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Analysis of Multi-Arm Caliper Data for the U.S. Strategic Petroleum Reserve

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Abstract

The U.S. Strategic Petroleum Reserve (SPR) has an increasing reliance on multi-arm caliper surveys to assess the integrity of casing for cavern access wells and to determine priorities for casing remediation. Multi-arm caliper (MAC) surveys provide a view of well casing deformation by reporting radial measurements of the inner casing wall as the tool is drawn through the casing. Over the last several years the SPR has collected a large number of modern MAC surveys. In total, these surveys account for over 100 million individual measurements. The surveys were collected using differing survey vendors and survey hardware. This has resulted in a collection of disparate data sets which confound attempts to make well-to-well or time-dependent evaluations. In addition, the vendor supplied MAC interpretations often involve variables which are not well defined or which may not be applicable to casings for cavern access wells. These factors reduce the usability of these detailed data sets.

In order to address this issue and provide an independent analysis of multi-arm caliper survey data, Sandia National Labs has developed processing techniques and analysis variables which allow for the comparison of MAC survey data regardless of the source of the survey data. These techniques use the raw radial arm information and newly developed analysis variables to assess the casing status and provide a means for well-to-well and time-dependent analyses. Well-to-well and time-dependent investigation of the MAC survey data provides information to prioritize well remediation activities and identify wells with integrity issues. This paper presents the challenges in using disparate MAC survey data, techniques developed to address these challenges and some of the insights gained from these new techniques.

Acknowledgments

I would like to thank Steven Knudsen and Zack Cashion for their thorough review of this work. Their comments and insight were most helpful in improving this report. This work was funded by the Strategic Petroleum Reserve program administered by the Office of Fossil Energy of the U.S. Department of Energy.

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NOMENCLATURE

API	American Petroleum Institute
BC	Bayou Choctaw SPR Site
BH	Big Hill SPR Site
BM	Bryan Mound SPR site
DOE	U.S. Department of Energy
ID	Interior Diameter
LAS	Log ASCII Standard
MAC	Multi-Arm Caliper
OD	Outer Diameter
SNL	Sandia National Laboratories
SPR	Strategic Petroleum Reserve
WH	West Hackberry SPR site

1 EXECUTIVE SUMMARY

The U.S. Strategic Petroleum Reserve (SPR) faces the challenge of operating and maintaining nearly 120 cased cavern wells across four sites in the storage complex over operational lifetimes spanning many decades. These cemented casings provide critical isolation of cavern fluids from the surface environment and groundwater. The results of well integrity monitoring at the SPR shows that some of the wells require remediation because their casing has been compromised. Remediation is required for a variety of issues including deformation, parted casing and leaky casings threads.

In an effort to better understand and characterize these issues, the SPR is conducting a program of multi-arm caliper (MAC) surveys of the inner-most cemented casing of all the SPR wells. Multi-arm caliper tools measure the inside diameter of the well casing by recording the radial movement of a series of feeler arms. The radial distances recorded by the tool directly measure any radial deformation of the casing and provides baseline information to characterize the wells and identify potential problems before they compromise pressure integrity. The challenge in this is that the different MAC survey vendors report their results in differing formats, so well-to-well or even time-dependent comparisons are difficult.

This report presents analysis variables developed to allow for the independent evaluation of MAC survey data regardless of the original survey vendor. The development and assessment of these variables has shown that one in particular, the coefficient of variation (C_v) of the measured diameter values, provides an excellent summary of radial casing deformation. Diameter C_v values are easily computed from the raw radial arm data which is available from each vendor in standard LAS file format. Custom Python computer code was developed as part of this project to read the LAS files, compute the analysis variables, and provide a summary of the results in tabular and graphical format. Figure 1-1 shows an example of C_v values computed for a well that is known to have significant casing damage and loss of pressure integrity.

Because C_v values can be computed from any MAC survey, individual wells can be compared to one another and against themselves through time. This provides a common basis by which to rank each well relative to their remediation needs. Examples of applying the analysis variables developed here for the grading of wells for remediation can be found in Lord et al., 2014.

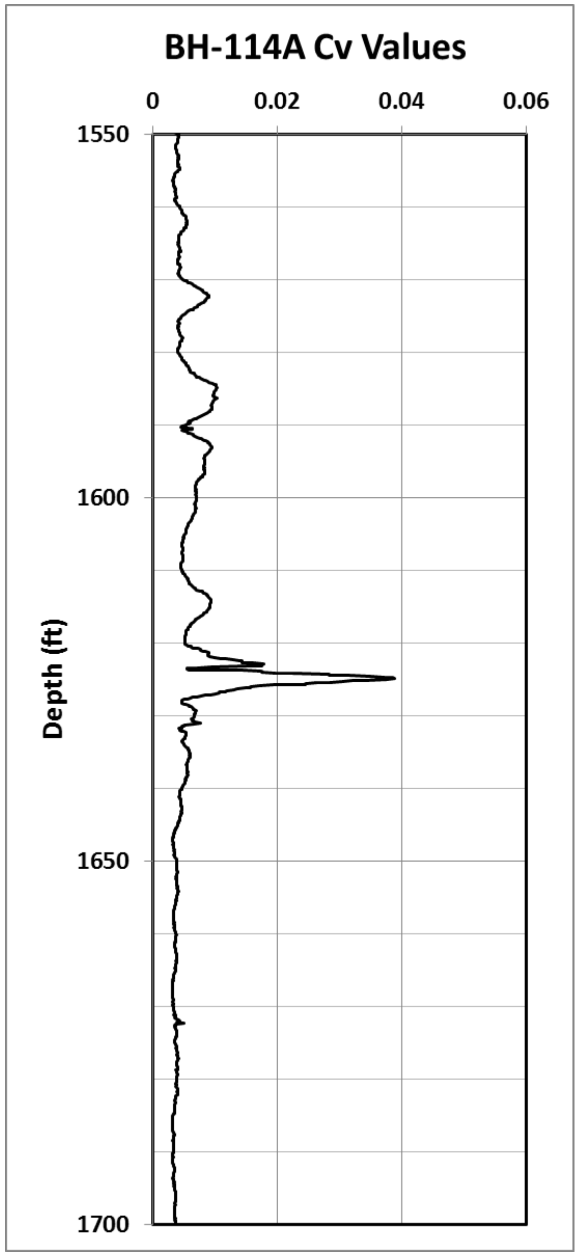

Figure 1-1. Cv values computed for well BH-114A showing radial casing deformation (high Cv values) at a depth of 1635 feet, near the salt-caprock interface.

2 INTRODUCTION

The U.S. Strategic Petroleum Reserve (SPR) holds a reserve of crude oil to help ease any interruptions in oil import to the United States. It was established in 1975 in response to the Arab oil embargo of 1973. The oil inventory as of February, 2015 is approximately 691 million barrels. The oil is stored in a set of 63 underground caverns distributed across four sites along the U.S. Gulf Coast. The caverns were solution mined into subsurface salt domes at each of the four sites. The salt domes were formed by the natural upwelling of the salt through the surrounding geologic layers (Halbouty, 1979). This upwelling occurs due to the relatively lower density of the salt compared to the surrounding materials, and is facilitated by salt's ability to flow as a plastic material. This plastic nature is beneficial for the storage of fluids as it heals fractures that may occur in the salt. Although the plastic nature of salt is helpful in maintaining the integrity of the caverns, it presents other challenges in the operation of storage caverns.

In order to create the caverns and then store fluids within them, it is necessary to have some manner to transport the fluids from the surface down into the salt dome. This is done using wells composed of metal casing and free-hanging pipe strings. These wells are used during the initial solution mining of the cavern, and then are employed to access the caverns themselves subsequent to cavern creation. The casings are commonly compound systems with a series of nested casings, one inside the other, with the annular space between them being filled with cement (Figure 2-1). The casing structure is designed to isolate the cavern system from the surrounding environment, protecting the overlying geologic media and groundwater from contamination.

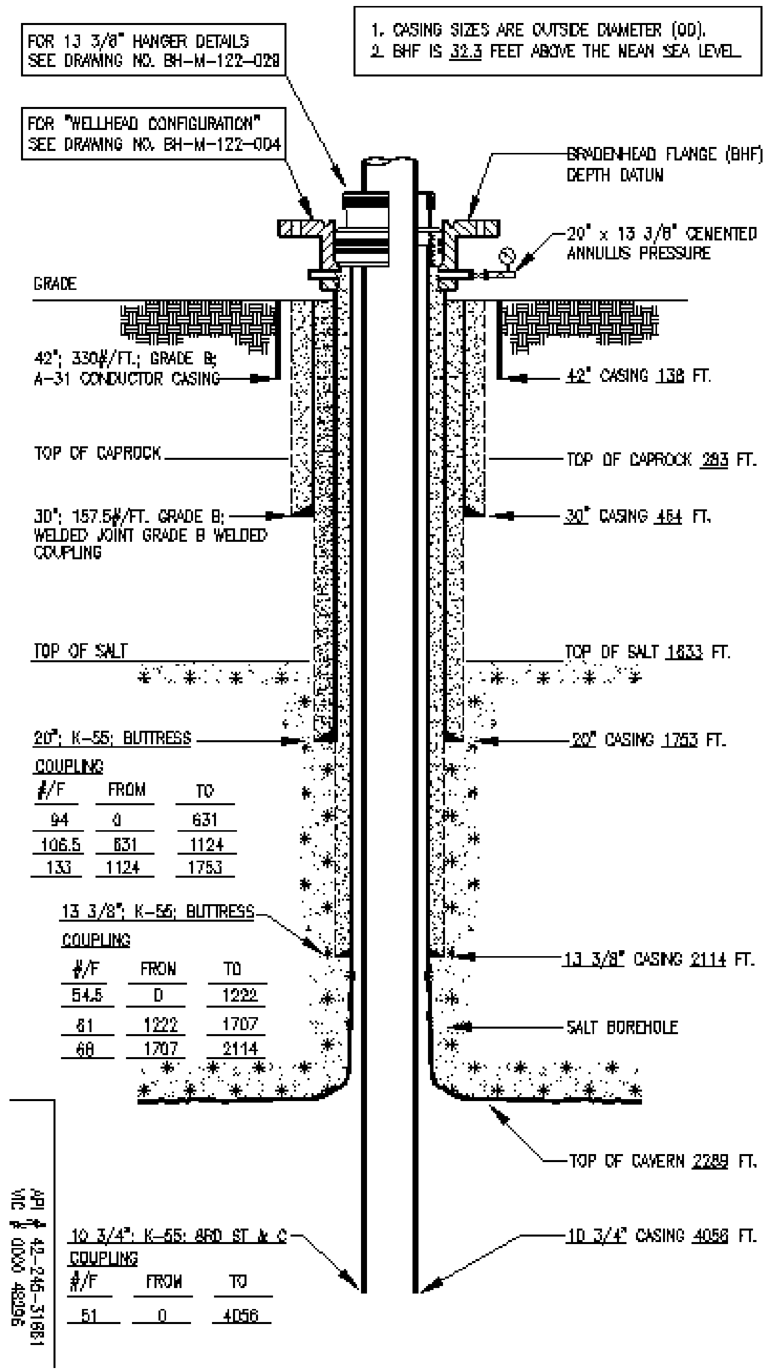

Figure 2-1. Example SPR well completion diagram showing nested casing strings with intervening cement.

The casing strings are composed of steel of appropriate weight and composition to withstand the burst and collapse pressures associated with cement injection and lithostatic collapse pressures at depth (Buschbom, 2012). For this reason they are very rigid when compared to the plastic salt. The introduction of a rigid casing string into plastic, dynamic geologic media is an incompatibility with consequences.

The SPR faces the challenge of operating and maintaining nearly 120 cased cavern wells across four sites in the storage complex over operational lifetimes spanning many decades. The cemented well casings provide critical isolation of cavern fluids from the surface environment and groundwater. SPR well integrity monitoring shows that the wells require remediation for a variety of issues including: (i) deformation and/or parted casing at the salt-caprock interface, (ii) deformation at the historical sulfur production zone in the Bryan Mound SPR site caprock, and (iii) leaky threaded casings (Lord et. al, 2013; Neal et. al, 1994; Sattler, et. al, 2002).

An effective technique to monitor the condition of installed well casing is to measure the cross-sectional shape of the casing as a function of depth. This technique can show radial deformation of the casing wall which can lead to casing integrity failure. These casing measurements are typically collected via a multi-arm caliper tool which determines the inner shape of the casing via a number of radial measurements. In addition to providing a measurement of casing deformation, multi-arm caliper measurement can also provide a measurement of the nominal thickness of the casing wall, referred to as the ‘weight’ of the casing. The analysis and interpretation of this multi-arm caliper data and its use in the analysis of radial casing deformation are the focus of this report. Although well casing may undergo many modes of deformation (longitudinal compression or elongation, lateral displacement, etc.), the discussion presented in this report will concentrate only on radial deformation. For the remainder of this report, when the word ‘deformation’ is used, it is meant to refer to radial deformation.

3 BACKGROUND

Multi-arm caliper (MAC) well logs are used within the SPR complex to determine if the casings in the cavern access wells are being deformed from their original circular cross-section. Radial deformation of this type is typically the result of rock mass movements from the surrounding geology. Deformations seen from these surveys can be indicative of potential future casing failures.

Multi-arm caliper tools measure the inside diameter of the well casing by recording the radial movement of a series of feeler arms. These arms are extended outward by spring action so that they ride against the casing wall during measurement. The number of tool arms varies by manufacturer and intended use, but typically is in the range of 24 to 80. Figure 3-1 shows the configuration of a Weatherford 60-arm MAC tool. This is typical of the type of tool used in collecting MAC survey data for SPR wells. Additional MAC tools used for SPR surveys include the E&P Wireline 56-arm tool and the Baker Atlas 80 arm tool.

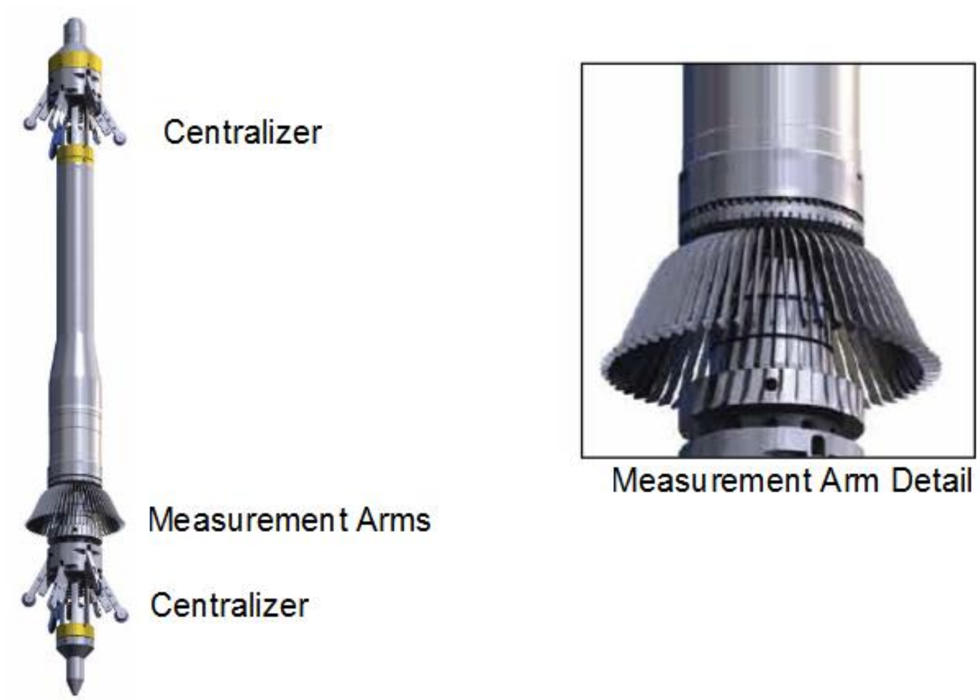

Figure 3-1. Weatherford 60-arm MAC tool.

In general, logging a well using a MAC tool is relatively uncomplicated. The tool is raised through the casing and the radial displacement of the feeler arms is measured as a function of depth. Typically the tool also contains a mechanism to record the general tool attitude. In wells with significant deviation from true vertical, this can be used to identify the "high arm" which can provide some general orientation information; in vertical or near-vertical wells, the high arm is not defined and is typically set to a constant value.

The data produced from the MAC logging tool consists primarily of the radial measurements of the feeler arms and the attitude of the tool in space. For straight, vertical or near-vertical wells the attitude information is not useful, so the remaining useful information is solely contained in the radial measurements. The radial arm data, and their change as a function of depth, are used by the logging vendor to calculate a series of values quantifying the shape of the casing and the amount of distortion from the casings original geometry. An example of the typical logging vendor presentation of the MAC survey results is presented in Figure 3-2. This plot shows summary information from the survey as a function of depth (vertical axis). This summary information includes the minimum, maximum, and average interior diameters (left-hand curves), computed nominal and minimum remaining wall thickness (middle curves) as well as representations of the raw radial arm measurements (right-hand curves).

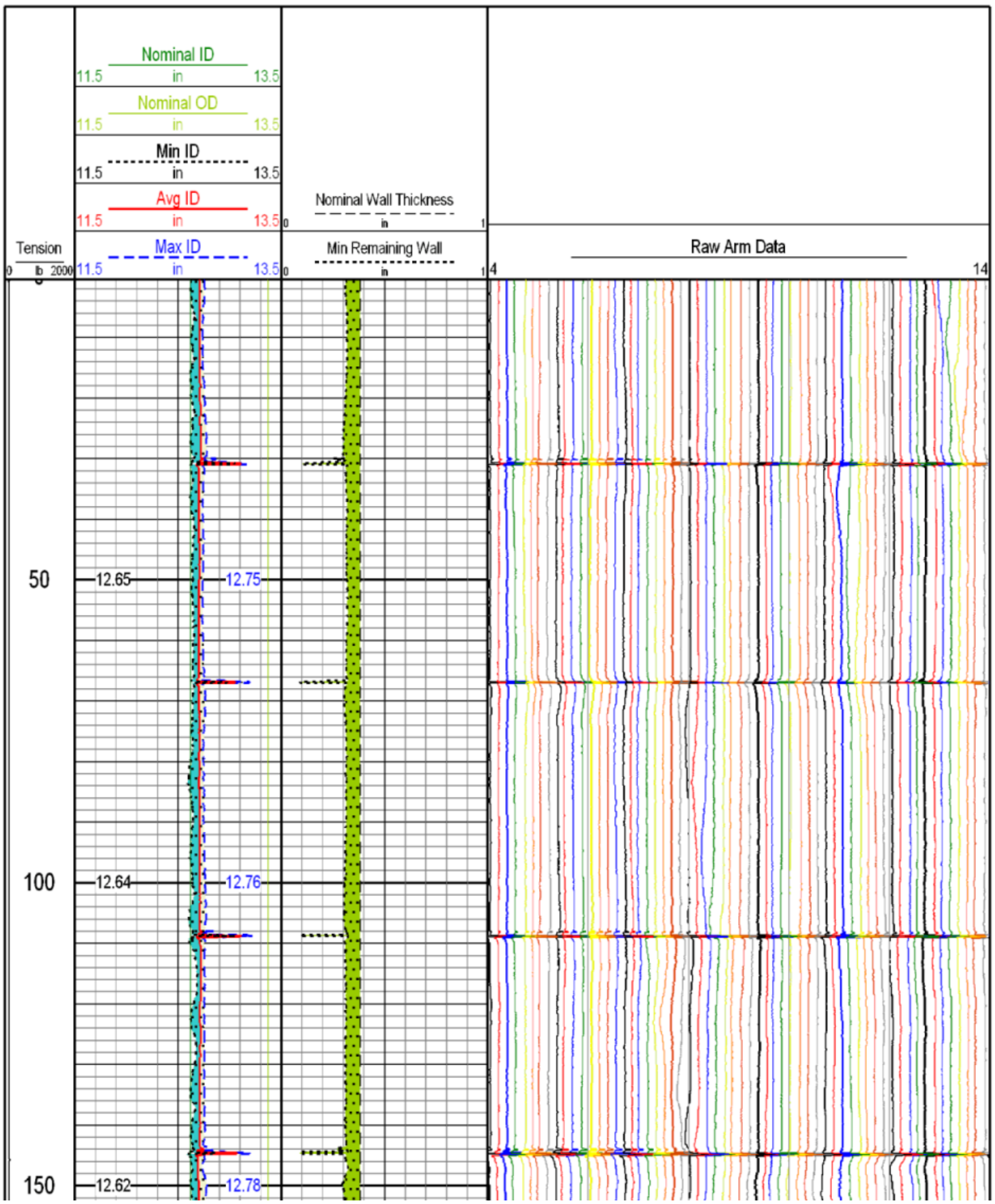

Figure 3-2. Typical MAC survey vendor well log report.

4 PROBLEM STATEMENT

At SPR storage sites, the salt surrounding the caverns is in a state of dynamic equilibrium, constantly adjusting to changes in stress in and around the salt dome. In addition to the natural upward buoyant flow of the salt due to its lower density, anthropogenic perturbations to the salt dome itself introduces additional stresses to the system. This includes the mining of large caverns in the salt, and the pressuring and de-pressuring of fluids held in those caverns (Sobolik, 2013).

The dynamic nature of the salt results in a discontinuity and slippage between the salt and surrounding geologic media which results in shear stress at this interface. This often results in radial casing deformation at the top of the salt dome where cavern access wells pass through this interface (Park and Ehgartner, 2012). Additional deformation can occur in the caprock which sits on top of the salt dome. The caprock is a collection of insoluble material (often gypsum and anhydrite) which is formed as groundwater dissolves the upper surface of the salt dome. As the dome rises, the soluble salts are dissolved leaving behind any insoluble material contained in the salt. In some cases, the caprock can contain economic concentrations of sulfur. The Bryan Mound salt dome, located along the Texas Gulf Coast, is an example of this. The solution mining of this sulfur results in voids in the caprock reducing its structural integrity. This can lead to deformation of well casings which pass through the caprock. In addition, sulfur in combination with surrounding fluids can create acids which have additional deleterious effects on the steel casing. The acidic formation fluids attack the casing outside of the casing further weakening it.

Without remediation, deformations in the casing can lead to casing failure. This can result in a loss of cavern fluids to the surrounding geologic environment. To characterize the existence and magnitude of any casing deformation, the SPR has been collecting MAC surveys of its cavern access wells.

A MAC survey is performed using a caliper tool which measures the inside radius of the casing as the tool is drawn through the well. These are typically recorded at vertical intervals of 0.1 to 0.02 feet; the number of radial arms is also variable, depending on the vendor, typically ranging from 56 to 80 arms. The large number of wells across the SPR sites, the high density of radial measurements, and the small vertical interval between measurements results in a very large data set. To date, the SPR MAC data comprise over 100 million individual radial measurements.

Once the MAC survey is completed, the logging survey company typically supplies a summary of the results in the form of a written report and graphical representation of the log values in standard well log format. This information also typically includes several parameters computed by the logging company designed to provide additional interpretation information to the client. These computed parameters do not have any standard definition and their specific derivation is not always well documented.

The lack of standardization of these computed parameters significantly reduces their value in making comparisons between MAC surveys collected from different vendors. The SPR MAC surveys have been collected over a number of years and have involved at least three different well logging companies. Each of these companies has generated their own proprietary report with their own company-specific computed parameters. These reports are informative on their own for any given well, but are less useful when attempting to compare surveys from another logging company. In addition to the report format, the radial arm data and computed parameters are also supplied in a digital data format known as a Log ASCII Standard (LAS) file (Struyk and Karst, 2009). This standard file format has a specific structure and contains the numeric data represented by the graphical log curves. The structure of the file provides metadata regarding the log and the measured log values as a function of depth.

Within the SPR, there are 120 cavern access wells distributed across the four site locations. The MAC surveys run in these wells are used to prioritize remediation resources so that wells showing greater deformation or risk of failure are given higher priorities. This requires well-to-well comparisons in order to rank wells against one-another based on deformation observed in the MAC survey data. The challenge arises when attempting to compare surveys from differing vendors. Since no standard comparative value is available in the vendor reports and log presentations, meaningful comparisons are impossible.

Figure 4-1 below shows a comparison of the graphical log output provided by two different well logging companies from MAC surveys for the same SPR well. These logs were generated by the logging companies and provided as part of their delivery package; both logs are from the same well, but were run three years apart from one another. The depth sections presented are from the upper-most section of the casing where there is little to no deformation.

As seen in this figure, although many of the curves present similar information (i.e. maximum diameter, minimum diameter, etc.), their presentation makes it difficult to make meaningful comparisons between the two surveys. In other cases, the curves present differing information which, while useful on its own, is not useable for comparison purposes. The end result is that the information collected from the MAC survey is not readily comparable across surveys by differing logging contractors.

What is needed is a common parameter which can be derived from any of the MAC surveys, regardless of the vendor, which would allow comparisons between individual surveys. Ideally, that parameter would be a single value representing the deformation level of the casing as a function of depth. This fundamental information could then be used to assess the relative amount of deformation each well is exhibiting, and allow a review of the relative rate of deformation given multiple surveys through time. Information such as this can then be used to rank the wells with respect to their future remediation needs. This type of ranking can then be used for planning resource expenditures. The following section of this report discusses the development of parameters designed to meet this goal.

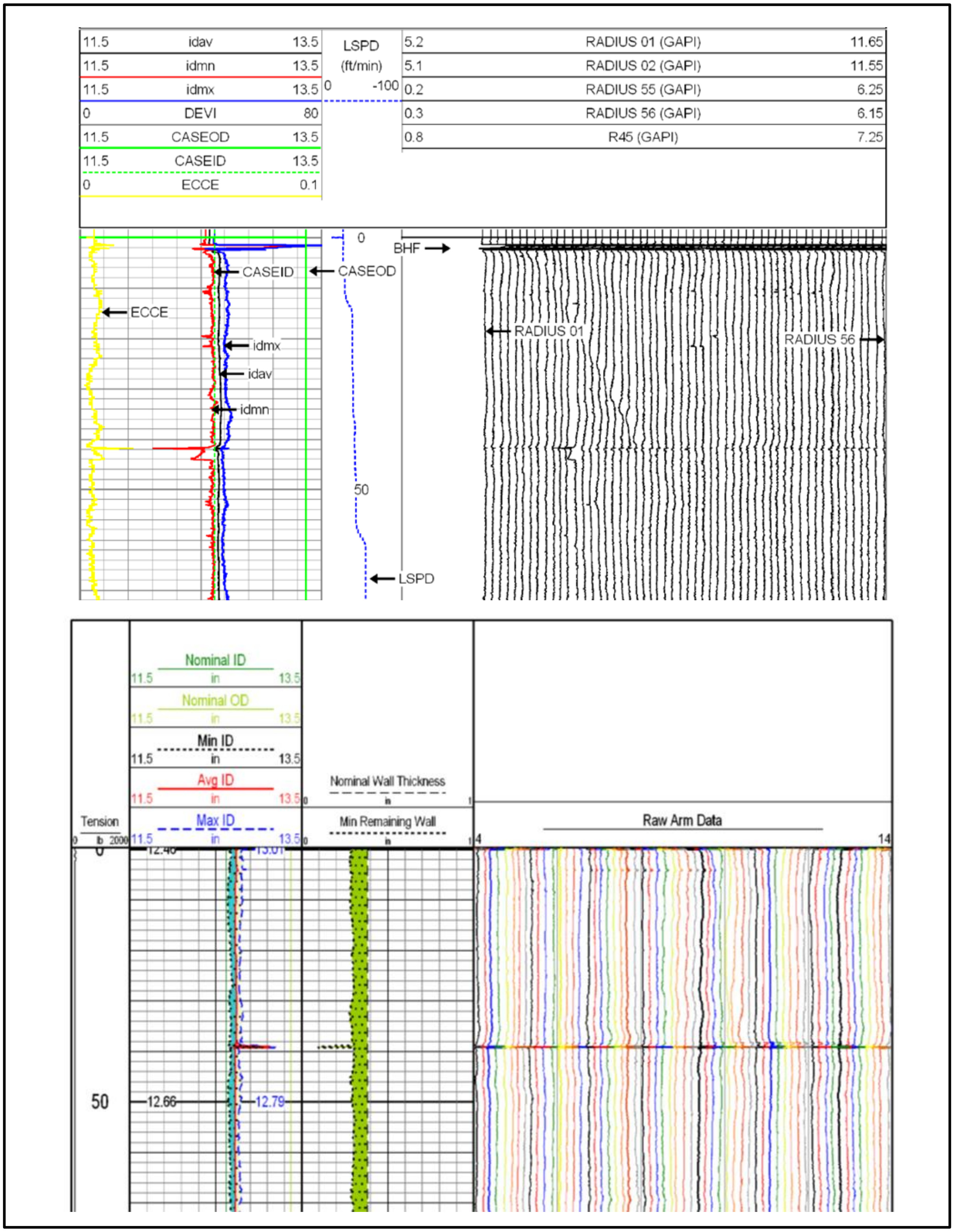

Figure 4-1. Top and bottom images show example output from multi-arm caliper surveys from two different logging companies for the same well.

5 METHODOLOGY

5.1 Fundamental Data

As discussed above, the challenge addressed here is the comparison of multi-arm caliper data collected from differing logging contractors across time and locations. Although each logging vendor provides thorough analysis reports and presentation of the logging data, each does so in their own proprietary format and using their own computational algorithms. This means that direct comparisons of these products from different vendors is difficult.

To address this issue it is necessary to go back to the fundamental data collected during the MAC survey, the raw radial measurements recorded by each arm in the tool. Starting from this basic data set allows one to trace and document the computations involved in formulating summary statistics for the logging data.

By their very nature, MAC surveys collect many measurements at each depth interval. Comparisons of each of these individual data elements (radial measurements) between separate wells are neither desirable nor informative. Differing tool orientation and de-centering means direct arm-to-arm comparisons are meaningless. What is more informative is a set of parameters that summarize all the radial arm data for each depth interval. These summary parameters need to present the radial arm data in a manner that relates the level of casing deformation as a function of depth.

The need to compute our own summary information from the MAC survey data requires starting with the raw radius values contained in the Log ASCII Standard (LAS) files delivered from the survey company. These files hold the radius measurements recorded by each of the radial arms as a function of depth. Given these raw data, any number of measurements of casing deformation can be computed.

5.2 Initial casing measurement parameter evaluation

During initial investigations of the MAC survey data, a series of different analysis variables were explored. These included basic statistics of the radial arm and diameter data as well as various other parameters believed to be indicative of casing deformation. Diameter values are computed by the addition of radius values from opposing radial arms. The parameters investigated as part of this research are listed in Table 5-1.

Table 5-1. MAC parameters investigated

Parameter	Description
Radial Arm Data Statistics	minimum, maximum, mean, standard deviation
Diameter Data Statistics	minimum, maximum, mean, standard deviation
Cross Sectional Area	Area of polygon described by radial measurements
Perimeter	Perimeter of polygon described by radial measurements
Isoperimetric quotient	Quantifies deviation of cross-section from a circle
Ovalization	Max minus min diameters divided by nominal diameter
Diameter coefficient of variation	Normalized diameter standard deviation
Relative wall displacement	Casing wall displacement relative to wall thickness

The parameters in Table 5-1 differ in their sensitivity to defining casing deformation. In addition, since they stem from the same basic data set or often have common computational roots, many of these parameters are highly correlated with one-another and hence are somewhat redundant. A series of initial investigations were performed to determine which of the parameters in Table 5-1 were most representative and responsive to casing deformation. Below is a brief synopsis of this analysis.

The first series of parameters investigated were the basic statistical factors of the radius and diameter values. As might be expected, the radial arm radius and diameter data follow similar patterns and hence generate similar statistics. Figure 5-1 shows a plot of radius and diameter normalized standard deviation values for Big Hill well 101A. Standard deviation is a good candidate as a proxy of casing deformation as any deformation would result in differing radius and diameter values which would increase the standard deviation value at a given depth. The depth section illustrated in Figure 5-1 contains a region with documented casing deformation occurring at a depth of 1665 feet (Weatherford, 2010a). This is represented by a large increase in the standard deviation values at this depth. The radius and diameter standard deviation values plotted in Figure 5-1 have patterns which are nearly identical along this depth section.

Although the standard deviation values for the radius and diameter values plot in a very similar pattern across a given depth interval, the populations of these values can be impacted by decentering of the MAC tool. As shown schematically in Figure 5-2, decentering of the MAC tool can cause large differences in the radius values, with lesser impact on the diameter values. In this schematic, a hypothetical 16 arm MAC tool is shown in cross-section. The tool is decentered having been shifted towards the bottom of the figure. Decentering of the tool shortens some radius values while lengthening others. The diameter values are less affected since their values represent the summation of opposing radius values; shortened and lengthened sections cancel out to a degree. This leads to an increased variance in the radial arm radius measurements; variance of the corresponding diameter values also increases but to a lesser degree.

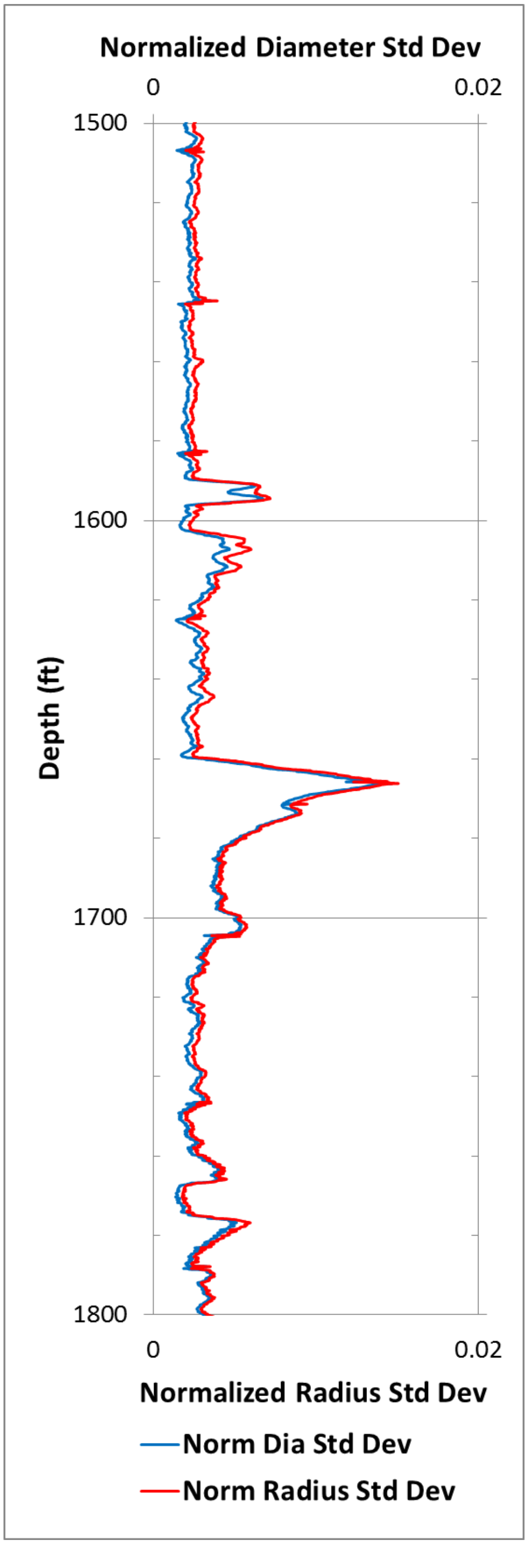

Figure 5-1. Normalized standard deviation of radius and diameter radial arm measurement values for BH-101A.

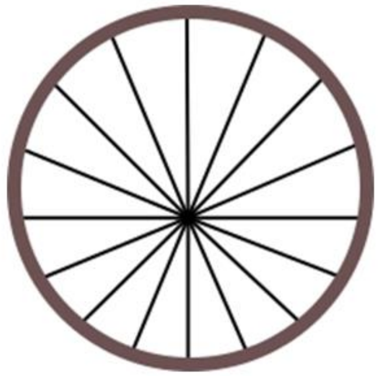

Figure 5-2. Schematic showing how decentering of MAC tool can impact diameter and radius values.

A comparative increase in radius standard deviation values is also demonstrated in Figure 5-3 which shows histogram outlines for diameter and radius normalized standard deviation values. The values have been normalized by dividing by the nominal casing radius or diameter so that the values would scale comparatively. These are equal to the coefficient of variation discussed later in this section. As seen in this figure, the normalized radius standard deviation values are skewed towards higher values. This is believed to be due to decentering of the MAC tool during the survey.

This analysis of radius and diameter values has shown that radius values have an increased sensitivity to tool decentering. The conclusion here is that diameter values are superior for use in evaluating casing deformation; radius values will not be considered further in this analysis.

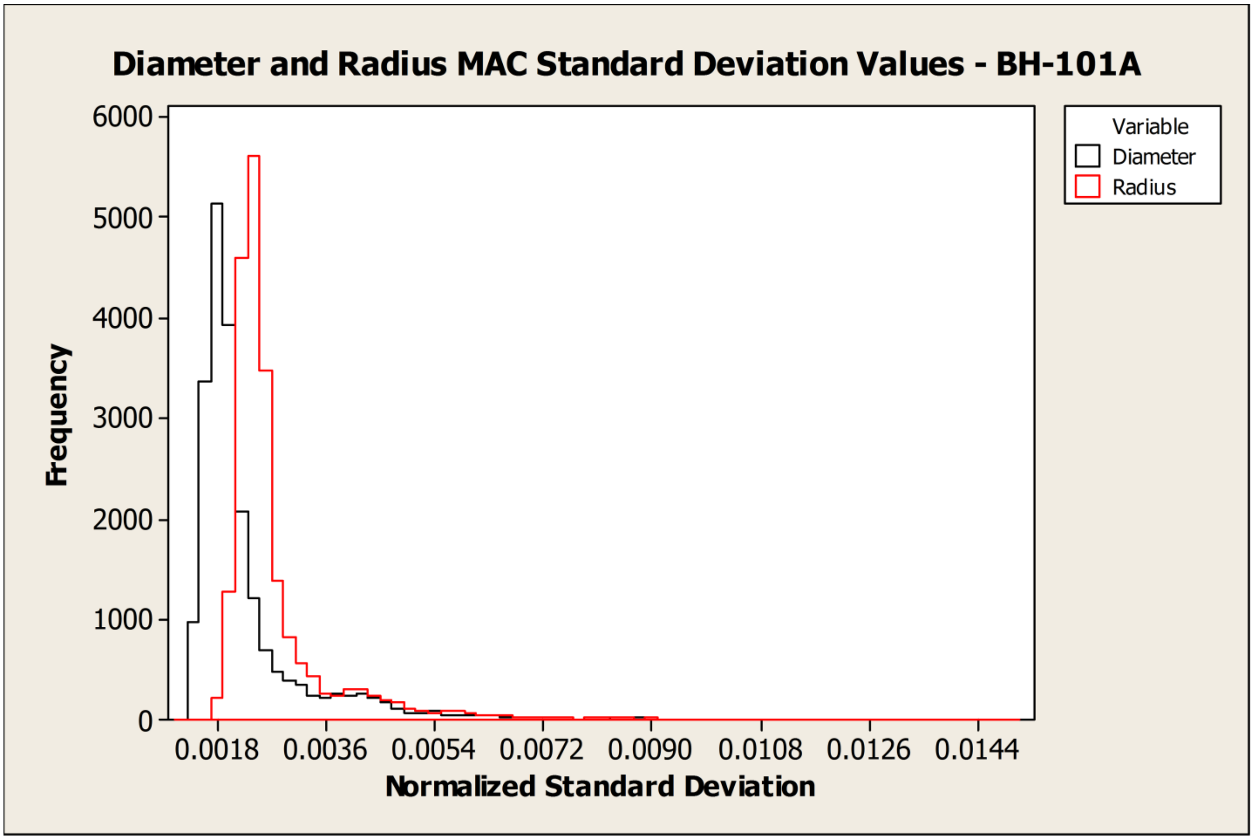

Figure 5-3. Histogram outlines comparing normalized standard deviation values of radius and diameters values of MAC survey of BH-101A.

The next series of casing deformation indicator values investigated are related to the overall geometry of the casing cross-section. These are the casing cross-sectional area, inner perimeter, and isoperimetric quotient. Since these parameters are related to the general configuration of the entire casing cross-section, they may provide a measure of casing deformation in a single value.

Figure 5-4 shows cross-sectional area (left), perimeter (middle), and isoperimetric quotient (right) for a section of well BH-101A. In each of these plots, the normalized diameter standard deviation is also shown as a reference for casing deformation. The large, short duration spikes seen in these plots represent measurements at the casing collar connectors and do not necessarily represent casing deformation. Also note that there is a change in the casing weight that occurs at a depth of 1704 feet. These can be observed in the plots as a step change in the cross-sectional area and perimeter values.

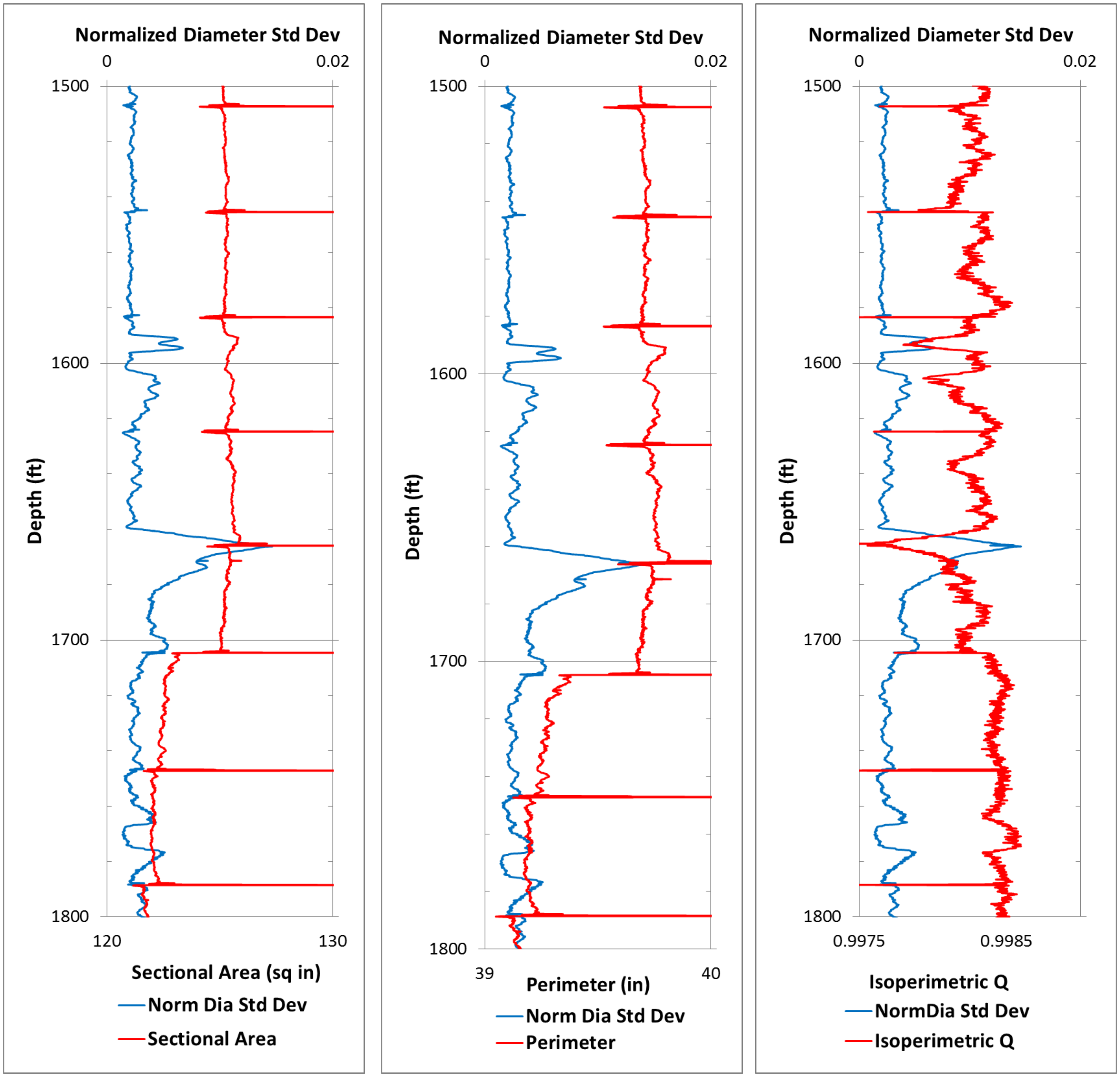

Figure 5-4. Comparison of casing normalized diameter standard deviation to cross-sectional area (left), perimeter (middle), and isoperimetric quotient (right) for well BH-101A. Systematic spikes in red curves are from casing collar connections spaced at 40 foot intervals.

As shown by the left-hand plot in Figure 5-4, the cross-sectional area of the casing interior (red line) is not as responsive to casing deformation as the baseline normalized diameter standard deviations (blue line). Although there is some response in the cross-sectional area curve, the main area of deformation at 1665’ is not recognized or is lost in the casing collar response. The main response in this curve is to changes in casing weight. Casing with different wall thicknesses is used at different depths of the well to withstand increasing lithostatic pressure with increasing depth. This wall thickness is represented by the casing weight in weight per length of casing (typically pounds per foot). Since the outside diameter of the casing remains constant, the inner diameter must decrease as casing weight (wall thickness) increases. The shift in the cross-sectional area curve of Figure 5-4 shows an increase in casing weight at a depth of about 1705 feet.

The middle plot in Figure 5-4 shows the casing interior perimeter (red line) and is again compared to the normalized diameter standard deviation. Not surprisingly, this curve shows a pattern similar to cross-sectional area and has a similar response to casing deformation. Again missing the deformation observed at the 1665’ depth.

The right-hand plot in Figure 5-4 shows the isoperimetric quotient (IQ) computed from the radial arm measurement data. IQ is a measure of how much a given polygon differs from a perfect circle by comparing the area of the polygon, casing cross-section in the case here, to its perimeter. The value is scaled so that a perfect circle has an IQ of one, and values less than one represent some deviation from a circle. For casing deformation studies, smaller values indicate increased casing deformation. Because most well casings are still fairly circular, even when deformed, the range in IQ values is relatively small (see x-axis range in plot). Although the IQ curve shows significant response to casing deformation, and accurately identifies the deformation at 1665 feet, the curves tend to be very noisy which distracts from the ready identification of specific areas of deformation.

Up to this point we have been plotting the parameters listed in Table 5-1 against a value we have been referring to as *normalized diameter standard deviation.* This curve was plotted as a reference to indicate where actual casing deformation was observed so that the parameter being investigated could be evaluated. The normalized diameter standard deviation is just the standard deviation of the MAC diameter values divided by the expected casing interior diameter. The expected casing interior diameter can also be considered the mean interior casing diameter. In main stream statistics the standard deviation of a population divided by the population mean is referred to as the coefficient of variation. From here on, we will adopt standard statistical terminology and refer to our normalized diameter standard deviation as the *diameter coefficient of variation* (C_v).

Equation 1 shows the definition of the coefficient of variation. In our use, we substitute the *expected* casing interior diameter as determined by the casing outer diameter and casing weight for the mean. Inner diameter values as a function of casing weight are readily available and standardized by the American Petroleum Institute. This has the advantage of tying the values back to the expected manufacturing specifications, and maintains a constant normalization factor for each section of casing. The disadvantage is that the expected casing interior diameter needs to be specified. This value is typically available from the well completion documentation.

Equation 1

$$C_v = \frac{\sigma}{\mu}$$

Where:

σ is the standard deviation of the diameter values
μ is the mean of the diameter values.

The next parameter considered from Table 5-1 is ovalization which is computed as a normalized difference between the minimum and maximum diameters. The left-hand plot of Figure 5-5 shows a comparison of C_v and ovalization values for well BH-101A. As shown here, ovalization and C_v are very highly correlated. Both parameters reflect casing deformation very well. Inspection of C_v and ovalization values from a series of wells showed C_v values to be somewhat less noisy than ovalization values. In addition, since C_v values are computed using every measurement value, they should be more representative of total casing deformation as contrasted with ovalization values which only use the maximum and minimum diameter values.

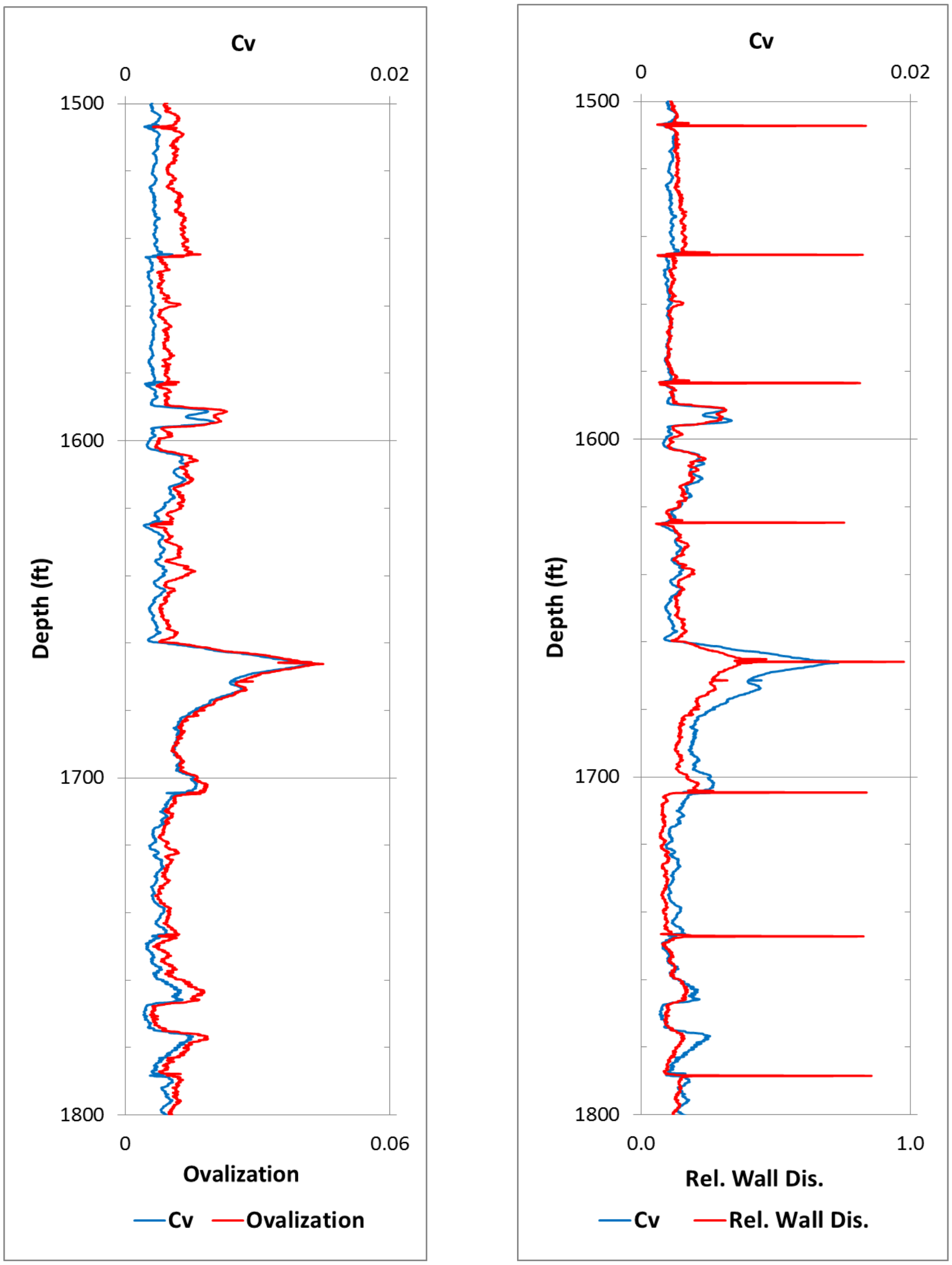

Figure 5-5. Comparison of diameter coefficient of variation (C_v) to ovalization (left) and relative wall displacement (right) for well BH-101A.

The right-hand plot of Figure 5-5 shows a comparison of C_v values to the final parameter of Table 5-1, relative wall displacement (RWD). RWD presents an indication of the maximum displacement of the casing wall as a function of depth. This is computed by determining the maximum difference between the measured internal casing diameter and the expected internal diameter which is a function of the casing weight. This difference is then normalized by dividing by the expected casing wall thickness. This results in a value that represents casing wall displacement scaled to the wall thickness; a value of one represents displacement of the equivalent of one casing wall thickness at that depth. RWD is computed as shown in Equation 2:

Equation 2

$$RWD = \frac{(Max\ ID\ Delta) * 0.5}{Expected\ Casing\ Wall\ Thickness}$$

Where:

$$Max\ ID\ Delta = \mathrm{MAX}(|(Min\_MID) - (EID)|\ ,\ |\ (Max\_MID) - (EID)|)$$

$$Expected\ Casing\ Wall\ Thickness = OD - EID$$

$Min\_MID =$ minimum measured internal diameter
$Max\_MID =$ maximum measured internal diameter
$EID =$ expected internal diameter
$OD =$ outer diameter

Although RWD is also highly correlated with C_v, it is somewhat less responsive to casing deformation and significantly more sensitive to casing collar features (see spikes in Figure 5-5).

5.3 Final parameter selection

From the above analysis, it was determined that the coefficient of variation of the measured casing diameters is the most effective summary measure of casing deformation. The coefficient of variation (C_v), is the standard deviation normalized by the mean (see Equation 1). It scales the standard deviation so that values from populations with different means are comparable. The applicability here is that it removes the overall casing diameter from influencing the standard deviation and will allow for comparisons between differing casing sizes if necessary.

For a perfectly circular object, the population of measured diameters would all have the same exact value; therefore the standard deviation would be zero. This would lead to a C_v of zero as well. In reality, no casing section is perfectly circular, even prior to installation, therefore virtually all diameter C_v values computed from radial arm measurements will be greater than zero; it is only relatively large C_v values that indicate casing deformation. A schematic showing casing cross-sections resulting in low and high C_v values is shown in Figure 5-6.

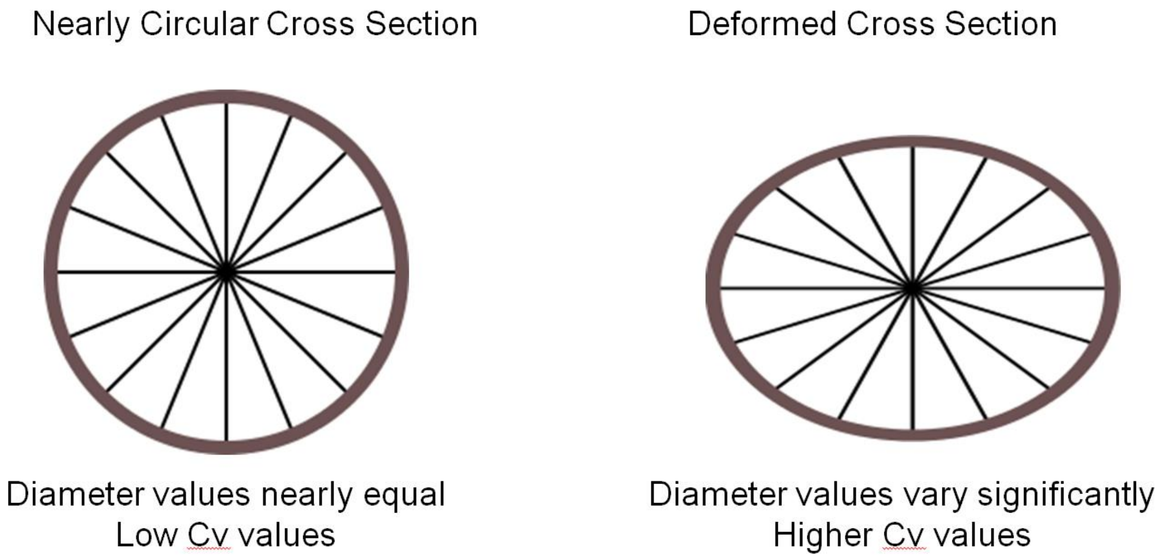

Figure 5-6. Schematic showing how radial casing deformation impacts diameter values resulting in low and high C_v values.

One caveat to this is that radial measurements where the survey tool is not centered in the casing will also lead to C_v values greater than zero, even in perfectly circular casing. This is because the radial values are not measured from the center of the casing and so do not represent true diameter measurements (Figure 5-2). Conversely, significant de-centralization of the tool is usually caused by some type of casing distortion and therefore, still indicative of casing issues. The use of diameter values in the C_v calculations helps to reduce the influence of tool de-centering.

Some MAC logging operators attempt to correct for this decentering of the tool and report these values as "corrected radius". Although this effort may have merit, the corrected radius values are not available for all the historic MAC surveys, and hence, don't provide a common data set for comparisons. For this reason, only raw radius values are used in the variable calculations presented here.

Figure 5-7 shows a comparison between diameter C_v values computed from corrected and raw radius values. These were obtained from a single MAC survey of well BM-2. In this case the survey contractor delivered the corrected and uncorrected raw radius values.
Figure 5-7 is centered on the depth interval showing the greatest deformation in this well. As this figure shows, although there are slight differences between the two C_v value curves, the curves are nearly parallel with both providing a good representation of the location and extent of the casing deformation. The conclusion here is that there is no disadvantage in using uncorrected radius values, and the advantage of having the raw radius values available for each well is paramount for comparative purposes.

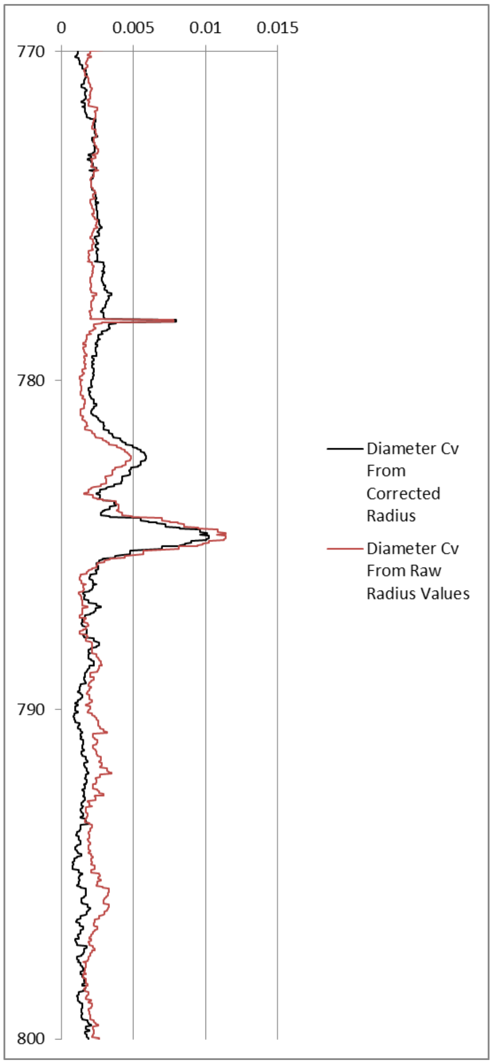

Figure 5-7. Comparison of diameter Cv values computed from corrected and raw radius values for well BM-2.

As a comparison of the distribution of C_v values that are observed in newly installed casing and in casing known to have significant deformation, pre and post-remediation C_v values for BH-114A were examined. BH-114A was known to have severe casing deformation at the salt-cap rock interface, and so was remediated by cementing an additional casing inside the existing configuration.

An examination of the C_v value distributions for BH-114A shows that the post-remediation survey has a mean of 0.0015 and a standard deviation of 0.00056, while the pre-remediation survey had a mean of 0.0024 and a standard deviation of 0.00229. As expected, the pre-remediation survey C_v values have a larger mean and standard deviation, a result of the significant casing deformation which led to the remediation of this well. These differences can be readily seen in Figure 5-8 which shows a comparison of the C_v values between the pre and post-remediation MAC surveys. As seen in this figure, there are significant differences in the distribution of C_v values between the two surveys; most notable is the shift in the pre-remediation values to higher C_v values.

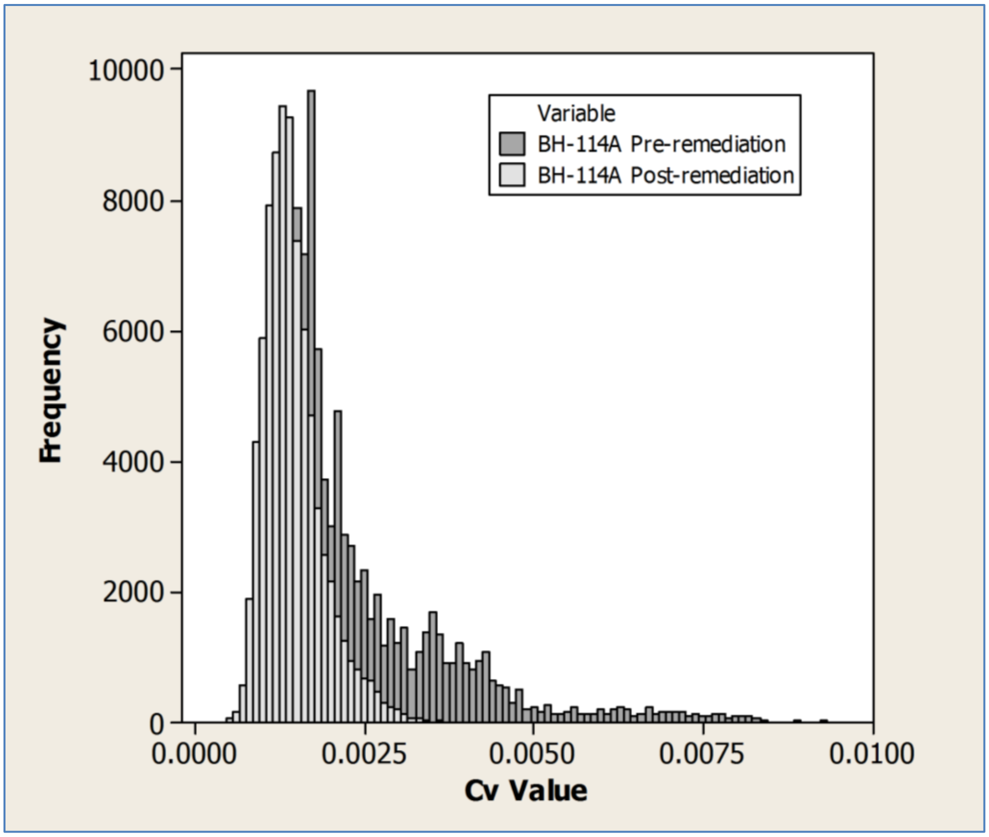

Figure 5-8. Overlaid histograms of C_v values for BH114A pre- and post-remediation MAC Surveys.

For well BH-114A, the maximum C_v pre-remediation values occur at the salt-cap rock interface at a depth of approximately 1625 feet, where the C_v reaches a value of 0.1; the post–remediation value at this same depth is on the order of 0.0008. This comparison clearly shows the sensitivity of the C_v to casing deformation.

In addition to C_v values, an additional variable, Relative Wall Displacement (RWD) was also found useful in summarizing casing deformation. Like C_v, RWD was computed directly from the radial arm values contained in the LAS files.

As discussed in Section 5.2, RWD presents an indication of the maximum displacement of the casing wall as a function of depth. This is computed by determining the maximum difference between the measured internal casing diameters and the expected internal diameters which is a function of the casing weight. This difference is then normalized by dividing by the expected casing wall thickness. This results in a value that represents casing wall displacement scaled to the wall thickness; a value of one represents displacement of the equivalent of one casing wall thickness at that depth.

The RWD variable was maintained because it gives a better indication of the actual maximum displacement of the casing wall than C_v values do. Although C_v and RWD values are highly correlated for a single well, in some cases they do not directly track one-another in which case RWD may be provide information not represented in the C_v values.

Figure 5-9 is a plot of the C_v and RWD values for well BH-113A for a depth interval encompassing the salt-cap rock interface. The C_v and RWD curves have the same general shape, but do differ significantly at various locations. This indicates that these two variables are providing different views of the radial arm data, each of which can provide insight into casing deformation levels.

The above examination has covered a number of variables thought to be useful in identifying casing deformation from MAC surveys. From this, a set of two variables, coefficient of variation of the diameter values (C_v) and relative wall displacement (RWD) have been identified as being most useful in characterizing casing deformation. These two variables have been used in setting well remediation priorities for the Big Hill SPR site (Lord et al., 2014).

The remainder of this report will focus on examination of casing deformation as represented by C_v values. C_v values are considered to be most representative of general casing deformation, and so are most useful in presenting examples of general casing distortion.

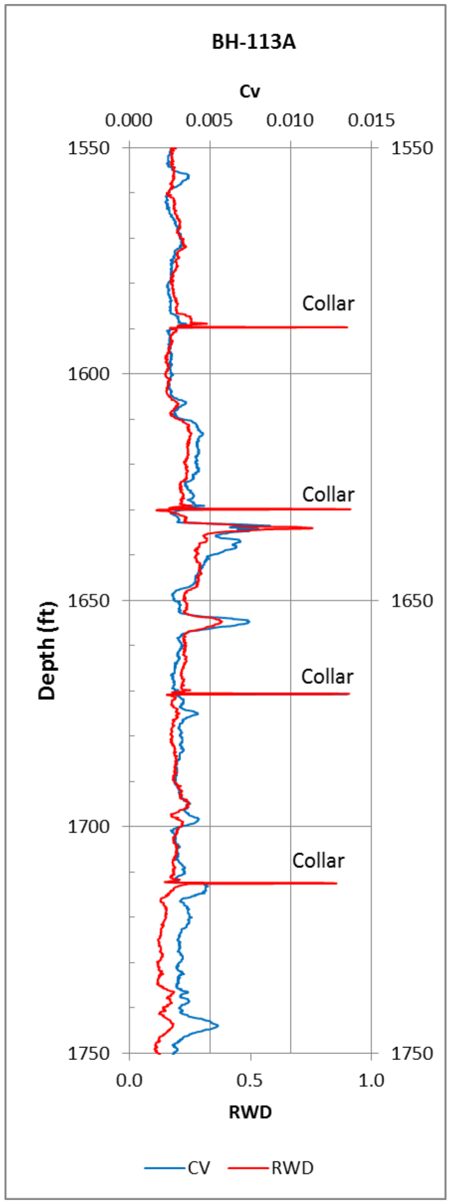

Figure 5-9. Comparison of Cv and RWD values for well BH113A.

5.4 Computational Techniques

As presented in Section 5.1 of this report, in order to compare MAC survey results from multiple vendors and across multiple survey dates, it is necessary to work with the raw radial arm data contained within LAS files. To facilitate this, a custom processing script was constructed using the Python programming language. This interactive script allows for the selection of the LAS file of interest, reads all curve data in the file, provides interactive selection of the radial arm data curves (curve names are not standardized), computes the variables described in Section 5.2, and then writes the results to an electronic spreadsheet complete with plots of the primary variables of interest.

To confirm the computational consistency between the vendor supplied LAS values and those computed using the Python analysis software here, comparison statistics on the basic diameter values were computed. This compared summary data computed from curve data contained in the raw LAS files to results from the custom analysis software developed for this project. Consistency between these summary data would confirm that the Python analysis script is processing the data in a fashion similar to the MAC survey vendor software.

Table 5-2 presents a comparison between a set of summary variables taken from the raw LAS files and the Python processing script results. The summary variables used were: average diameter, minimum diameter, maximum diameter, and diameter standard deviation. These values were compared for each depth station listed in the LAS file. The "Summary Variable" column in Table 5-2 indicates the variable used in the comparison. The remaining columns present the difference statistics for that variable. The difference values were computed as Python script value minus vendor LAS file value. The comparison statistics were computed using the MAC survey results from a survey Bryan Mound well 106A performed on June 4, 2009. This survey reported radial arm measurements for 19,805 depth stations; all of these stations were used in computing the comparison statistics.

As seen in Table 5-2, the values computed by the Python analysis script are virtually identical to those taken directly from the LAS file. The minor differences seen in the comparison are likely rounding errors. Most importantly, the mean differences are all zero showing there is no bias in the differences between the two processing procedures. This affords some verification that the Python code is computing values in a similar manner to the vendor code. This provides confidence in the analysis of results from the Python code.

Table 5-2. Comparison statistics for summary variables.

Summary Variable	Mean Value	Min. Value	Max. Value
Average Diameter (in.)	0.000000	-0.000035	0.000037
Minimum Diameter (in.)	0.000000	-0.000100	0.000100
Maximum Diameter (in.)	0.000000	-0.000100	0.000100
Diameter Std. Dev.	0.000000	-0.000033	0.000033

Figure 5-10 through Figure 5-13 show plots of C_v values as a function of depth alongside the survey vendor's logs for the same depth interval. Figure 5-10 shows this data for well WH-117A for a section of the well noted in the vendor's report for showing signs of casing deformation (Weatherford, 2010b). The report notes evidence of ovality at depths of 2200 feet and 2275 feet. This can be seen in the vendor's log plot (left side of Figure 5-10) as an increase in difference between the maximum and minimum inner diameter curves. Evidence of this same deformation is well displayed in the C_v value curve (right side of Figure 5-10) as a significant increase in C_v values at these same locations.

Figure 5-11 shows a second example of this type of comparison for well BH-101A. This well shows deformation at a depth of 1665 feet, just below the salt-caprock interface as noted in the vendor's report (Weatherford, 2010a). The C_v value curve also reflects this area of deformation and another region of deformation at a depth of 1692 feet. Again, the C_v value curve mimics the vendor's logs and identified areas of deformation.

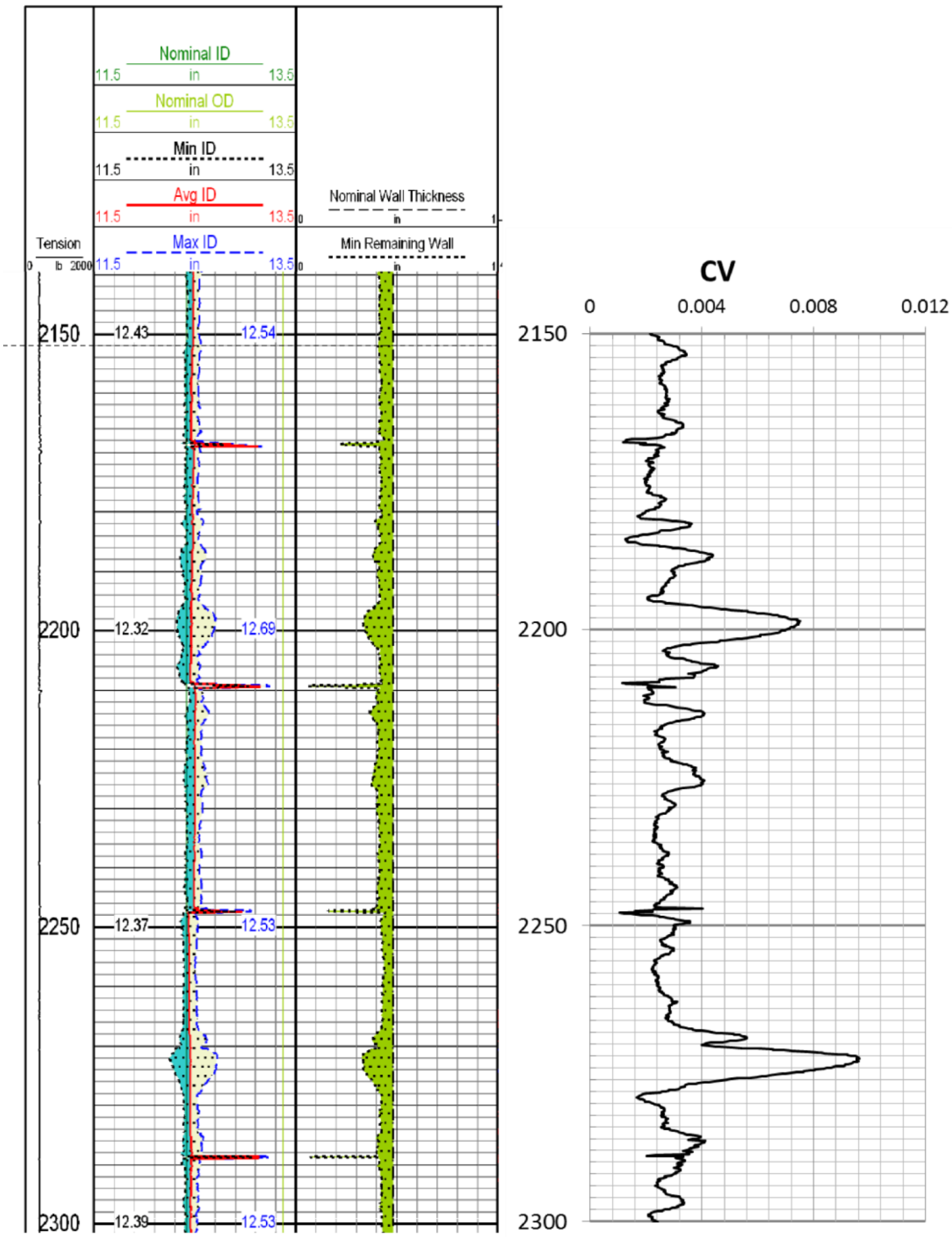

Figure 5-10. Comparison between vendor supplied MAC log representation (left) and plot of C_v values (right) for well WH-117A.

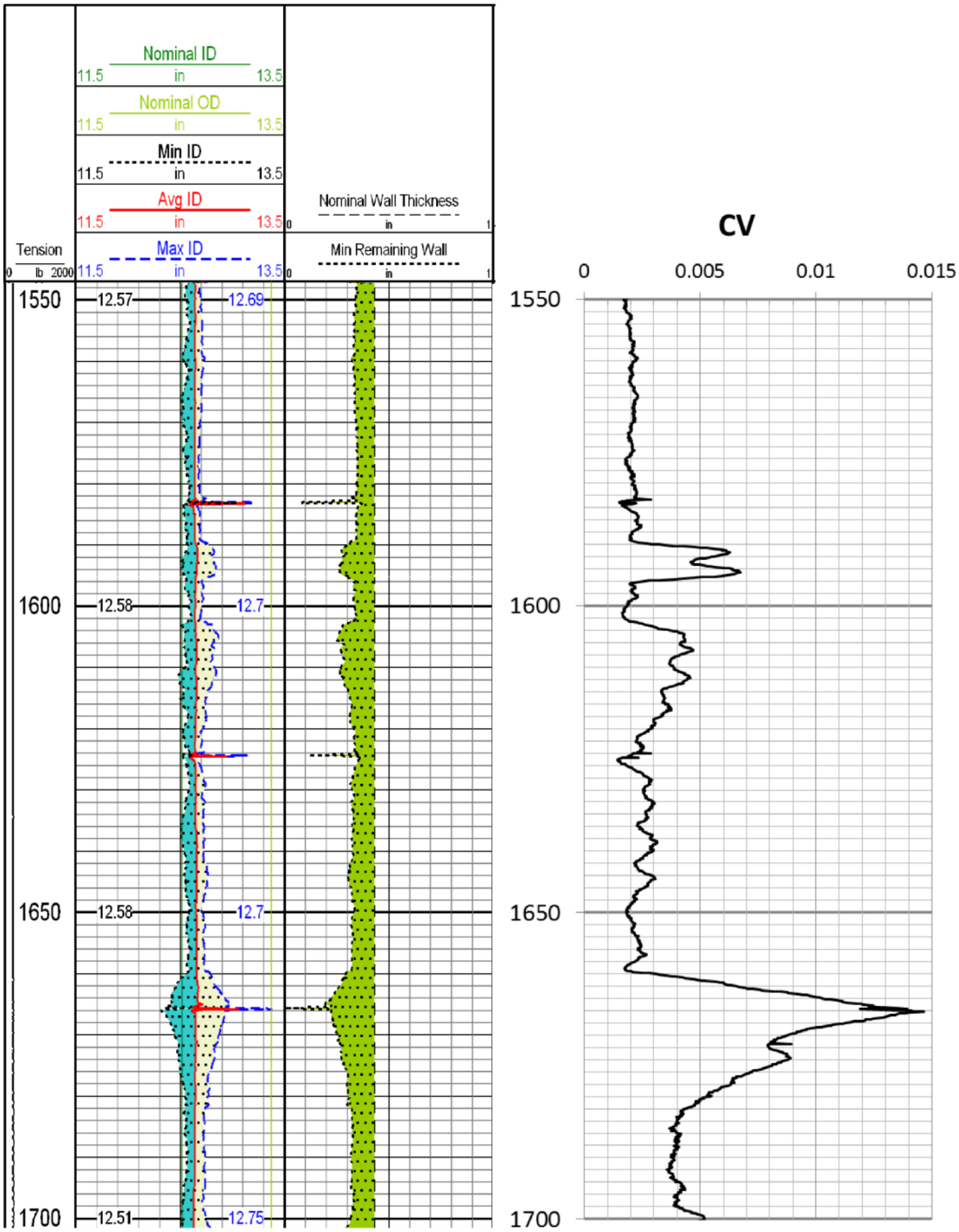

Figure 5-11. Comparison between vendor supplied MAC log representation (left) and plot of C_v values (right) for well BH-101A.

Figure 5-12 shows another comparison between the vendor MAC logs and C_v values. This particular depth segment was chosen to compare the curves in a region with a single isolated zone of deformation surrounded by areas showing little to no deformation. The C_v value curve follows the vendor's log closely; displaying high C_v values in the deformed area (1050 foot depth), and low values in the un-deformed areas. In this case, the C_v value curves also shows strong signals at the casing collar locations.

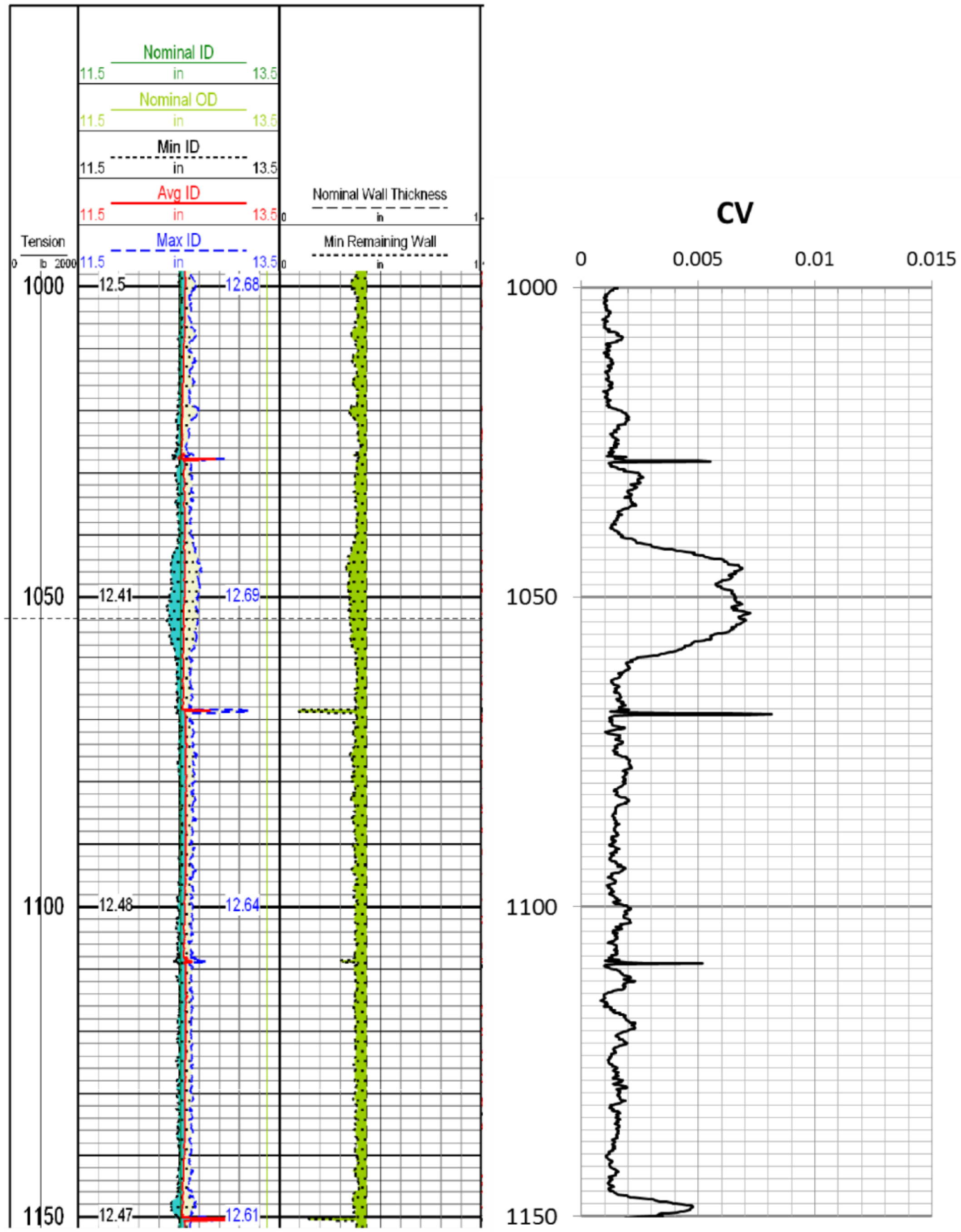

Figure 5-12. Comparison between vendor supplied MAC log representation (left) and plot of C_v values (right) for well BM-108A.

A final comparison between the vendor's log results and C_v values is shown in Figure 5-13. For this example, the C_v values are shown adjacent to the raw radial arm values. This example is for well BC-15 and shows how the C_v values closely mimic small undulations seen in the raw radial arm data for an un-deformed section of casing. These undulations are likely manufacturing artifacts as their frequency and amplitude is different for each casing segment. This demonstrates the relative sensitivity of the C_v values to minor changes in casing diameter.

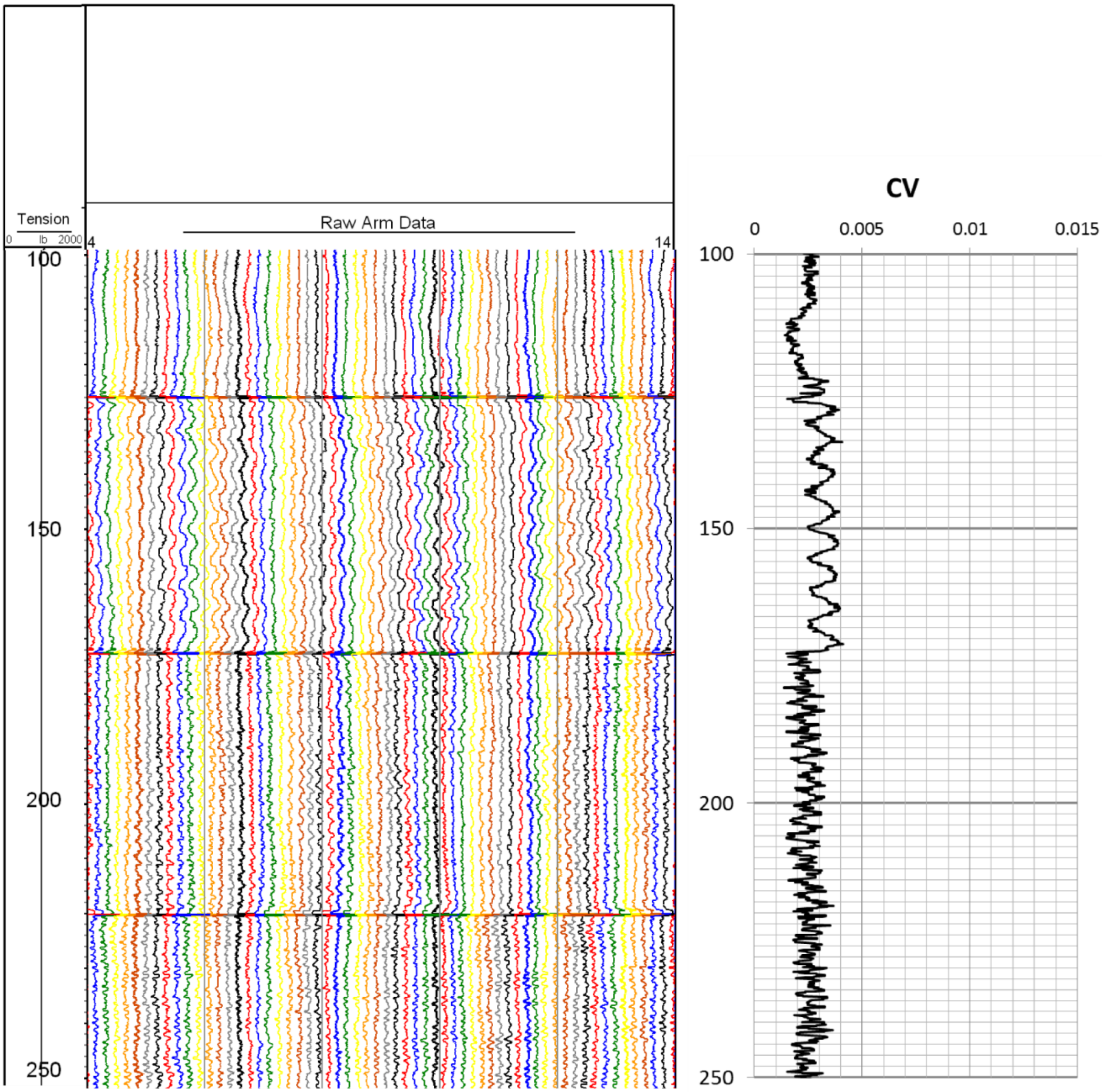

Figure 5-13. Comparison between vendor supplied MAC log representation showing raw radial arm data (left), and plot of C_v values (right) for well BC-15.

The above comparisons between the vendor's survey logs and C_v values provides confidence that these values are mimicking the same responses that the survey vendors are employing for casing analysis. This indicates that the computational code used in processing the raw radial arm data from the LAS files is producing results consistent with the vendor's computations. The benefit in using C_v value curves is that they provide a consistent framework across all the MAC logs and so allow well-to-well, and time-dependent comparisons of the MAC survey results regardless of the vendor.

6 ANALYSIS

The above discussion has demonstrated the need and development of common evaluation parameters for MAC survey data. These parameters allow for the comparison of MAC survey results across multiple vendors. This section presents evaluations of MAC data using one of these new parameters (C_v) and discusses its use in well integrity evaluation.

6.1 SPR Well Configurations

The SPR spans multiple sites, each of which is composed of multiple caverns. These caverns have differing development histories which results in a mixture of well completion configurations. Initial SPR well completions consist of a series of nested casings stepped to different total depths, with the inner-most casing having the greatest depth. Only the inner-most casing is open and available for MAC surveys.

Figure 6-1 through Figure 6-4 display examples of different well configurations as installed across the SPR. While not comprehensive of all the well configurations, these figures provide a representative sampling of the most common well installations.

Figure 6-1 shows the well configurations for BC-101B which has a 13-3/8 inch OD inner-most casing. This is one of the most common inner-most casing diameters used in initial well construction at the SPR. This well has no hanging string, a section of freely-hanging casing suspended within the cemented casing, and is commonly referred to as a “slick hole” as its primary use is for oil movement. Well BM-102C (Figure 6-2) is also a slick hole and was installed with a 16 inch inner-most cemented casing.

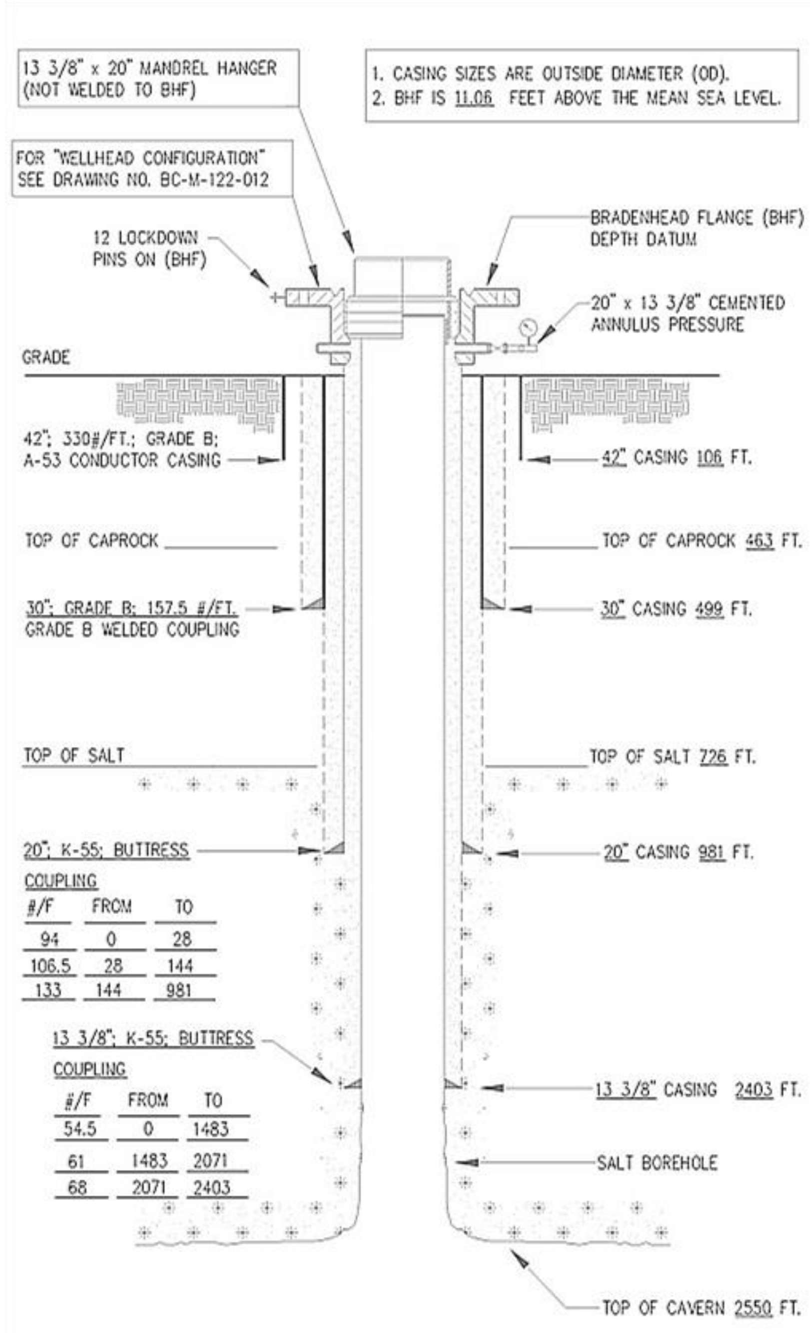

Figure 6-1. Well configuration for well BC-101B.

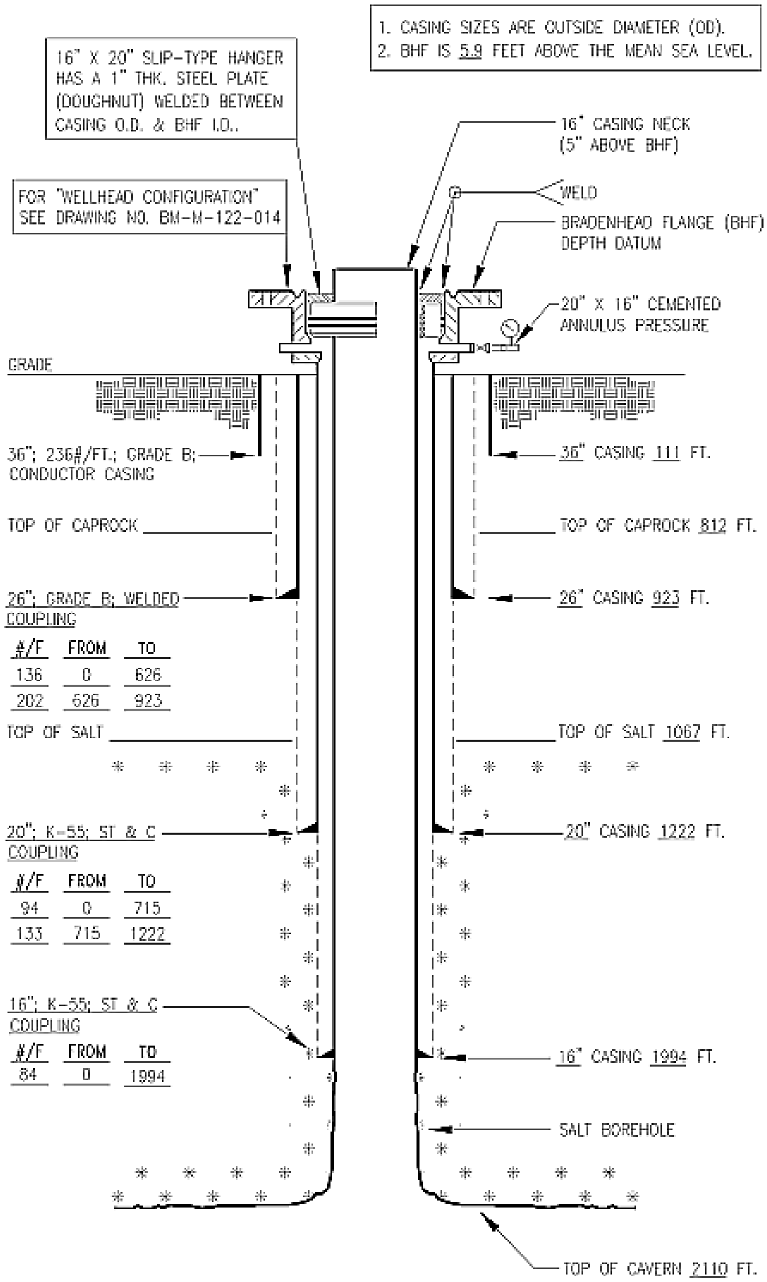

Figure 6-2. Well configuration for well BM-102C.

Well BM-110A (Figure 6-3) contains a hanging casing string used for moving water or brine to the lower portions of the cavern. It was completed with the common 13-3/8 inch inner-most cemented casing.

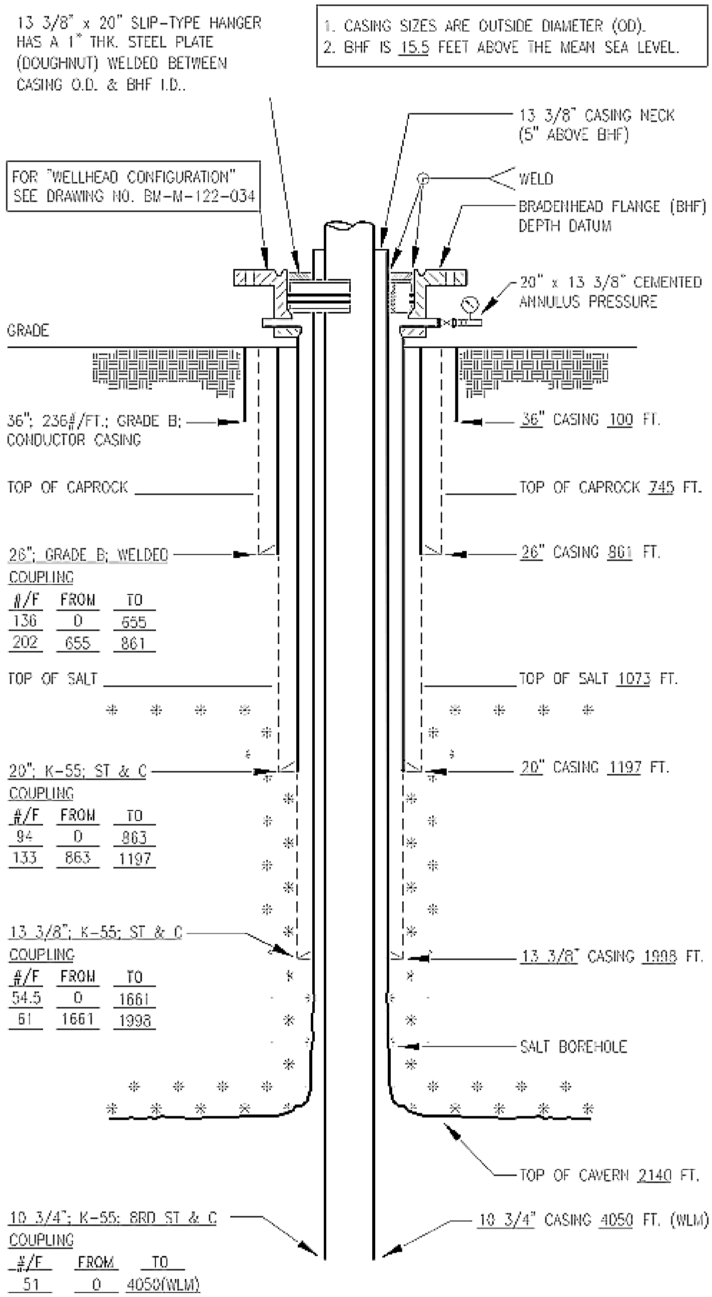

Figure 6-3. Well configuration for well BM-110A.

Figure 6-4 shows the well configuration for well WH-108. This well has a large 20 inch inner-most casing and also contains a hanging string.

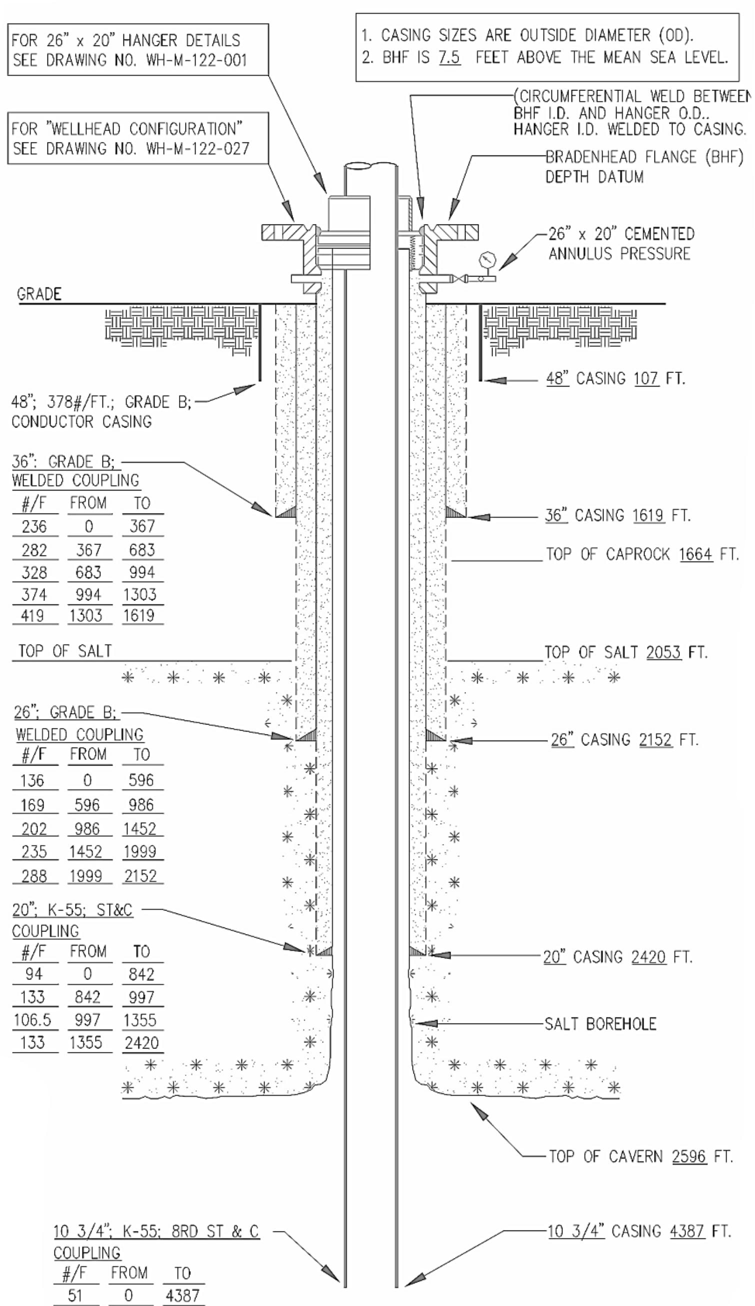

Figure 6-4. Well configuration for well WH-108.

As demonstrated above, the well configurations at the SPR vary considerably. In addition to the differences in OD between wells, for a single well, the ID of the inner-most casing may also vary. This occurs because differing wall thicknesses, or "weights", are available for a given casing OD. The differences in weights lead to differing casing strengths. Typically, thicker wall casing (higher weight) are installed in the deeper sections of the borehole to resist the greater lithostatic pressures and cement weights during installation (Buschbom, 2012).

As seen in Figure 6-1 through Figure 6-4, different sections of the inner-most casing may be composed of differing casing weights. This is done to efficiently use higher casing weights only where they are needed. Casing weights are specified in the units of pounds per foot. Table 6-1 lists some of the casing weights and nominal inner diameters for the inner-most cemented casing commonly used at SPR sites. As expected, the inner diameter of the casing decreases as weight, and wall thickness, increases. Full standard casing specifications appear in the latest edition of the American Petroleum Institute (API) Specification 5CT (API, 2011).

Table 6-1. Common API casing weights used at the SPR (Halliburton, 2010).

Casing OD (in.)	Weight (lbs./ft.)	Casing ID (in.)
13.375	54.50	12.615
13.375	61.00	12.515
13.375	68.00	12.415
16	84.00	15.010
20	94	19.124
20	106.5	19.000
20	133	18.730

6.2 Example Casing Analyses

This section provides examples of the use of C_v values for casing analysis. The examples shown here where selected to demonstrate particular situations within the well casing and in some cases represent extreme situations. This discussion provides examples of casing deformation known to be associated with a loss of integrity of the well system. This was typically diagnosed by the failure to maintain expected well pressures.

6.2.1 Big Hill 105

Cavern BH-105 developed notable pressure anomalies in early 2010 (Ehgartner, 2010). Subsequent MAC surveys of both of the cavern access wells (BH-105A and BH-105B) showed that both wells had casing deformation at the salt-caprock interface, with BH-105B showing significant deformation. Both wells have similar constructions. The original well configuration for well BH-105B is shown in Figure 6-5.

Figure 6-6 shows C_v values for BH-105A from a MAC survey conducted in May of 2010. The plots in this figure show the C_v values in the region of greatest deformation as a function of depth and two additional plots showing the radial arm data at specific depths. The radial arm plot depths were selected to show the casing ID perimeter at the point of greatest deformation and a contrasting point with little to no deformation. These are labeled with the selected depth and the corresponding C_v value at that depth. These plots can be viewed as cross-sections through the casing at that depth; the radial arm identifying numbers are shown along the perimeter.

The upper radial arm plot of Figure 6-6 shows the casing ID at the point of greatest deformation for BH-105A. The dashed circle in this plot shows the expected casing ID for that depth based on as-built drawings. The MAC measured casing radius values (blue line) deviate from the expected ID in several locations along the perimeter. These deviations are notable, but not extreme. The C_v value at this location is 0.0117. The lower radial arm plot shows the measured ID for a region with virtually no deformation; the C_v value here is 0.0014. The average C_v value for the entire casing length is 0.0018. In the lower plot, the measured radial arm data directly overlie the expected casing ID masking the dashed reference line.

Similar data is shown for well BH-105B in Figure 6-7 from a MAC survey conducted in June, 2010. This well shows a much higher maximum C_v value (0.0359) than the A-well. This is confirmed in the lower radial arm plot showing radius measurements at the point of greatest casing deformation. Here the measured radius values significantly exceed the documented casing ID for a majority of the perimeter, indicating considerable casing deformation. The upper radial arm plot in Figure 6-7 shows measured values for a relatively un-deformed portion of the casing. The C_v value for this location is relatively low (0.0030) indicating that all the radial arm measurement values are similar. However, the upper radial arm plot shows the measured values exceeding the expected casing diameter for a majority of the perimeter. There are two primary explanations for this, either the MAC tool was mis-calibrated, leading to incorrect measurement values, or, the as-built documentation does not match the actual casing installation. The MAC measured average diameter at this depth (1570 feet) is 12.709 inches. The documented casing weight for this depth is 61 pounds per foot (Figure 6-5) corresponding to an interior diameter of 12.515 inches (Table 6-1). This is nearly 0.2 inch difference. If the 12.709 inch average ID measurement is accurate, this would correspond to casing weight of 48 pounds per foot (Halliburton, 2010). Inspection of the tool calibration data for this survey shows that the MAC tool seems to have been properly calibrated. This indicates that the installed casing weights may not match the as-built drawings.

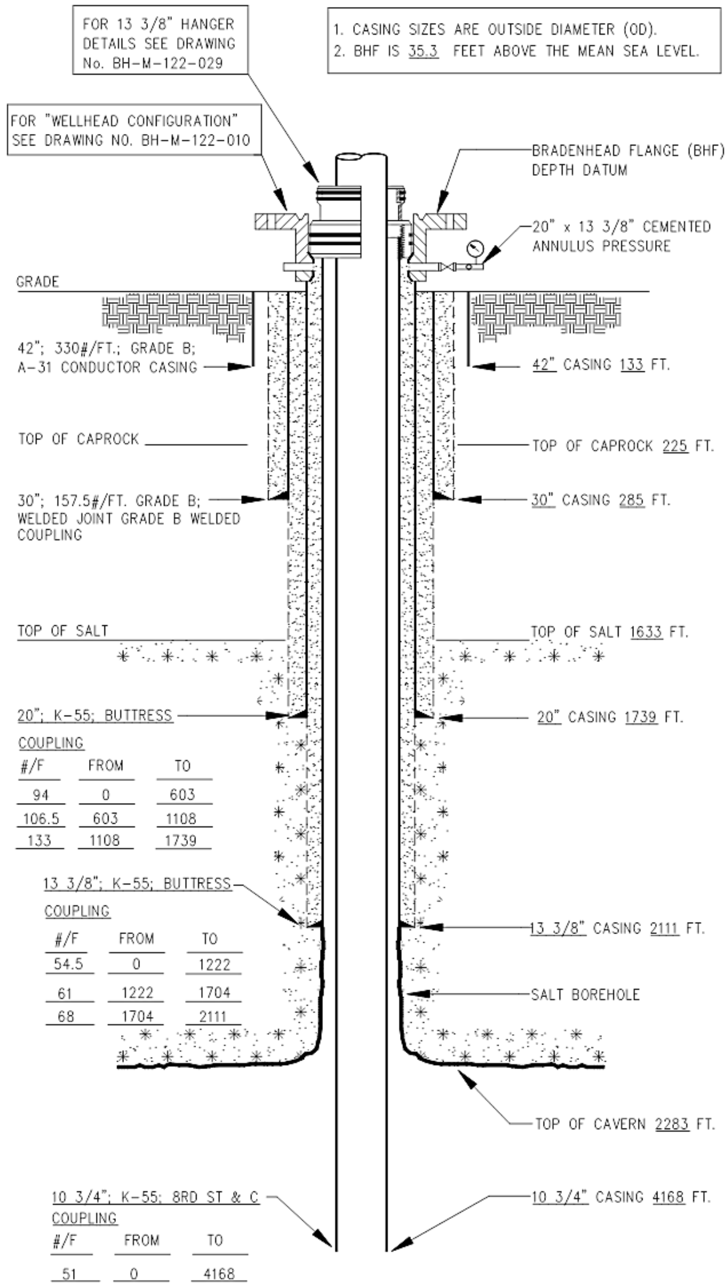

Figure 6-5. Original well configuration for well BH-105B.

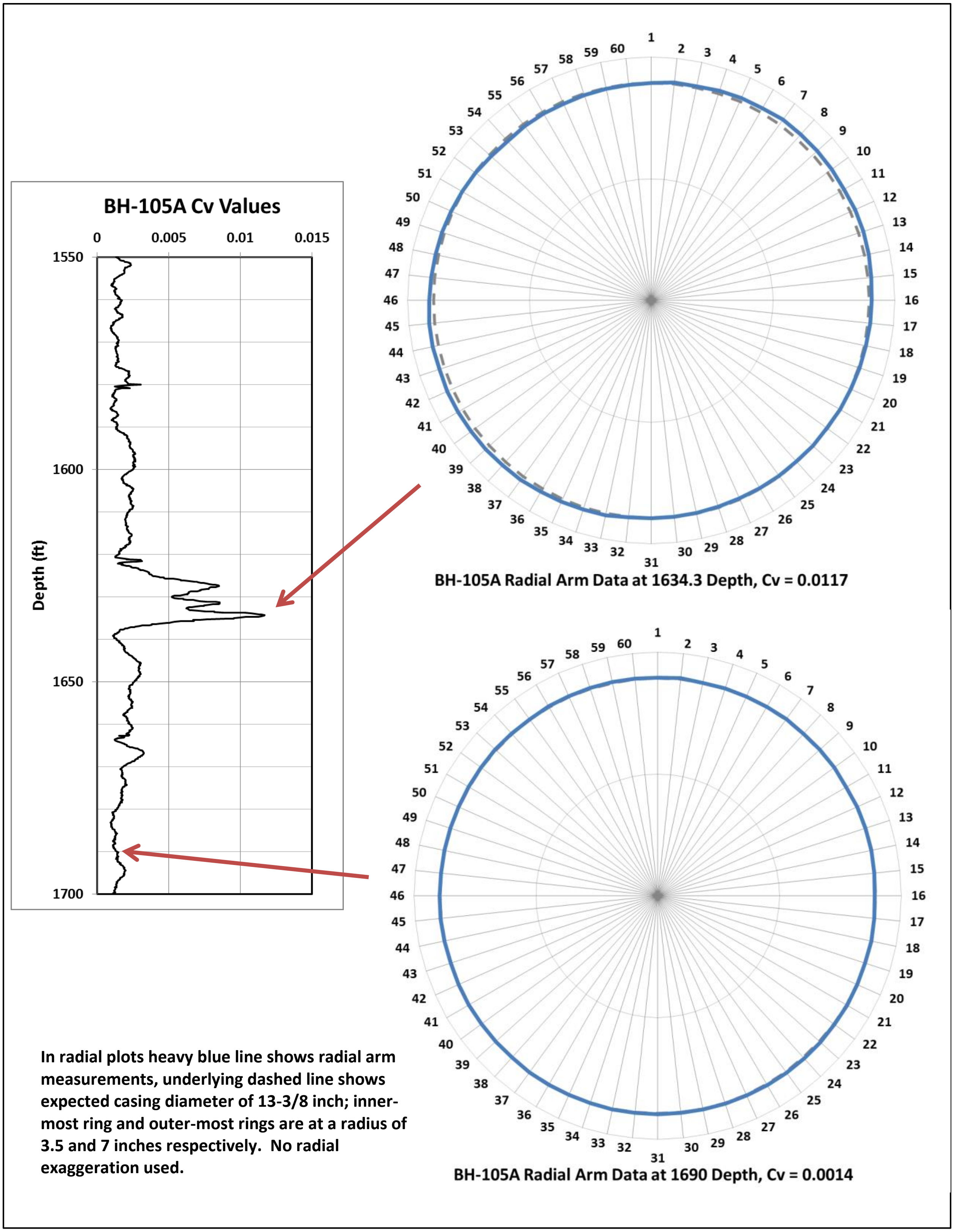

Figure 6-6. Cv value curve for BH-105A and corresponding radial arm measurement data from 2010 survey at points of greatest deformation (top) and little deformation (bottom).

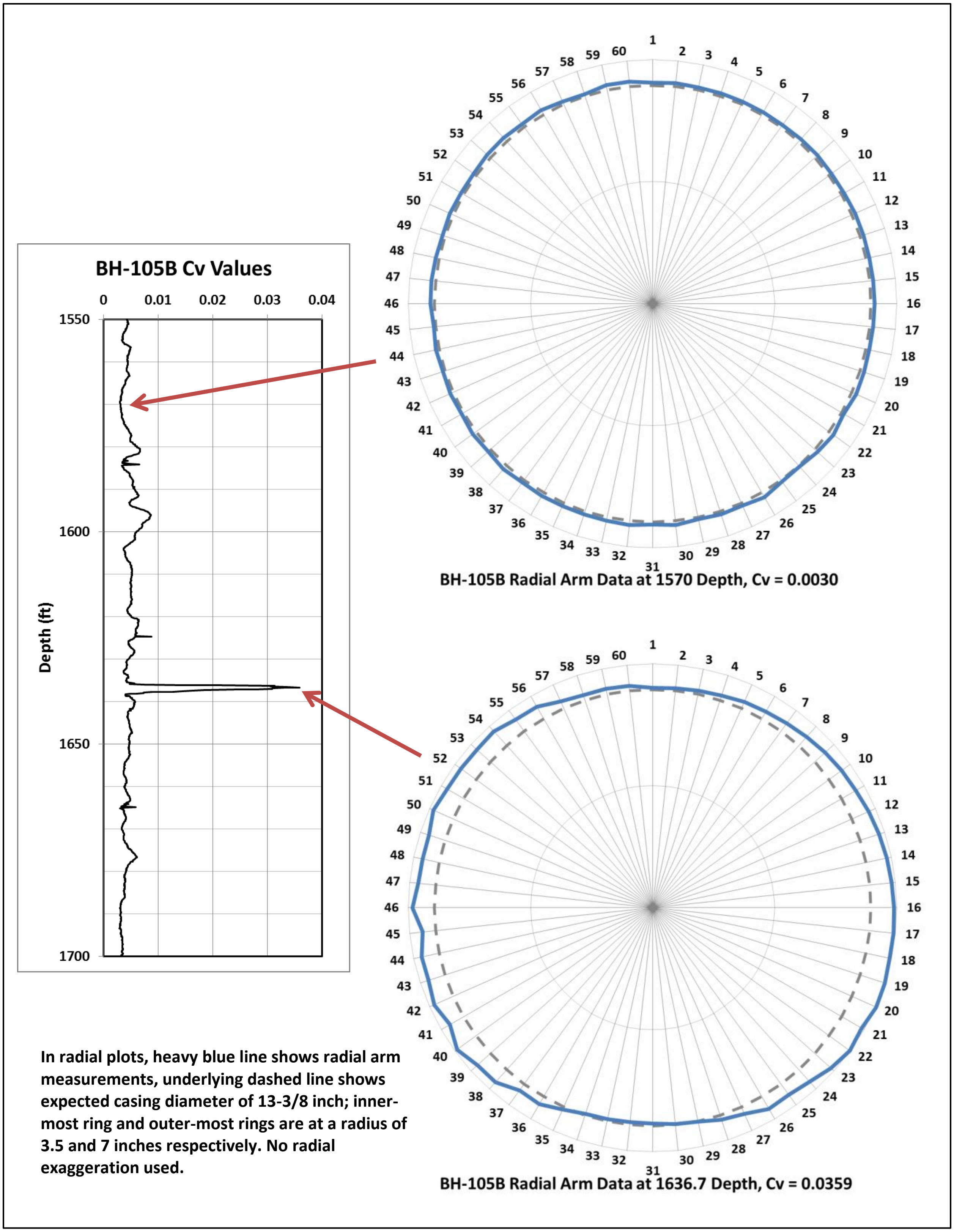

Figure 6-7. Cv value curve for BH-105B and corresponding radial arm measurement data from 2010 survey at points of greatest deformation (bottom) and lesser deformation (top).

Figure 6-8 shows the C_v values for wells BH-105A and BH-105B plotted together for the area with the greatest casing deformation. This shows how much greater the C_v values for BH-105B are compared to those from BH-105A. The B well shows severe deformation over a very small depth interval compared to the A well where the deformation is less severe and is distributed over a greater depth range. Each of these MAC surveys used a vertical sampling interval of 0.1 feet and both were completed within a month's time of each other. Both wells were subsequently remediated by installing interior liners.

Figure 6-9 shows a comparison between the pre and post-remediation C_v values for BH-105B. As expected, the C_v values after liner installation are significantly lower than the pre-remediation numbers.

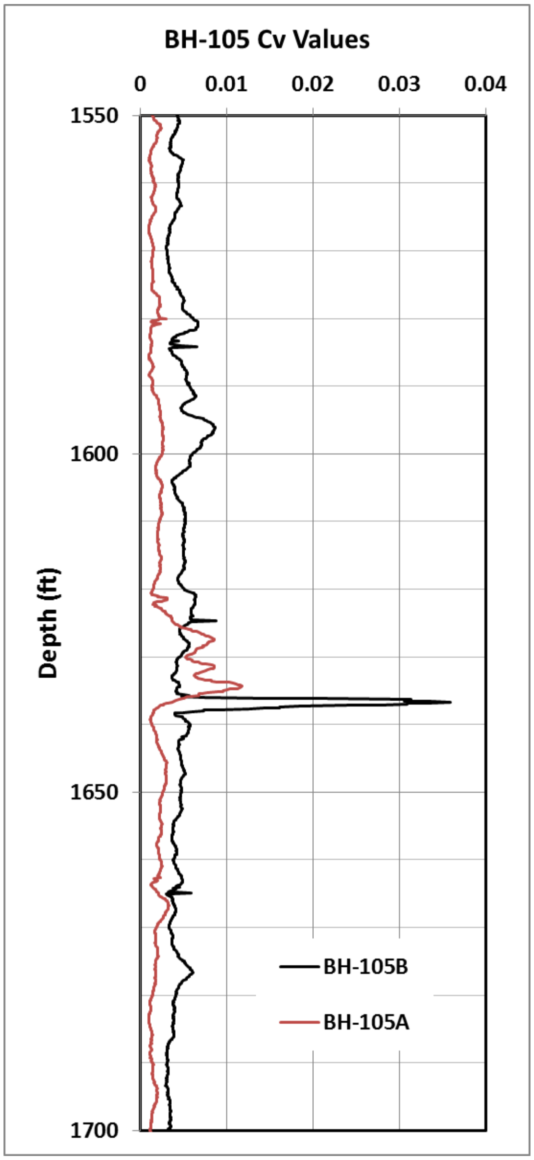

Figure 6-8. Cv value curves for BH-105A and BH-105B from 2010 survey for region showing greatest casing deformation.

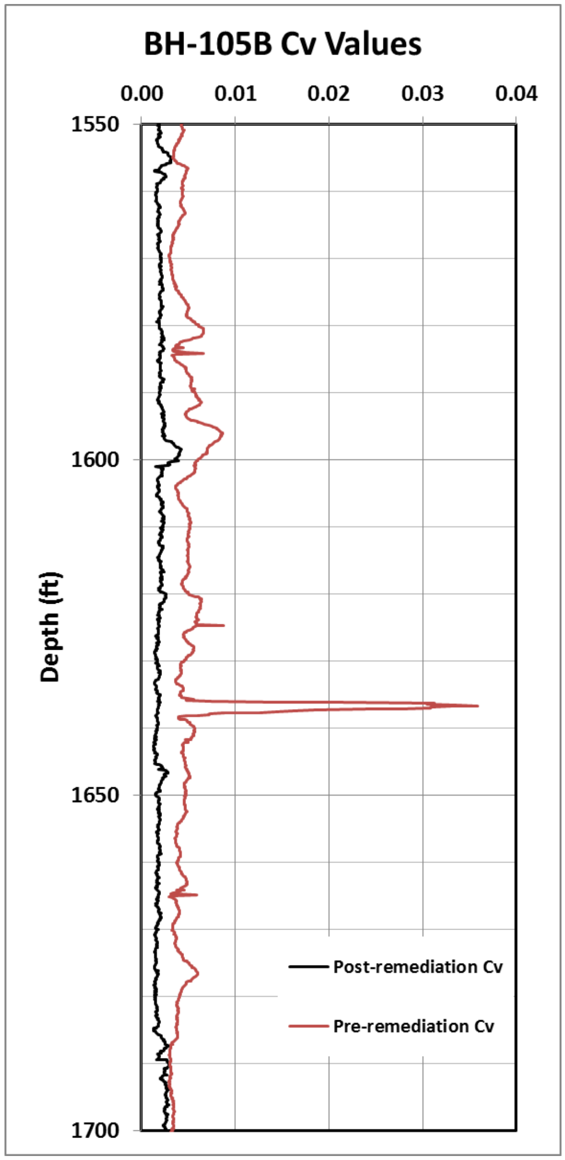

Figure 6-9. Comparison of pre and post-remediation C_v values for well BH-105B.

6.2.2 Big Hill 114

A loss of pressure integrity was identified for Big Hill cavern 114 in late summer of 2012 (Lord et al., 2013). Subsequent nitrogen injection testing confirmed a leak in well BH-114A near the salt-caprock interface at a depth of about 1630 feet. This well had a series of MAC surveys performed on it. The first was before the estimated start of the leak, the second shortly after the leak was identified, and the third subsequent to remediation of the well by installation of a liner. Figure 6-10 shows the general time-line of the surveys relative to the estimated leak start date (Lord, et al., 2013). Although no leak was identified in the B well, it was also remediated due to casing deformation. This well has had two MAC surveys; one pre-remediation and one post-remediation.

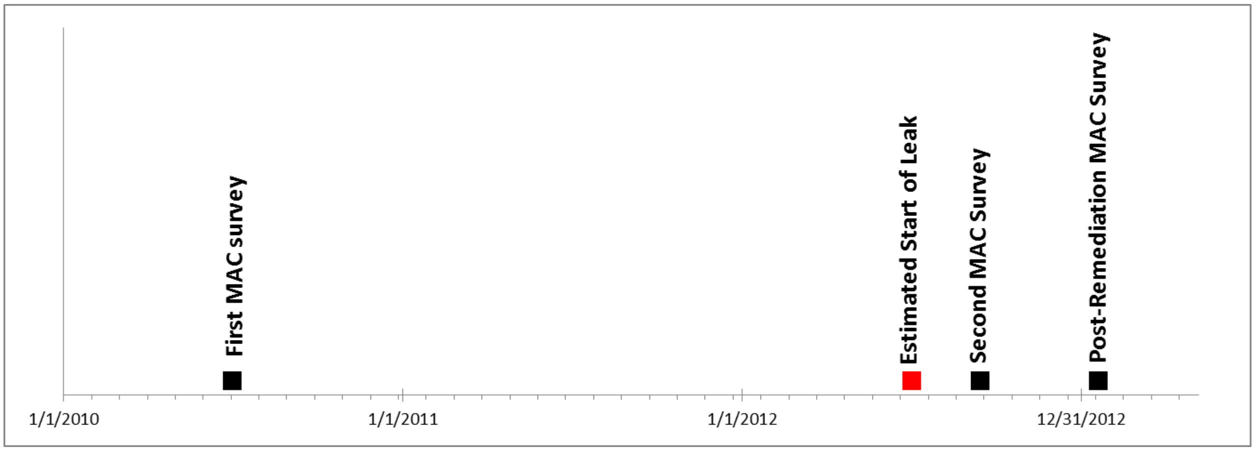

Figure 6-10. General time-line of BH-114A MAC surveys

For well BH-114A, the first MAC survey, performed in 2010, was collected before there was any indication that the well had loss pressure integrity.

Figure 6-11 shows the C_v values and radial arm data plots from this survey at the zone of greatest deformation. This data was collected at a 0.1 foot vertical sampling rate. The well completion for all of the Big Hill cavern wells is the same, so the well configuration is as shown in Figure 6-5, except that BH-114A does not have a hanging string and the depth to top of the salt varies by a few feet. The casing weight at the salt-caprock interface is documented to be 61 pounds per foot.

As seen in Figure 6-11, there is an area of significant deformation at the 2010 survey depth of 1625 feet. The lower radial arm data plot shows that the casing is deformed to an oval shape with two areas being pushed inside the expected casing ID, and others being extended out beyond it. This results in a C_v value of 0.0387 at this depth. The upper radial arm plot shows data for a depth with little deformation; the C_v value here is 0.00319. Although this is a relatively low C_v value, the casing does show some deformation based on the radial arm plot.

In addition, the majority of the casing perimeter in the upper plot of Figure 6-11 plots slightly outside of the expected perimeter (dashed line) indicating a mismatch between the documented and measured casing inner diameters. The documented casing weight for BH-114A at this depth range is 61 pounds per foot for an outer diameter of 13.375 inches. This gives an expected inner diameter of 12.515 inches (Table 6-1). The MAC measured diameter is closer to 12.70 inches. This may be a calibration issue or difference between documented and installed casing weight.

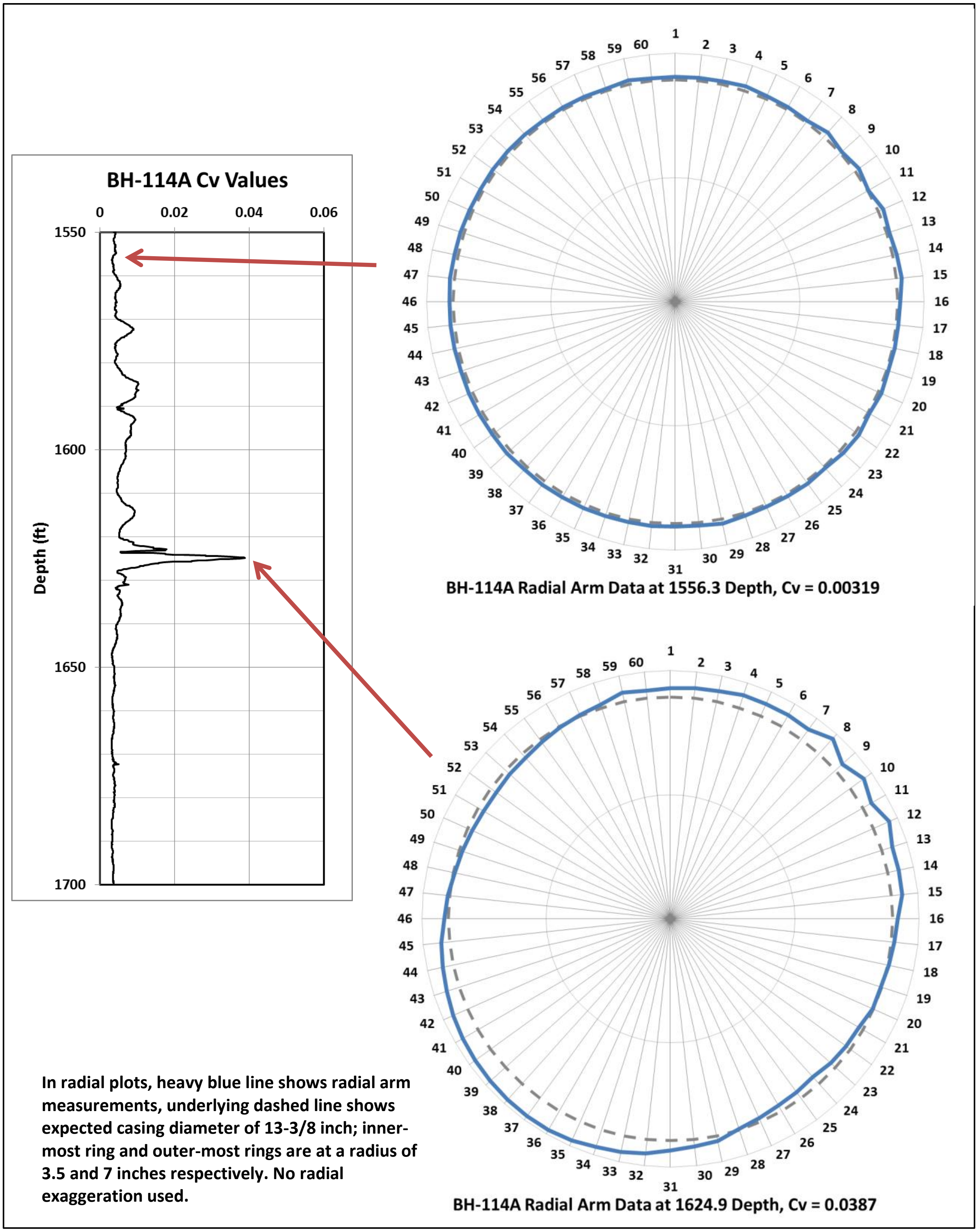

Figure 6-11. Cv value curve for BH-114A and corresponding radial arm measurement data from 2010 survey at points of greatest deformation (bottom) and lesser deformation (top).

Subsequent to the initial discovery that cavern BH-114 had lost pressure integrity, a second MAC survey of BH-114A was performed to characterize the casing situation at that time.

Figure 6-12 shows the Cv values and radial arm data from that survey for the region of greatest casing deformation. This survey was performed in 2012 using a depth sampling interval of 0.02 feet; five times the vertical resolution of the 2010 survey. Note that the 2010 and 2012 MAC surveys have a depth offset difference of about 13 feet.

The maximum Cv value in the 2012 survey of BH-114A is 0.1015 a value substantial higher than the maximum value recorded in the 2010 survey (0.0387). This is confirmed by the bottom radial arm data plot in Figure 6-12 which shows that the casing is highly deformed, having large displacements from the expected ID. Although an exact comparison against the radial arm plot from the 2010 survey (Figure 6-11) is not possible because the orientation of the number one arm is not known for certain; one can clearly see increased casing deformation in the 2012 survey. One other complicating factor in the comparison of these two surveys is the differing vertical resolutions. The substantial increase in maximum Cv value in the 2012 survey is most likely due to an actual increase in casing deformation in the 26 months between the two surveys, but it may also be due to increased resolution of the 2012 survey. The increased vertical sampling may have been capable of sampling the most deformed sections of the casing which may have been missed in the lower resolution 2010 survey.

Figure 6-13 addresses this concern of vertical resolution. It shows C_v values for the individual depth measurement locations from the 2010 and 2012 MAC surveys as individual data points. As shown by this plot, the 2010 survey should have adequate vertical resolution to see the enhanced deformation evidenced in the 2012 survey. This confirms that the increase in C_v values between the two surveys is real and reflects increased casing deformation over time.

C_v values computed from the 2010 and 2012 MAC surveys of well BH-114A for a 150 foot section around the area with greatest deformation is shown in Figure 6-14. This demonstrates that the greatest deformation is limited to a very discrete zone near the salt-caprock interface, and shows the significant increase in casing deformation occurring over 26 months' time.

With multiple MAC surveys available through time, it is possible to not only identify areas of casing deformation, but also make estimates of the rate of deformation. If one assumes there was no deformation of the casing when the casing for BH-114A was installed in 1985, and the deformation observed in the 2010 survey accumulated linearly, then that initial deformation rate would be (0.0387 C_v units) /(25 years) or about 0.0015 C_v units per year. In a similar fashion, the rate calculated between the 2010 and 2012 surveys would be on the order of 0.0314 C_v units per year; a factor of 20 greater. This shows how the deformation of the BH-114A casing was increasing through time; a fact that likely led to its eventual loss of pressure integrity. Although only a rough estimate, and based on values that reflect total casing deformation, the above example calculations give an idea of the types of analyses which could be used to monitor and act on casing deformation rates.

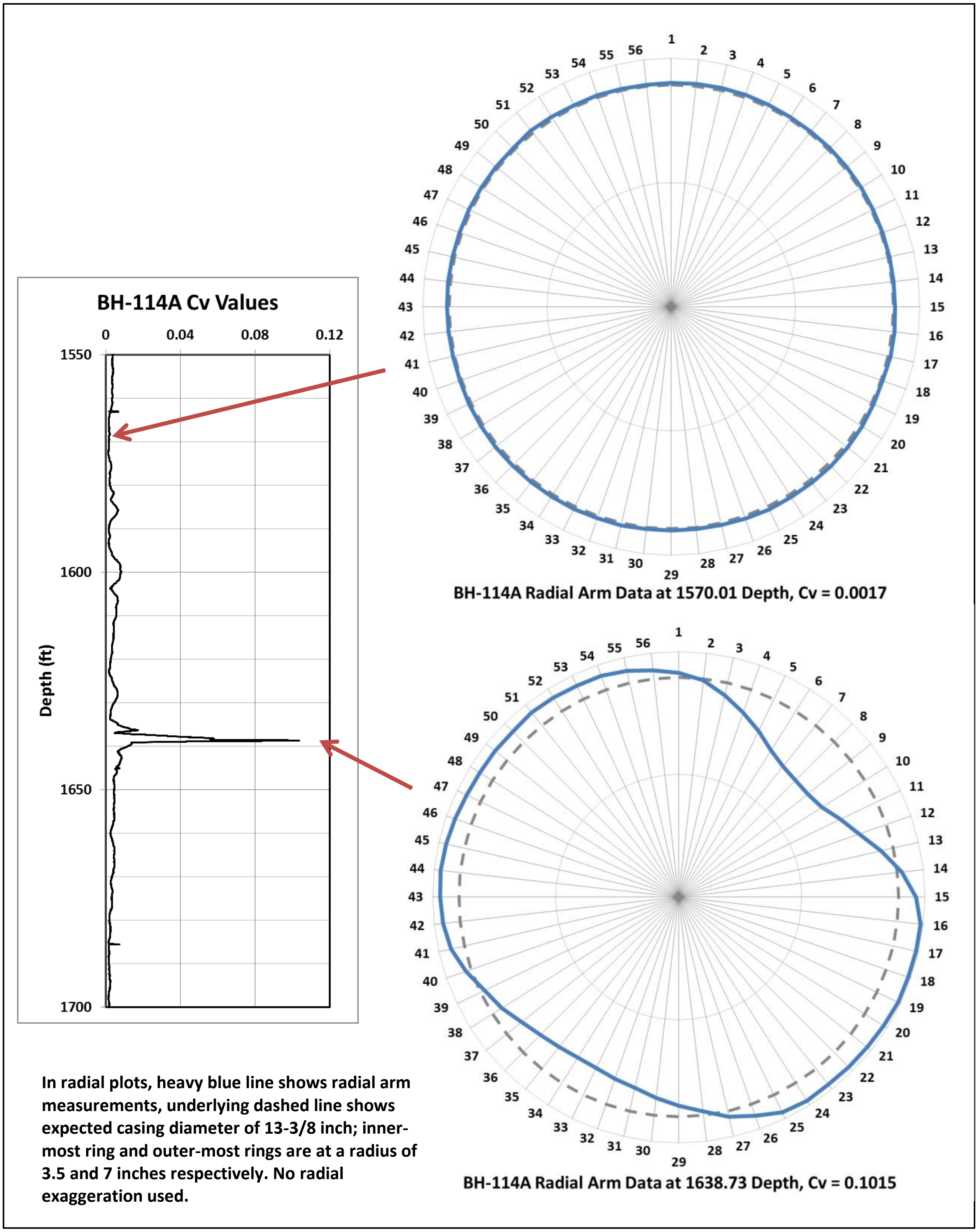

Figure 6-12. Cv value curve for BH-114A and corresponding radial arm measurement data from 2012 survey at points of greatest deformation (bottom) and lesser deformation (top).

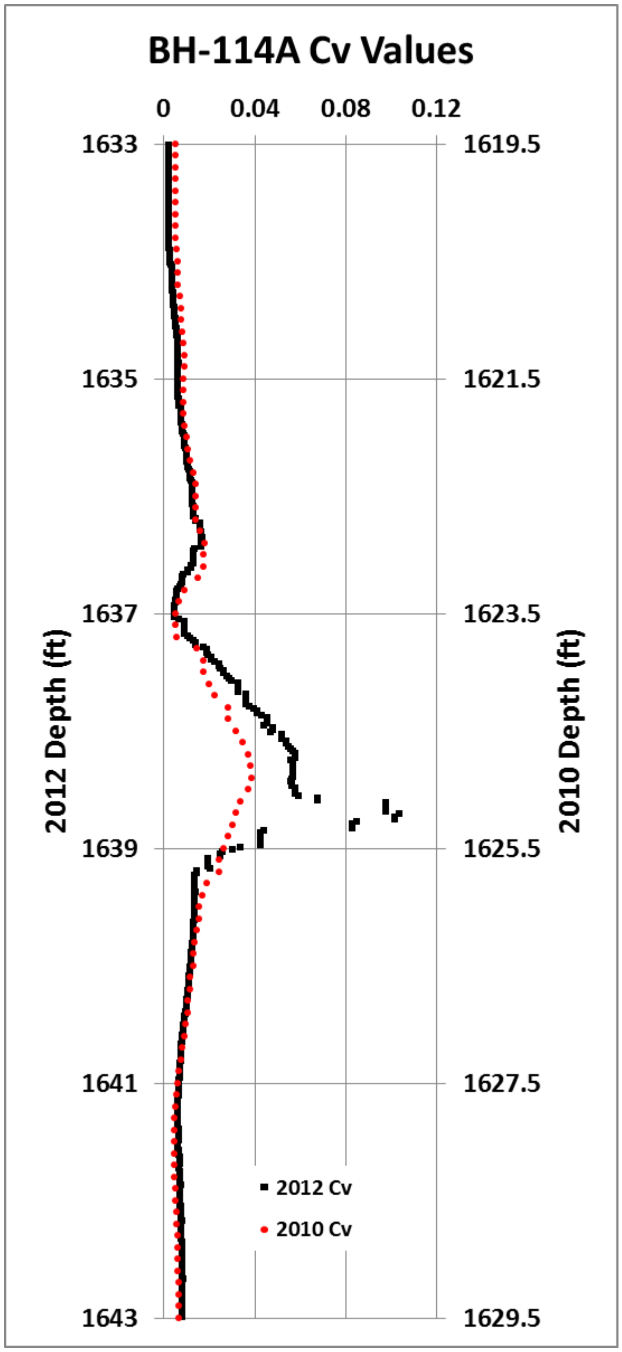

Figure 6-13. Cv values for BH-114A from 2010 and 2012 MAC surveys. Dots show individual depth measurement locations.

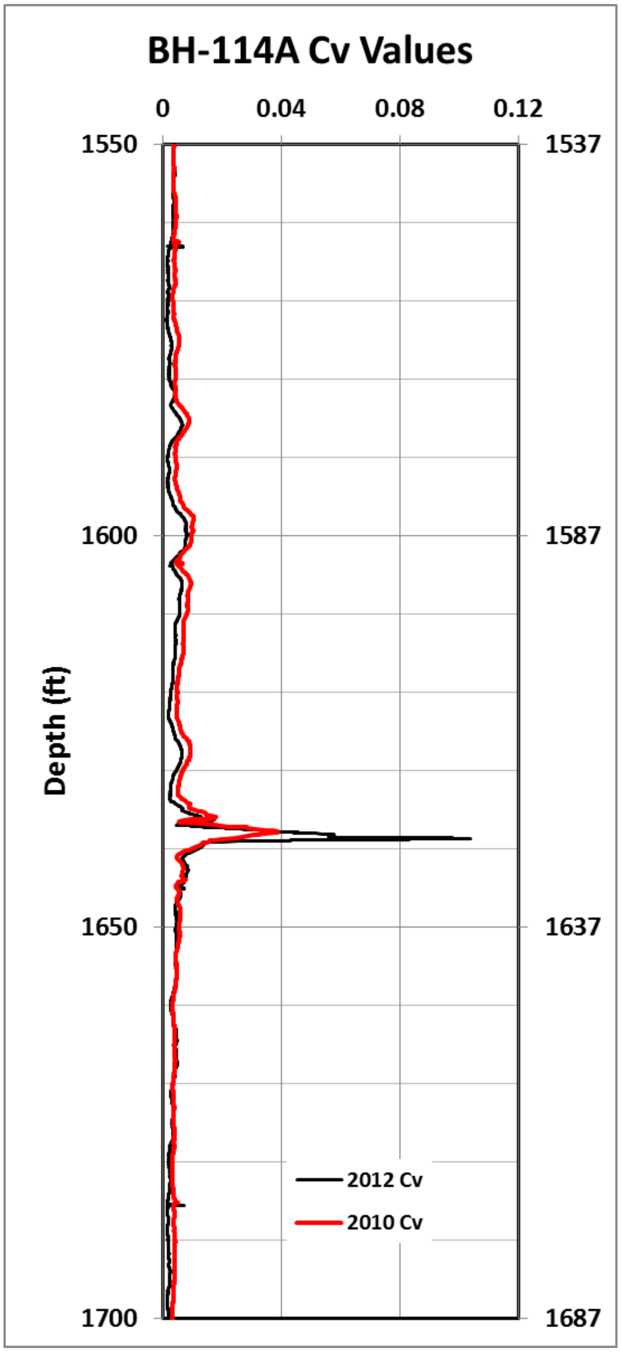

Figure 6-14. Comparison of Cv values for BH-114A from 2010 and 2012 MAC surveys for area with greatest deformation.

Well BH-114B had its first MAC survey performed in 2012; a second survey was performed in 2013 after the well was remediated. Figure 6-15 shows the C_v values and radial arm data plots for the 2012 survey for the area of greatest casing deformation. The lower radial arm plot shows the area of greatest deformation and has a C_v value of 0.0152. The radial arm plot shows notable, but not severe radial deformation. The upper radial arm plot shows the casing shape in an area with virtually no deformation. The C_v value here is 0.0010 and the radial arm measurements closely match the expected ID values documented in the as-built drawings. The well configuration is the same as BH-114A with a casing weight of 61 pounds per foot at the salt-caprock interface.

Figure 6-16 shows a comparison between the BH-114A and BH-114B 2012 C_v values. This shows the significant differences in casing deformation between these two wells. Based on C_v values, the deformation in well BH-114A is a factor of six times that seen in the B well.

The above discussion shows the utility of C_v values in assessing casing deformation at the SPR. Although the actual level of casing deformation which leads to a loss in casing integrity is not completely predictable, C_v values do provide a means to compare levels of casing deformation between wells, and allows for the time-dependent tracking of casing deformation. This is important in identifying casings with high rates of on-going deformation, and those experiencing little on-going deformation.

Because C_v values can be compared through time and from well-to-well, they can provide a common basis by which to rank well relative to their remediation needs. Wells showing high levels of increasing deformation would be candidates for immediate remediation, regardless of if they have yet to experience pressure irregularities. Conversely, wells with low C_v values which remain relatively static with time would fall much further down the list of remediation priorities. Examples of applying C_v and RWD values for the grading of well for remediation can be found in Lord et al., 2014.

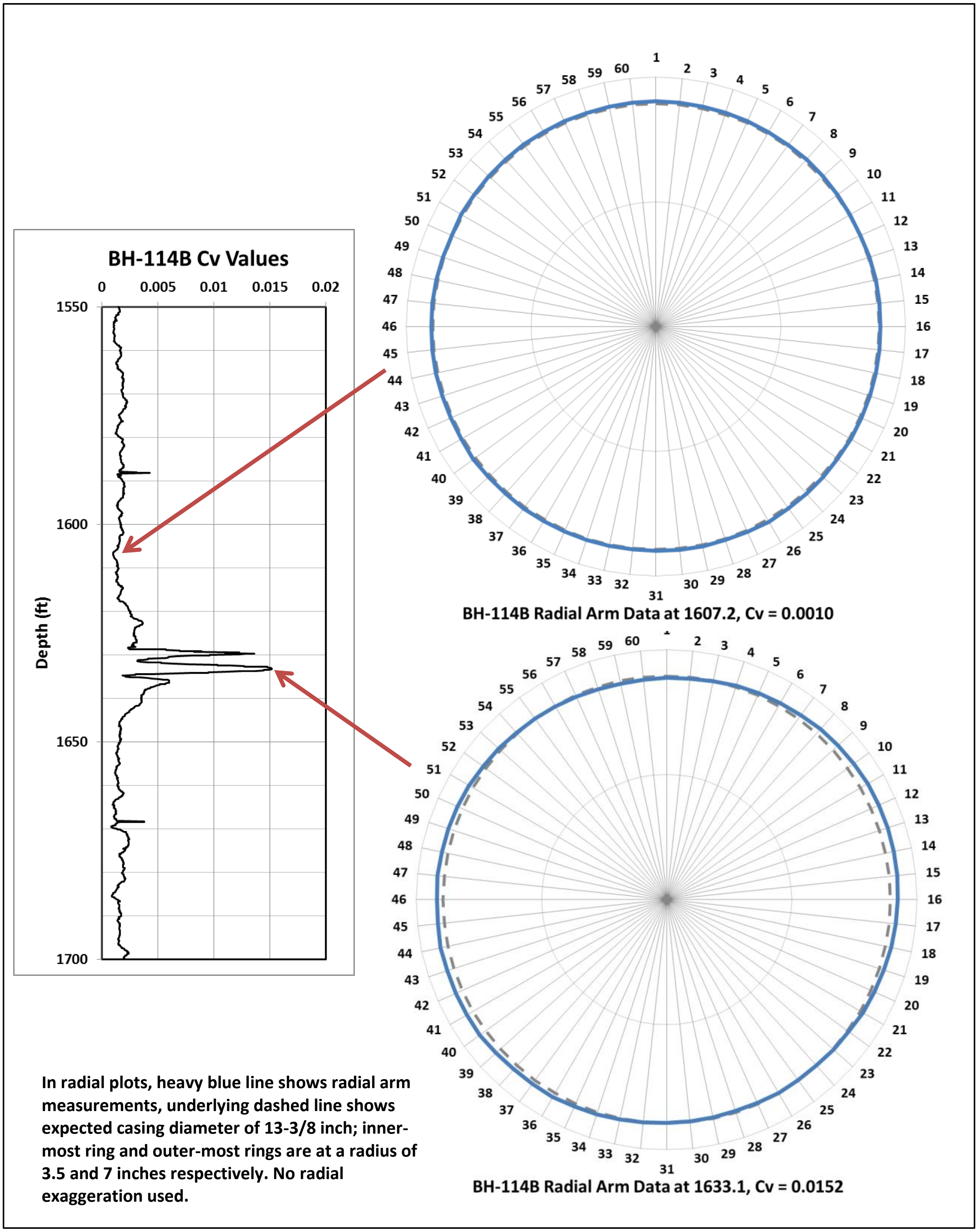

Figure 6-15. Cv value curve for BH-114B and corresponding radial arm measurement data from 2012 survey at points of greatest deformation (bottom) and lesser deformation (top).

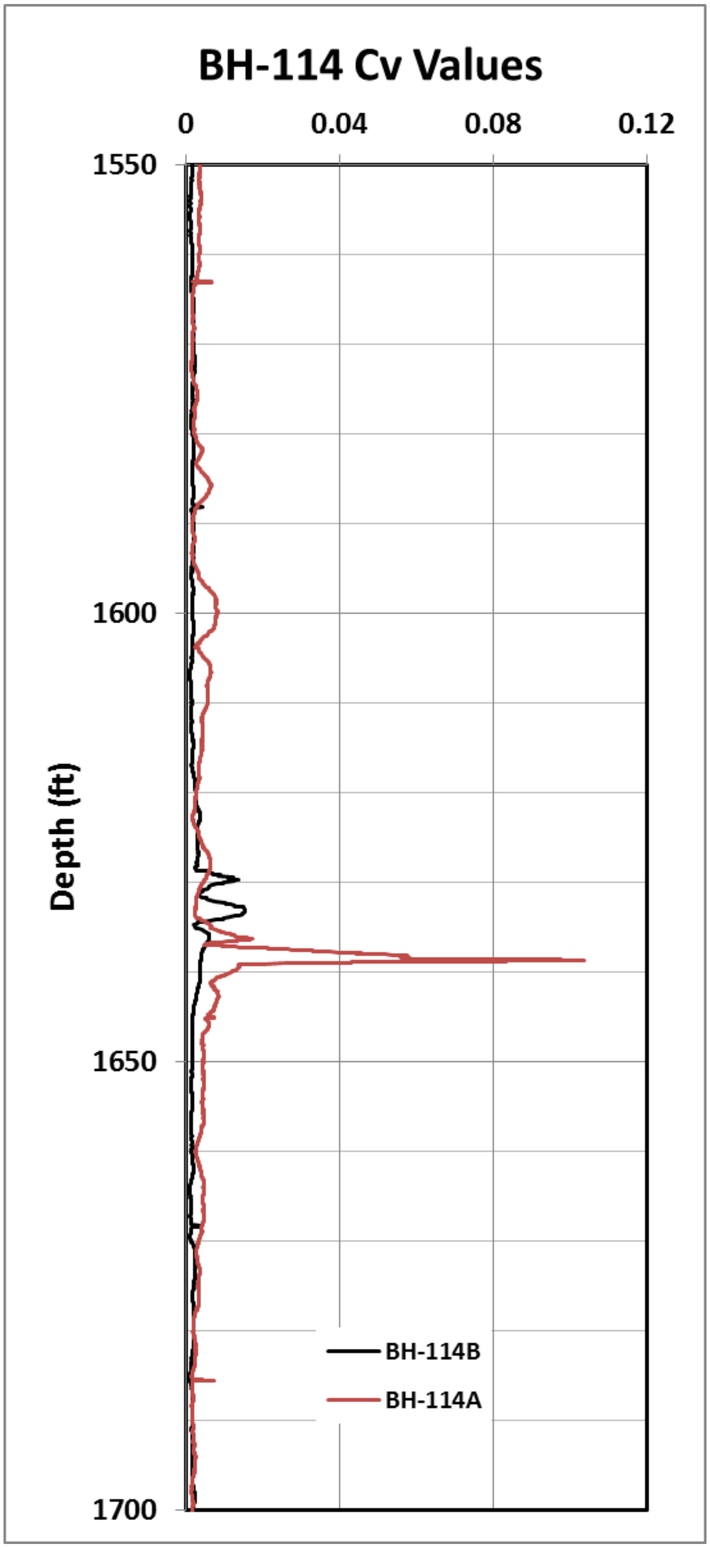

Figure 6-16. Cv value curves for BH-114A and BH-114B from 2012 survey for region showing greatest casing deformation.

7 CONCLUSIONS

The U.S. SPR has experienced a series of well integrity issues related to deformation of well casings. In an effort to better understand and characterize these issues, the SPR is conducting a program of multi-arm caliper surveys of the inner-most cemented casing of all the SPR wells. These surveys provide baseline information to characterize the wells and identify potential problems before they compromise pressure integrity. The challenge in this is that the different MAC survey vendors report their results in differing formats, so well-to-well, or even time-dependent comparisons are difficult.

This report has presented analysis variables developed to allow for the independent evaluation of MAC survey data regardless of the original survey vendor. The development and assessment of these variables has shown that one in particular, the coefficient of variation of the measured diameter values, provides an excellent summary of casing deformation. Diameter C_v values are easily computed from the raw radial arm data which is available from each vendor in standard LAS file format. Custom Python computer code was developed as part of this project to read the LAS files, compute the analysis variables, and provide a summary of the results in tabular and graphical format. This analysis process has been used successfully in providing information for well grading at the Big Hill SPR site (Lord et al., 2014).

This text has provided several examples confirming consistency between vendor supplied casing analysis and those resulting from the research presented here. This gives confidence that the analysis variables developed here are responding to the raw data in a fashion similar to what is observed in the vendor reports. This avoids conflicts in the comparison against the vendor supplied analysis reports. The advantage of the process presented here, is that the analysis variables can be compared well-to-well, or even in a time-dependent manner without concern of which survey vendor was used to collect the original data. In addition, by working with the raw radial arm data directly, one has the ability to perform additional analysis commonly not provided in the standard vendor reports and know the exact computational techniques employed. In addition, these analyses can provide information regarding the installed casing weights, or even identify potential errors in the original survey data.

Maintaining pressure integrity of the SPR caverns is of upmost importance in protecting the environment and maintaining the SPR in a state of readiness. The results from this research will be used to aid in guiding remediation priorities at all the SPR sites. This work will allow the analysis of MAC survey data in a vendor-independent manner providing important baseline data in evaluating the future integrity of the SPR cavern wells.

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