCOMBINED BRYAN MOUND

□ BM1 m'=0.95
♦ BM3 m'=0.91

Sonar Volume (MMb) (y-axis)
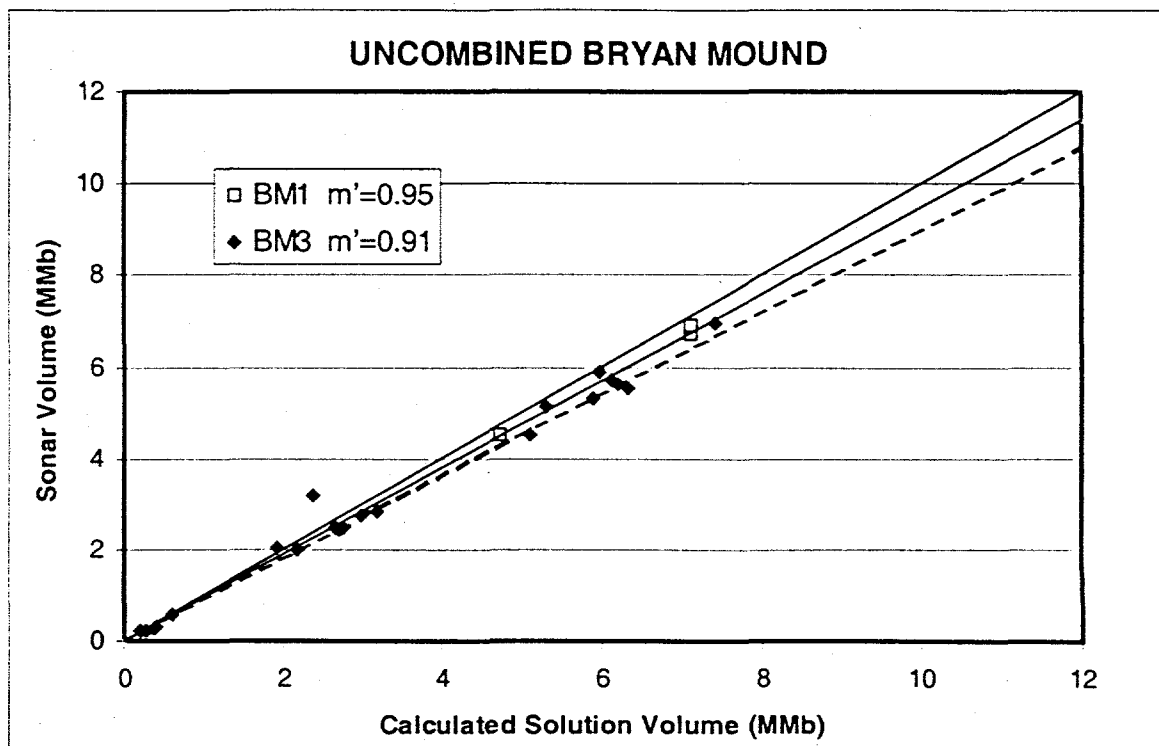*Calculated Solution Volume (MMb)* (x-axis)

Figure 3. Solution Volume vs. Uncombined Sonar Volume for Bryan Mound

BMC1 and BMC3 are combined volume data-sets. Solution volumes and uncombined sonic volumes from Bryan Mound are compared in Figure 3. Also shown on this plot are the perfect correlation line and two trend lines. The BM1 data-set has a slope (*m'*) of 0.95, which seems to pass through the data reasonably well. The BM3 data-set is best fit by a line with slope (*m'*) of 0.91. While bias values differ between the data-sets of the two survey companies, they have the same sign. Furthermore, the bias is in a direction consistent with the argument that surface roughness should produce a slightly smaller sonar volumes. The biases observed are however somewhat greater than those found for Big Hill, +5% to +9%, as opposed to about +/-2%. Here BM1 was obtained by the same survey company as BH1* and BH1. It should be noted that the uncombined sonar volumes apply principally to the earlier stages of cavern construction.

As in the previous analysis, the fractional deviation of the uncombined sonar volume from the solution volume can be determined. The data have been adjusted by removing the apparent bias. These results are plotted in Figure 4. Even though the construction of the Bryan Mound caverns was quite complex, the scatter of the these data seem to be no greater than those of the Big Hill caverns, with the exception of those very early in the construction where the deviation may be up to 40%. Clearly, with these very small volumes, even a reasonable error can be exaggerated. Remember, the three well Bryan Mound caverns often experienced isolation of parts of the solution void and complete sonar volumes were difficult to obtain. As a consequence, accounting of the various volumes was also often inaccurate, especially in the early stages of solutioning.

Because of the concurrent oil filling in the Bryan Mound caverns, there is a relatively large database for the combined sonar volumes, where it was necessary to add the partial sonar volumes and the oil inventory volumes. BMC1 and BMC3 results are plotted in Figure 5. They show considerable scatter, perhaps more than could be expected. At this point there is no real
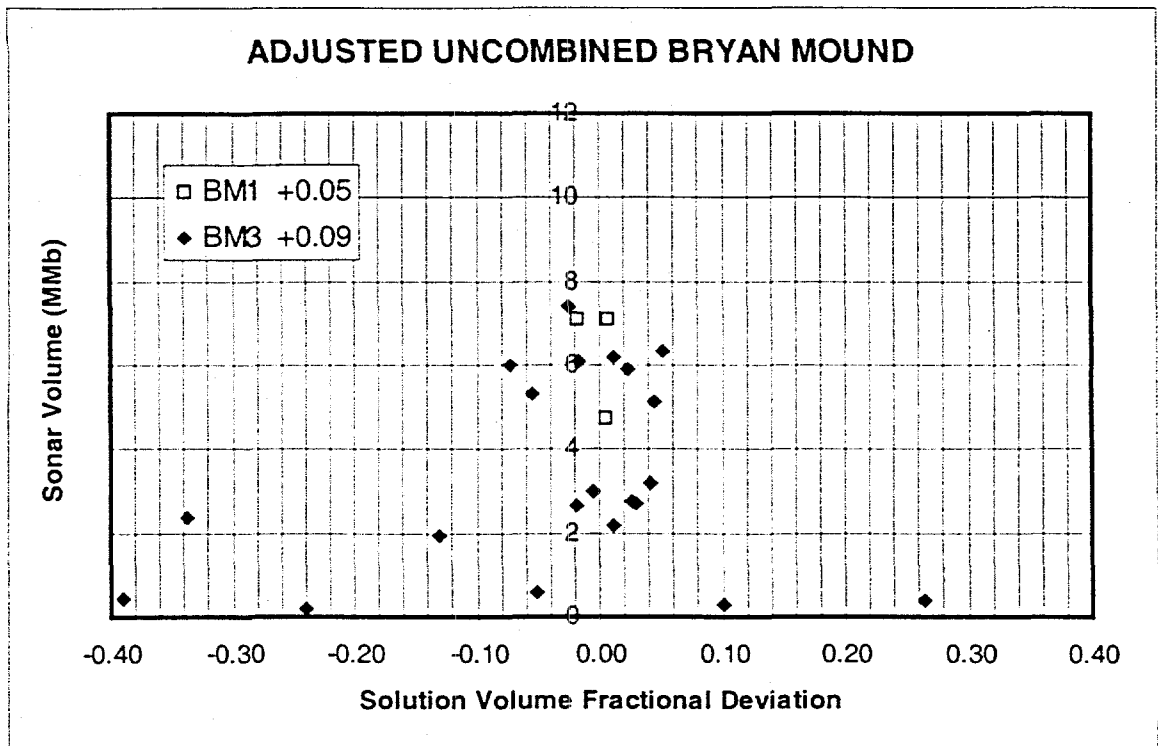
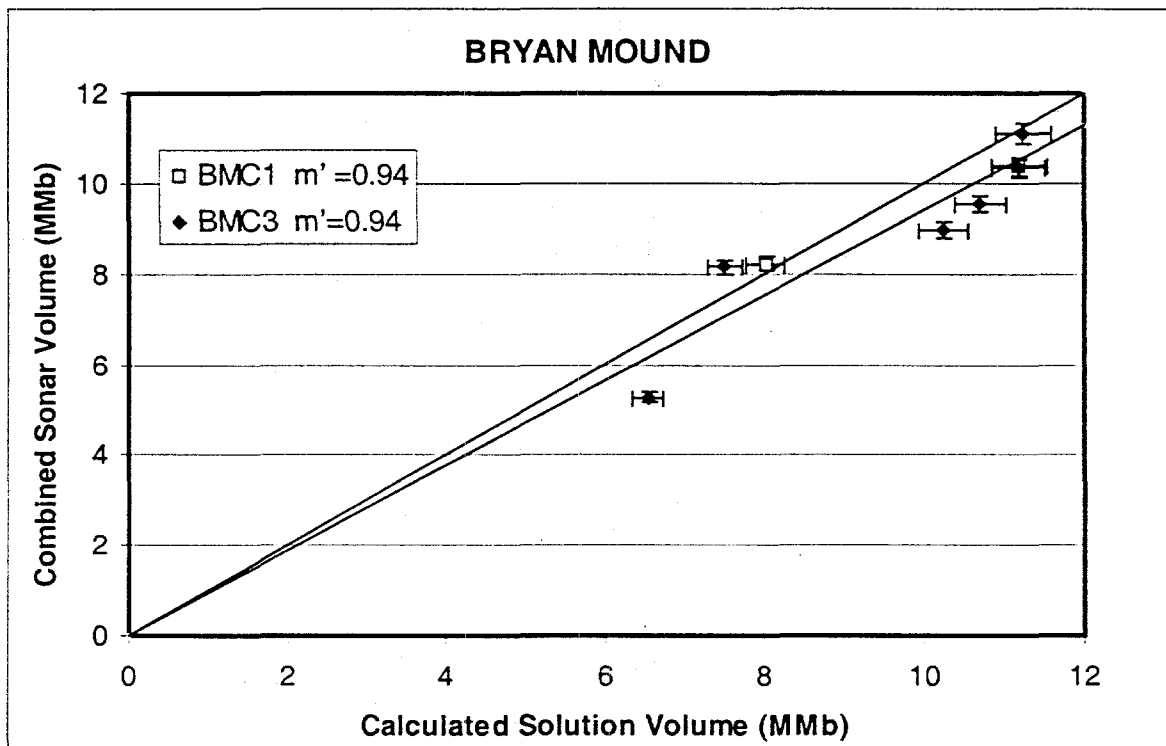Figure 4. Calculated Solution vs. Uncombined Sonar Volumes for Bryan Mound.

Figure 5. Solution Volumes vs. Combined Sonar Volumes.

explanation of the scatter, although it could be additional evidence of difficulty in accounting for the various volumes in these three-well caverns. It should be noted the Bryan Mound caverns were the first caverns to be constructed by the SPR and the various practices were probably not as refined as in later cavern sites. Also, when retrieving the data from the Bryan Mound records, it was found the construction contractor sometimes had difficulty in reconciling the sonar and solution volumes. The tendency was to make arbitrary adjustments in the solution volumes, and while great care was taken when retrieving the data to find the unadjusted solution volume values, perhaps this was not always successful. The combined data are shown with a trend line having a slope (m') of 0.94. Also shown are error bars of +/-3% in solution volume and +/-2% in combined sonar volume. Obviously, these errors are not sufficient to explain the scatter.

These data can be treated as shown in the previously data-sets, with the fractional deviation of the solution volumes from the combined sonar volumes determined, and then the bias removed. This gives the effect of the scatter alone. Although not shown, the results are very similar to those of Figure 4, except for a greater range of the scatter.

West Hackberry, which has a similar history of construction and filling as Bryan Mound, also has both uncombined and combined data-sets. These data-sets are quite extensive, but are not shown here. However, the bias and scatter effects are similar to Bryan Mound, but with somewhat less scatter. Undoubtedly, the use of one-well cavern construction (actually, one cavern had two wells) resulted in somewhat better control of the solutioning and filling process. There were no hidden solution volumes apparent in these caverns, and the accounting and data were more straightforward.

Equivalent Sonar Volumes and Oil Inventories

This database permits the comparison and evaluation of the equivalent sonar volumes and the oil inventories. An equivalent sonar volume is that part of the sonar survey that corresponds to the portion of the cavern occupied by the oil. In order to determine the applicable part of the sonar survey it is necessary to have the depth measurement to the oil/brine interface as determined by wireline methods.

Because the data-sets from the four sites are quite similar, only the data-set from *Bryan Mound* will be presented here. While the analysis is essentially of the same form as given previously for the solution volume vs. sonar volume data-sets, it is no longer simple to identify the sonar operator. As a result, the data are presented according to the principal types of crude oil in the inventory: sweet or sour. This presentation is logical because the total inventory of these two types within a given facility must agree with the custody transfer amounts for each crude type. This must be true even in the event of split- streaming of the incoming crude. However, now a different kind of problem occurs. Evan within the comparisons of the equivalent sonar volume with the oil inventories of a given crude type, it is possible that different survey operators were involved. Consequently, this presents the possibility that different bias values apply to the sonar volumes within a given crude type. In fact, this appears to be the case. The equivalent sonar volumes compared to the oil inventories for Bryan Mound, at the data of 10/99, are shown in Figure 6. A perfect correlation line with a slope of one is shown in the figure, together with a trend line with a slope (m') of 0.93.

The appearance of the data in Figure 6 suggest that they are either associated with the perfect correlation line or with the trend line. This observation is confirmed when the data are reduced to a fractional deviation of the equivalent sonar volumes from the oil inventory. Then the data separate into two distinct groups, with different bias values. A group of data with a constant bias
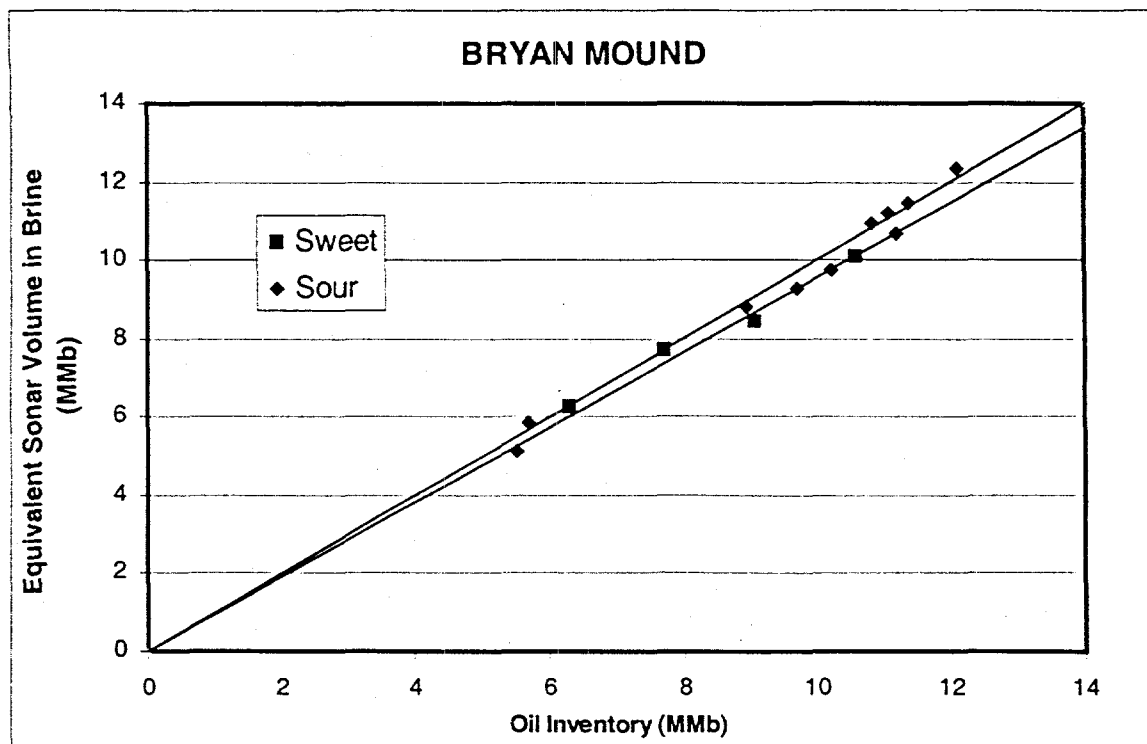
12

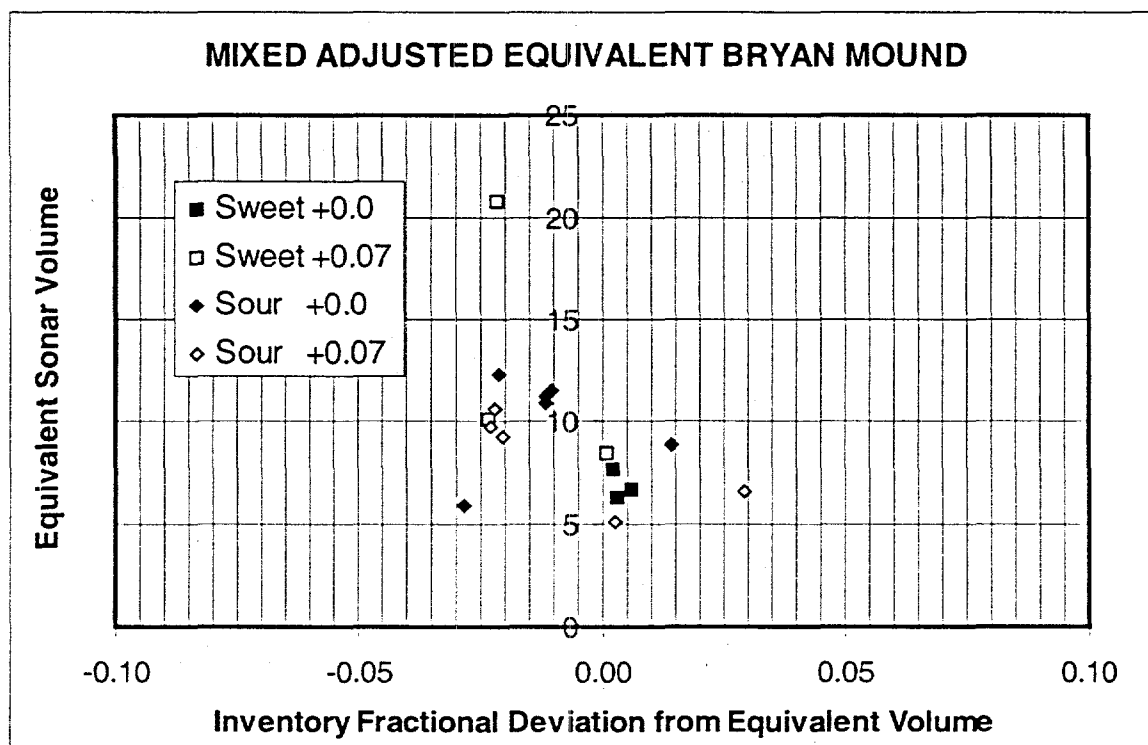Figure 6. Equivalent Sonar Volume vs. Oil Inventory for Bryan Mound (10/99).

Figure 7. Adjusted Mixed Equivalent Sonar vs. Inventory for Bryan Mound.

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value, however, can contain both sweet and sour crude. When the data are adjusted (corrected) for the applicable biases, the resultant "mixed" corrected deviation is as shown in Figure 7.

Although not shown here, the comparisons of the equivalent sonic volumes to the oil inventories for *Big Hill*, *West Hackberry*, and *Bayou Choctaw* are fundamentally the same as those given above for Bryan Mound. Differences are relatively insignificant, while still maintaining the two different, mixed crude type, bias groups. Again, the analysis of the data comparisons for all of the sites are given in complete detail by Munson [2000].

Based on the examples of the data analysis given above, it is reasonably clear that the data comparisons exhibit both biases and scatter. All of the comparison data-sets show this behavior. This is certainly in agreement with the simple theoretical interpretation of the sources of uncertainty in the data. Whereas biases are thought to be associated with systematic errors in the measurements, the scatter is thought to be caused by the random errors in the measurements. The artifact of removing the bias from the data-sets does not diminish the importance of the bias. This artifact merely lets one examine these two uncertainties independently of each other. Consequently, the implications of these two uncertainties are treated separately.

SYSTEMATIC BIAS

Examination of all of the data-sets for systematic error has led to the determination of the biases for each set. These biases are summarized in Table 1 for comparisons between the calculated solution volumes and the uncombined sonar volumes, comparisons between the calculated solution volumes and the combined (plus fill oil) sonar volumes, and the equivalent sonar volumes and the oil inventories. Also given in the table are extremes in the scatter of the data from a given data-set. The number of points in each data-set indicate the relative importance of the data-set to the statistical analysis of the scatter.

The biases encompass a rather broad range of both negative and positive values spanning from +20% to -9%. However, it should be noted the extreme values of +13% and +20% are for a very few points, suggesting that these are rather abnormal data. The more typical range of biases is from +9% to -9.0%. The data-sets, BH1* and BH1, that are considered the best quality from the stand point of the simplicity of the construction process are from Big Hill. The uncombined data have a bias of only +2.5%, with a scatter of -5% to +6%, while the combined data also have a bias of 2.5%, with a scatter of -9 to +9%. For Bayou Choctaw caverns, which were completely constructed before filling, the data-sets are also very good, with BC1 having a bias of +6.0% and a scatter of -1.0 to +5.0% and BC2 having the same bias and a scatter of -6.0 to +3.0%. The remaining data-sets may exceed these values, but cannot be judged any less accurate.

While the analysis does not permit the systematic biases to be attributed to a specific cause, it is has been argued that the nature of the sonar reflection from a rough surface should produce a slight smaller apparent radius. This according to the fractional deviation would appear as a positive bias. Estimates of the magnitude of the systematic deviation is about +2% [Munson, 2000]. Certainly there is no consistency among the biases found from the data to suggest, or deny, such a value.

STATISTICAL ANALYSIS

The volume measurement databases present an opportunity for quantitative statistical analysis. The intent is to determine the distribution and standard deviation for the random uncertainty or

Table 1. Summary of Bias Adjustments and Remaining Scatter.

Category Facility Type	Data-set	Bias (%) $100(1\text{-}m')$	Resid. Scat. (%)[#] $100(\Delta\varepsilon_{min/max})$			No. Points	Remarks
Solution vs.							
Uncombined (Sonar)							
Big Hill	BH1*	+2.5	-5.0	to	+6.0	17	Best Data
	BH1	+2.5	-9.0	to	+9.0	4	Small Volume
	BH2	-2.1	-14.0	to	+14.0	27	
	BH3	+13.0				1	Single Datum
West Hackberry	WH1	+5.0	-2.0	to	+10.0	3	
	WH2	-9.0				1	Single Datum
	WH3	+5.0	-19.0	to	+15.0	30	
	WH4	+4.0				1	Single Datum
Bayou Choctaw	BC1	+6.0	-1.0	to	+5.0	2	
	BC2	+6.0	-6.0	to	+3.0	2	
	BC3	+20.0				2	
Bryan Mound	BM1	+5.0	-2.0	to	+1.0	3	
	BM3	+9.0	-40.0	to	+26.0	21	Small Volume
Solution vs.							
Combined (Sonar + Oil)							
West Hackberry	WHC1	0.0	-4.0	to	+2.0	4	
	WHC3	+4.0	-4.0	to	+9.0	9	
Bryan Mound	BMC1	+6.0	-8.0	to	+2.0	2	
	BMC3	+6.0	-14.0	to	+14.0	6	
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 [@]
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 [@]
Bayou Choctaw	Sweet	+0.00	-5.5	to	-1.0	2	Plus [@]
	Sour	+0.00&+8.00	+1.0	to	+3.0	4	Plus [@]
Bryan Mound	Sweet	+0.00&+7.00	-2.0	to	+1.0	4	
	Sour	+0.00&+7.00	-3.0	to	+3.0	10	

[#] After the bias is removed the residual scatter 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 SPR acquired commercial caverns at these facilities were included in these results.

scatter. 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 or scatter produced by the uncertainty of the measurement system. Normally, where a uniform bias is common to all the data, a statistical analysis can be made and the bias appears as a skewing 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, as previously noted, the raw deviation results will be first adjusted by removing the bias before being analyzed statistically. Biases as determined to this point are summarized in Table 1. Table 1 separates the databases according to the category of data, just as previously, and by SPR site and, by operator data-set or crude type.

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%). From the bin quantities, a cumulative distribution was determined. As the categories of Table 1 indicate, the analysis first treats the most populous 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, however the results are not shown graphically. And then, the comparison of equivalent sonar volumes through brine and the oil inventories are analyzed statistically.

Solution and Uncombined Sonar Data Statistics

According to the procedure described above from these adjusted deviation results, the cumulative numbers of caverns in each fractional 0.002, or 0.2%, wide bin were counted. The plot for the uncombined sonar data is given in Figure 8. The figure also shows the plot of the normal, or Gaussian, 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
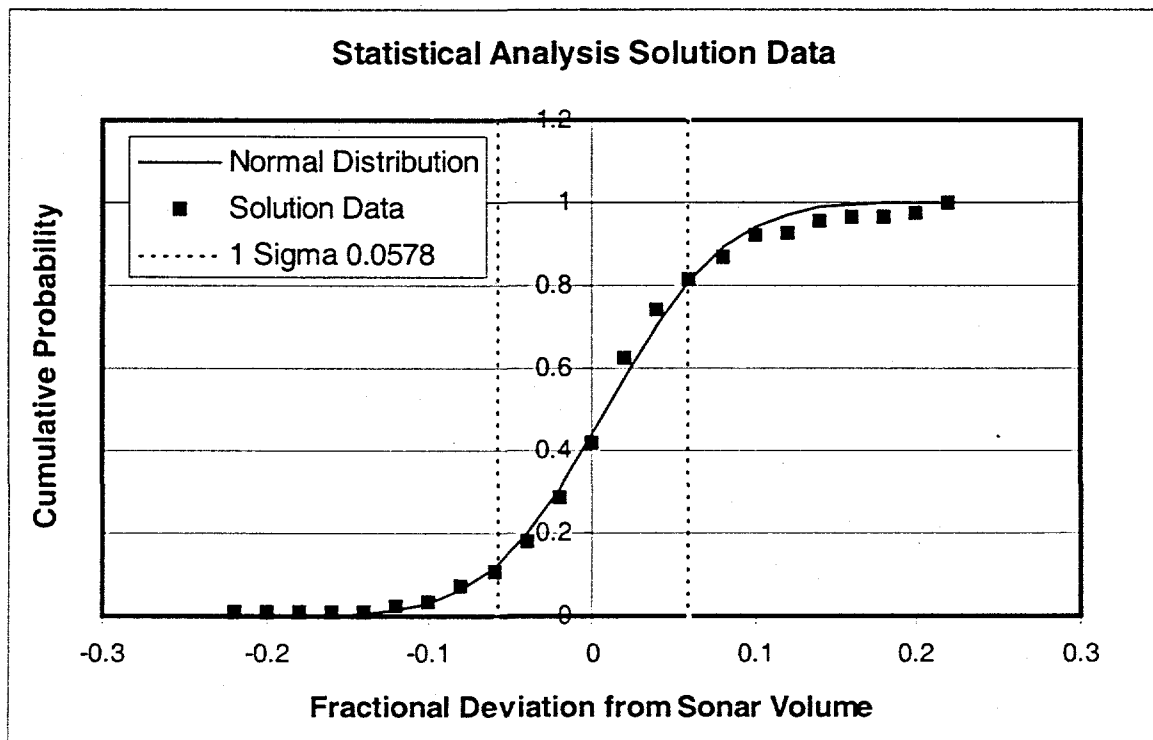

Figure 8. Cumulative Distribution for All Solution and Uncombined Sonar Data.

volume is random. Also shown on Figure 8 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 sum of the individual uncertainties, according to Eq. 5. The statistical analysis essentially confirms again the +/- 2% scatter in sonar volume and the +/-3% uncertainty in solution volume deduced previously during the initial comparisons. However, these values remain somewhat less than the , the +/-5% in the sonar volumes and solution volumes as usually assumed by the operators. The mean of the distribution is +0.90%, or reasonably close to zero. It is satisfying is that the results of the statistical analysis are exactly what would be expected in terms of random uncertainty, and seem quite reasonable.

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. Analysis of the combined sonar data proceeded in the same manner as described above. 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. Although not shown, as in the case of the uncombined sonar data, the combined sonar data conform very well to the normal distribution. But, 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. Here the mean was determined to be −1.20%.

Equivalent Sonar and Oil Inventory Data Statistics

Perhaps one of the more significant comparisons is between the oil inventory and the equivalent, truncated portion of the sonar survey above the oil/brine interface. The significance resides in the fact the oil inventory seems to be very accurate, with the uncertainty of the cavern meters minimized. This implies only the very small +/-0.25% uncertainty of the custody transfer meters is evident in these comparisons. These equivalent surveys took place through the brine prior to the filling with oil, and are therefore relatively easy to perform. Some data, where the unknown equivalent volume was assumed to be identical to the inventory, were questionable and were not included in the analysis.

While 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.

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. The statistical analysis of these results is shown in Figure 9. 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 (1.69%) and a mean of -0.0083 (-0.83%).

STATISTICAL ANALYSIS MIXED EQUIVALENT DATA

Legend:
- ♦ Equiv. Mixed Data
- — Normal Distribution
- ····· 1 Sigma 0.0169
- ✕ Equiv. Unmixed Data

Y-axis: Cumulative Probability
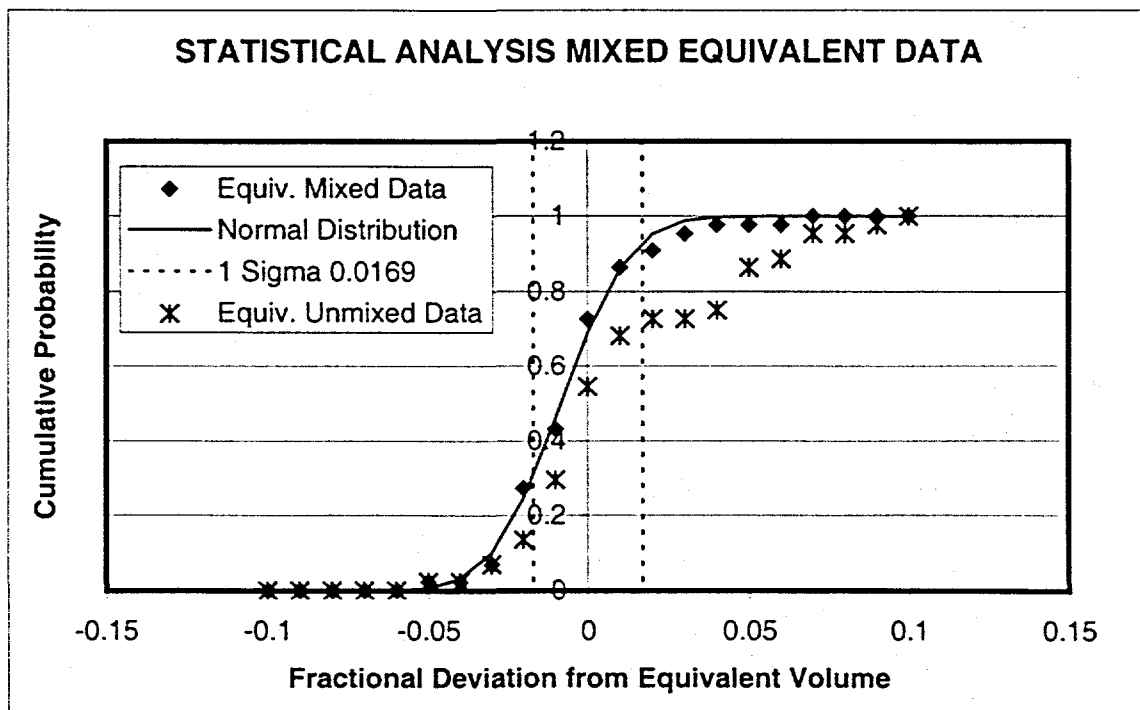X-axis: Fractional Deviation from Equivalent Volume

Figure 9. Cumulative Distribution for All Equivalent Sonar and Oil Inventory Data.

Actually, as previously noted, the +/- 1.69%. 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, the statistical analysis appears to be in fundamental agreement with the previously 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 because it is consistent with the earlier results of the comparisons of calculated solution volumes to the sonar volume 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 The cumulative distribution of these data is also shown in Figure 9. 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.

SUMMARY

One of the most important findings of this study was that the measurements appear to contain two distinct errors, a systematic deviation (bias) from the perfect correlation and a scatter caused by random error. Based on the significant differences in the biases of the data-sets, it appears that the biases depend upon survey company, and perhaps on the specific survey tool.

When the deviations from the underlined uncombined sonar volumes as compared to solution volumes 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%. Because the standard deviation is the sum of the uncertainties, this suggests a possible +/-2% uncertainty in the sonar volume and a +/-3% in the solution volumes. These numbers are somewhat less than the commonly accepted +/-5% for sonar volume and the +/-5% uncertainty for solution volumes commonly quoted by the operators. The standard deviation for the deviations in the combined sonar volumes compared to the solution 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.

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 measurements, most of the uncertainty in these databases is thought to be a consequence of the uncertainty in the sonar measurements. Thus, the standard deviation value is very consistent with the customary uncertainty of about +/-2% stated by the operators.

The results of this study, in general, indicate that measurement methods are really quite good, and in fact are somewhat less than those values of uncertainty customarily associated by the technical community with each type of volume measurement. The measurement bias should be kept in mind, with the possibility that the bias is an experimental factor that perhaps can be eliminated. One recommendation suggests an independent calibration of the sonic velocity measurement device associated with each sonar tool. This could potentially improve the sonar survey results.

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