Gauge Repeatability and Reproducibility Study on a Hemi-shell with a Brown & Sharpe® Coordinate Measuring Machine (U)

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Gauge Repeatability and Reproducibility Study on a Hemi-shell with a Brown & Sharpe® Coordinate Measuring Machine (U)

By

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Abstract

In engineering at LANL, everything relies on the quality of a product or process. Today dimensional inspection is a necessity to ensure customer specifications are met to the highest standard. Currently LANL’s main processes for dimensional inspection on hemi-shells are conducted on uniquely designed machines - Sheffield or Shell Measuring Machine (SMM). These specialized rotary contour machines were built to measure only the wall thickness, inner and outer contours of a hemi-shell. These machines are heavily dependent on the inspector and typically have very few personnel trained to use them. With no manufacturer support and age leading to production down time, this leads LANL to exploring other, newer technologies to support future endeavors. LANL has currently invested in newer technologies to account for these problems. Coordinate Measuring Machines (CMM) are a staple in the manufacturing engineering realm at LANL. CMMs utilize newer off-the-shelf technology, require less inspector involvement and can support a variety of different geometrically shaped parts produced at LANL. LANL, like all government funded laboratories, must use calibrated instruments for working processes. All measurement instruments must follow standards traceable to the National Institute of Standards and Technology (NIST). A Gauge Repeatability and Reproducibility (GR&R) study is utilized to ensure that the PMM-C LANL currently has in production is measuring correctly by utilizing measured data from a hemi-shell’s radial wall thickness and analyzing it for total process variation. The GR&R will also indicate to LANL if the PMM-C is passing a 4:1 measurement uncertainty ratio from general requirements of government specification 9900000. This report states that the PMM-C that is used in the GR&R study did meet ≤ 10% total process variability for the pole, midpoint and equator locations of a hemi-shell. The PMM-C also met and surpassed the 4:1 measurement uncertainty ratio utilizing the inner contour tolerances of the hemi-shell which was well under the 25% testing accuracy need to conduct production work at LANL.
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1.0 Introduction

1.1 Background

Los Alamos National Laboratory (LANL) was founded during World War II as a scientific research facility to develop the first nuclear weapon, also known as the Manhattan Project. With a nuclear weapon, the only means of testing its design was to detonate it. This became a concern after some time, so alternative methods were researched. Now with device testing on large scale, by way of underground nuclear testing treaty, no longer permitted, LANL has researched, developed and adapted new ways to test components. Utilizing three dimensional model simulations and dimensional inspection data, scientists and engineers can certify components and ensure performance specifications are met. LANL has developed programs using high-accuracy, high-precision, calibrated dimensional measurement machines to meet the performance specifications that are brought forth by customers. Every element of the dimensional inspection process is taken into account: temperature controlled environments, surface finishes of components, machine calibration, operators of the machines, etc. All variables of the dimensional inspection process must follow a set of rigorous standards to maintain the pedigree necessary for War Reserve (WR) quality components for our nation’s defense.

1.2 Rotary Contour Machines (Sheffield and SMM)

Rotary contour machines, Sheffield and Shell Measuring Machine (SMM), are uniquely designed machines LANL has developed in order to specifically measure and record geometries of hemispherical shelled (hemi-shell) shaped components. The rotary
contour machines, or rotary contour gauges, are designed to have two directly linear opposing sensing probes that measure inner contour, outer contour and radial wall thickness as the hemi-shell is rotated. The rotary contour machine is designed with two rotating tables allowing for full access to all surfaces on the hemi-shell. The rotating tables rotate about the azimuth angle, 360° of the hemi-shell, and the polar angle, 90° of the hemi-shell. The sensing probes collect thousands of data points during the inspection process to verify part conformance to drawing specifications. The rotary contour machines are also a single point failure. If a single portion of the inspection process fails the resulting data is entirely affected. LANL’s goal is to eventually move from these rotary contour machines and focus on developing newer dimensional inspection methods on newer technology.

1.3 Coordinate Measuring Machine (CMM)

Coordinate Measuring Machines (CMMs) are highly-accurate, highly-precise machines that are calibrated to National Institute of Standards and Technology (NIST) traceable standards. CMMs are used to verify if a product is within manufacturing tolerances, as well as identifying trends in a manufacturing process.

CMMs utilize three axes of translation (x, y and z coordinates) and a measuring probe head to measure physical geometries (i.e. components). The probing head collects either single data points (touch trigger) or drags along the surface of the part collecting thousands of data points (scanning). Every CMM is equipped with a granite table top where the parts are positioned on and measured.
CMMs are designed to handle a variety of part geometries. Parts range from turbine blades, gears to the components dealt with at LANL. CMMs are also available in ultra-precision versions, called Precision Measuring Machines, which will be part of the focus of the project. The main focus of this project is to quantify total process variability of a specified CMM.

1.4 Gauge Repeatability and Reproducibility (GR&R)

Gauge Repeatability and Reproducibility, or GR&R, is a measure of the total variability of a gauge or measuring instrument to obtain the same measurement reading every time the measurement process is undertaken for the same characteristic or parameter. In other words, the GR&R indicates the consistency and stability of the measuring instrument and operator. The ability of a measuring instrument to provide consistent measurement data is important in the control of any process. Operator consistency is also important because a good process should be able to be done by any qualified person. Repeatability is the variation in the measuring instrument and can be traced back to the precision. Reproducibility is variation due to the operator and can be traced to the accuracy. The GR&R study will determine and quantify where most of the process variability exists.

Variability is interchangeable with sampling error, so variability will be used rather than error for methodology purposes. The variability of measurement can be directed at two different types of causes: random and systematic error. Random error, results from many individual causes that cannot be identified and can be related to
precision. Systematic error can be traced back to some assignable cause and can be related to accuracy. With both random and systematic error accounted for, total variability of the measurement can be evaluated and quantified.

There are two statistical methods for analyzing GR&Rs. One method is the $\bar{X}$ (average) and R (range) charts and the second is Analysis of Variance (ANOVA). $\bar{X}$ and R is a set of control charts for variable data (data that is both quantitative and continuous in measurement, such as a measured dimension or time). The $\bar{X}$ chart monitors the process location over time, based on the average of a series of observations, called a subgroup. The R chart monitors the variation between observations in the subgroup over time. The ANOVA statistical method will be the method of choice and implemented in this GR&R study for accuracy purposes [11]. The ANOVA method is explained in greater detail in section 3.2.

With a GR&R, the analysis method is different for both $\bar{X}$ and R and ANOVA. The $\bar{X}$ and R method uses a root-summed-square analysis, while the ANOVA uses a sum-of-squares or standard deviations analysis to calculate the Precision-to-Tolerance (P/T) ratio. The P/T ratio, also known as the gauge capability ratio, is the measure of the precision of the measurement to the given performance specifications. The sum-of-squares and P/T ratio will be explained in section 3.2. Both methods quantify total process variability. The repeatability and reproducibility along with the P/T ratio will tell LANL and Lawrence Livermore National Laboratory (LLNL) the variability associated with the process and if the PMM-C is capable of meeting performance specifications.
1.5 Government Specification 9900000 “General Requirements”

Government Specification 9900000 “General Requirements” covers general product fabrication and inspection requirements. It also provides interpretation of certain requirements specified on product drawings, models and electronic files. Specific requirements on product drawings, models and electronic files take precedence over these general requirements and interpretations [6].

From Government Specification 9900000 “General Requirements,” all of LANL’s dimensional measuring equipment requires a 4:1 measurement uncertainty ratio. The collective uncertainty of the measuring equipment shall not exceed 25% of the acceptable tolerances for each feature being measured [6]. If a measurement of 10 ± 1 mm is needed, the measurement would require a calibrated instrument with a minimum accuracy of 0.25 mm. A more detailed description of the shell’s 4:1 measurement uncertainty ratio is discussed in section 3.3.

2.0 Previous Work

Gauge repeatability and reproducibility studies are conducted on all types of measuring instruments, from simple micrometers and calipers to tensile testing machines to basically any type of machine that can take a physical or electrical measurement. GR&R studies have been used on simple parts to quickly measure variability of the process using the P/T ratio [1]. The P/T ratio is calculated for only a single part that is measured, by a single operator, multiple times. The part may be subject to being removed or not removed from a holding fixture [1]. LANL’s project will also measure the total process variability, but the components must be measured randomly and at
different time frames, therefore a completely new setup must be done every time the measurement process is conducted. LANL’s project will also quantify the P/T ratio for total process variability, but will utilize more parts and more inspectors.

GR&R software has also become a staple for analyzing measuring instruments. This software is used to both measure and analyze the data from a measuring instrument. Some GR&R software used is GR&R wizard software, which is used to analyze and present the data [1]. LANL’s approach will utilize the metrology software, QUINDOS 7, to program and collect data from the shells and use Minitab® statistical analysis software for the analysis and representation of the data.

Hexagon™ Metrology has conducted and recorded GR&R studies on CMMs. Hexagon™ Metrology is a manufacture of Brown and Sharpe© CMMs. GR&R studies must be done in order to certify set specifications for measuring [2] before marketing. Parts of simple geometry, like gage blocks or ring gauges, are measured on the CMMs and analyzed for performance before the machine is to be sent into production. LANL’s purpose is to not only meet manufacture specifications of the machine, which a calibrated machine should, but to meet government and customer specifications for WR quality products. The 4:1 measurement uncertainty ratio of the government specification 990000 general requirements and the shells tolerances are customer specifications.

Round robin testing has also been recorded on CMMs. Round robin testing utilizes multiple sites, a single or set of multiple parts, and recording and analyzing the variation between the different laboratories. These results are then compared and conclusions are drawn from the results [4].
Another GR&R study was evaluated [5] with multiple probing head configurations. The different probing configurations were interchanged on an articulating (free to rotate about the probing head origin) probe head of a CMM and multiple measurements of a single diameter ring gage were recorded. The variation of the measuring process was evaluated for each individual configuration use. Selected probing setups were utilized to measure and collect data from the individual diameter that was measured. The ring gage was also moved accordingly to position the different probing configurations. An ANOVA statistical technique was used to analyze the data. From the ANOVA statistics, conclusions were drawn that changing the probing head configuration and probing stylus length or size, the measuring results did not repeat for the various combinations. LANL’s project will also use ANOVA techniques and multiple probing head configurations, but the CMM being used will have a rigid probing head, no rotation of the probing head. This reduces error in the measurement, since the probing head will not be moving, thus reducing dynamic error to only the scanning of the and the not the machine movement in the measurement. In theory it should help reduce error in repeatability, but will have to be examined. Another difference is that six shells will be measured, not a single part. Also, more geometrical features will be measured; the inner contour, outer contour and radial wall thickness will then be calculated. The positioning of the measuring setup will stay stationary and not be reconfigured around the working volume of the CMM. These will all be accounted for in the program that is used to measure the shell. The GR&R data will be analyzed with respect to the customer’s specifications and needs.
LANL research on a new Shell Inspection Process has been on and off for the past seven to ten years on the development for the replacement of rotary contour machines, but funding and allotted time has been the major issue for completing the research and development. As recently as June 2010, the project has picked up steam and progress has been made. The project is called Shell Inspection Equivalency and uses a high-point data density routine. The high-point data density portion is the number of data points collected during a hemi-shell inspection, which is in the range of 44000 points. The Shell Inspection Equivalency project is trying to match the exact measuring process and accuracies as the rotary contour machines here at LANL. This GR&R is more of a preliminary tool for developing a full Shell Inspection Process on a CMM.

A more useful programming technique is applied to the shell QUINDOS 7 program and is easier to understand and implement. A mounting fixture base was also designed to replicate the 45° angle at which the hemi-shell is positioned on the rotary contour machines. This mounting fixture, along with various other fixtures, will be utilized for the GR&R. The calculation methodology used for the Shell Inspection Equivalency project is much different to the one that will be utilized on the GR&R. The calculations are a point-to-point method, in which each point is analyzed using the range value of the points, which there are 44000 points to consider on one hemi-shell. The GR&R will not have as many points to consider, because this project is not for qualification purposes but preliminary purposes. ANOVA statistical method will be the analysis methodology of choice and Minitab® statistical software will be utilized for the calculations portion.
3.0 Methodology

This section describes the methodology of LANL’s current hemi-shell process, why there is a need for a better process and how LANL plans to solve the problem. It also describes the methodology behind the new technologies and methods that are being implemented to develop a new Shell Inspection Process.

3.1 Motivation

3.1.1 Current LANL Hemi-Shell Inspection Process

The current LANL process for measuring hemi-shells is done on rotary contour machines. The Sheffield and SMM are the machines dedicated to measuring the hemi-shell components. There are only five of these rotary contour machines in existence. LANL currently owns four rotary contour machines and LLNL owns the fifth rotary contour machine. The Sheffield is an original 1960’s rotary contour measuring machine. It was specifically made for the WR quality stockpile parts that LANL currently manufactures. Without manufacturing support and age becoming a factor, LANL was in need of a machine to replicate Sheffield’s capability. The SMM was a project designed at LANL to replace Sheffield. Moore Tool Company won the bid and built the SMM. In essence, it is exactly the same as a Sheffield, but with more up to date software and hardware and is capable of reproducing similar accuracies. Moore Tool Company eventually went out of business and left LANL back at its starting position. With manufactures for both the Sheffield and SMM no longer in existence, LANL has a great need to find an equivalent or better process for hemi-shell inspections.
Operations at Technical Area 55 (TA-55) are at an all time high, the Shell Inspection Process is an everyday and all day event. The normal time for a hemi-shell inspection on a rotary contour machine is approximately eight hours, an entire work day for an inspector. Inspectors must follow a working procedure when measuring a hemi-shell. Inspectors must master the rotary contour machine, reach a steady state, place the hemi-shell on a rounding ring, then on the rotary tables and align the origin of the part. If all the previous tests pass, then the inspection process can begin. This process not only increases inspection time, but also adds unwanted human error to the process. With the need to produce good results, in a timely manner, a newer and more efficient process needs to be developed to meet WR quality needs.

LANL recently developed a crude method of shell inspection on a mock up hemi-shell using a development CMM. The process could use some refinement, the CMM that it was developed on is not made for scanning and the manufacturing stated accuracies are not as good as the PMM-C that is used on the GR&R.

### 3.1.2 LANL goal for Project

The goal for this GR&R study is to find if the PMMs and CMMs used in LANL’s production processes are capable of handling the type of work currently done on rotary contour machines. The GR&R study will be conducted to quantify the hemi-shell process variability of the PMMs LANL currently has available.

With either a CMM or PMM, all signs indicate that it will approximately be a little less than half the time to run the same Shell Inspection Process as the rotary contour machines. With less setup time and inspector interaction, a significant amount of time
can be saved. Saving a large portion of time could potentially double hemi-shell inspection throughput per machine. With CMMs and PMMs largely available, LANL has the option of purchasing machines for higher demand.

LANL’s customer for the GR&R study, LLNL acting as the design agency for the project, relies on the knowledge and expertise of the production agency, LANL, to produce appropriate data and results for their production purposes. The GR&R study will help LANL and LLNL understand if the PMMs and CMMs have the accuracy needed to perform a Shell Inspection Process. Inspection processes on the rotary contour machines are done by three qualified inspectors, while CMMs can be operated by inspectors and engineers considering its large user base and simplified inspection process. Ease of transition from hemi-shells to other WR component processes can be as simple as part setup and program execution. The fact that multiple part geometries can be dimensionally inspected on CMMs is another massive production throughput increase.

LANL’s approach to the WR Component Production Program is to not only fulfill customer specifications, but strive for the best possible quality of the product. With scheduled deadlines fast approaching, the end of old projects and the arrival of new projects, LANL will need to have an approved process intact to have an ease of transition.
3.2 ANOVA GR&R Statistical Methods and Software

3.2.1 ANOVA GR&R Method

ANOVA is a statistical method using the statistical approach of Analysis of Variance. Analysis of Variance is a collection of statistical models, and their associated procedures, in which the observed variance is partitioned into components due to different sources of variation. ANOVA uses either fixed-effect or random-effect modeling systems to assess the statistical system. ANOVA is a chosen method for measurement systems, because of better accuracy in the results.

ANOVA GR&R considers several factors that affect the measuring system: operators, testing methods, part setup, performance specifications and the measuring instrument itself. ANOVA GR&R methodology is more accurate because it not only captures the repeatability and reproducibility, but it also breaks down the reproducibility portion into operator interaction and operator by part interaction [11]. This can be explained by one operator having more variation between measuring components of smaller size compared to measuring components of larger size.

Figure 1 demonstrates the methodology of an ANOVA GR&R:
3.2.2 ANOVA Statistics for GR&R

3.2.2.1 Factors for Analysis of Variance

With ANOVA, the statistics can be based off single-level factors or multi-level factors. Factors are points of interest and can be described as a tensile test of a piece of 1040 steel or the hardness test of reinforced concrete, the factors being the strength of the 1040 steel and the hardness of the reinforced concrete. The previous examples are single-factor experiments. Single-level factors can have multiple sub-levels to them, such as, increasing the pulling force on the tensile test by a certain percentage and testing that percentage multiple times.

Multi-level factors are more than one point of interest like, length and width of a gauge block. A two-level factor method is the bases for LANL’s ANOVA GR&R and will be explained more thoroughly in section 3.2.2.2.
These factor effects can be either fixed or random-effected models. Fixed-effects models are known factors for analysis. Conclusions from these factors can only be considered in the analysis. Random-effects are selected from a population of random samples. Conclusions from any factor in the random sample can be analyzed, even if it was not first thought to be part of the experiment. The GR&R is fixed-effects because the factors for analysis are known and only conclusions will be drawn from these factors. Though the GR&R is fixed-effects, the data measurement is randomized to ensure best data analysis.

3.2.2.2 Analysis of Variance for GR&R

These two-factor experiments, r and R, are the main components for the measured data. R will be reproducibility and r will be repeatability. With each of these factors, they can also have multiple sub-levels. These sub-levels have direct correlation to the factors that are being assessed, like part-to-part variation for repeatability and operator and operator*part variation for the reproducibility of the GR&R [12]. The repeatability and reproducibility along with the P/T ratio can then be quantified into total GR&R. Total process variation is quantified with total GR&R variation and variation from operator, operator*part and part-to-part. The total process variation of a two-factor analysis is a completely random designed experiment.

The formulation can be described as a linear two-factor statistical model:

\[
Y_{ijk} = \mu + \tau_i + \beta_j + (\tau\beta)_{ij} + \epsilon_{ijk} \quad \begin{cases} 
    i = 1, 2, \ldots, a \\
    j = 1, 2, \ldots, b \\
    k = 1, 2, \ldots, n
\end{cases}
\]
Where $Y_{ijk}$ is equal to the $k^{th}$ measurement on the $i^{th}$ part, by the $j^{th}$ operator; where $\mu$ is the mean of all measurements taken by all operators (an unknown constant); where $\tau_i$ is the effect of the $i^{th}$ level of factor $r$; where $\beta_j$ is the effect of the $j^{th}$ level of factor $R$; where $(\tau\beta)_ij$ is the effect of the interaction between $r$ and $R$, and $\varepsilon_{ijk}$ is the random error component having a normal distribution with a mean of zero and variance of $\sigma^2$. Equation 1 is also known as the components of variance model or the fixed-effects model [13]. This linear statistical model is the basis for both the ANOVA method and the $\bar{X}$ and R control charts method for a GR&R study. The general equation of this model is the basis for which Minitab\textsuperscript{®} statistical software is built.

This basic linear model can then be used in a sum-of-squares (SS) analysis to quantify process variability. SS equations represent the variability of a measurement process with four sources of variation to get the total variation: sum-of-squares for factor $r$ (SS$_r$), sum-of-squares for factor $R$ (SS$_R$), sum-of-squares for interactions (SS$_{rR}$) and sum-of-squares for error (SS$_E$), which can be summed up for total corrected sum-of-squares (SS$_T$).

To clarify some of the following equations, letting $y_{i.}$ denote the total observations under the $i^{th}$ level of factor $r$, $y_{.j}$ denote all observations under the $j^{th}$ level of factor $R$, $y_{ij.}$ denote the total of all observations in the $ij^{th}$ interaction, and $y_{..}$ denote the grand total of all the observations. $\bar{y}_{i.}, \bar{y}_{.j}, \bar{y}_{ij.}$ and $\bar{y}_{..}$ are defined as the averages of the corresponding row, column, cell and grand averages. The dot subscript means all values have been summed over all values of that subscript while holding the other subscript values fixed. These equations expressed mathematically are:
From these equations the SST can be expressed as:

\[
\sum_{i=1}^{a} \sum_{j=1}^{b} \sum_{k=1}^{n} (y_{ijk} - \bar{y}_{...})^2 = \sum_{i=1}^{a} \sum_{j=1}^{b} \sum_{k=1}^{n} \left[ \sum_{i=1}^{a} \sum_{j=1}^{b} \sum_{k=1}^{n} \left( \sum_{i=1}^{a} \sum_{j=1}^{b} \sum_{k=1}^{n} (\bar{y}_{i..} - \bar{y}_{...}) + (\bar{y}_{.j} - \bar{y}_{...}) + (y_{ijk} - \bar{y}_{ijk}) \right)^2 \right. \\
- \left. \left( \sum_{i=1}^{a} \sum_{j=1}^{b} \sum_{k=1}^{n} (\bar{y}_{i..} - \bar{y}_{...}) + (\bar{y}_{.j} - \bar{y}_{...}) + (y_{ijk} - \bar{y}_{ijk}) \right)^2 \right]
\]

\[
= bn \sum_{i=1}^{a} (\bar{y}_{i..} - \bar{y}_{...})^2 + an \sum_{j=1}^{b} (\bar{y}_{.j} - \bar{y}_{...})^2 \\
+ n \sum_{i=1}^{a} \sum_{j=1}^{b} (\bar{y}_{i..} - \bar{y}_{.j})^2 + \sum_{i=1}^{a} \sum_{j=1}^{b} \sum_{k=1}^{n} (y_{ijk} - \bar{y}_{ijk})^2
\]

The SST has been portioned into \( SS_r \) for “rows” or factor \( r \); \( SS_R \) for “columns” or factor \( R \); \( SS_{rR} \) for interactions between \( r \) and \( R \); \( SS_E \) for error. This is the fundamental equation for a two-factor ANOVA. Equation 6 can be written symbolically as:

\[
SS_T = SS_r + SS_R + SS_{rR} + SS_E
\]

Repeatability of an ANOVA GR&R is similar in use for both ANOVA and \( \bar{X} \) and \( R \) control charts. The difference in obtaining these values is the difference in calculations. The \( \bar{X} \) and \( R \) control charts utilize the averages and ranges of the data.
ANOVA utilizes the total SS equations to formulate the repeatability and calculate the standard deviations.

Reproducibility of an ANOVA GR&R is also similar that of the $\bar{X}$ and R control charts, but adds another sub-level. In $\bar{X}$ and R control charts, only the operator is accounted for in the calculations. In ANOVA the operator is one portion while there is also an operator*part portion. The operator*part portion uses the fact that the operator could be different from part-to-part. This is the main difference with the reproducibility. ANOVA also utilizes total SS to formulate the reproducibility and calculated the standard deviations.

Repeatability and reproducibility are calculated from the standard deviations of the part-to-part, operator and operator*part variations.

The formulas for the standard deviations are:

$$S_{ijk} = \sqrt{\frac{1}{k-1} \sum_{k=1}^{k} (Y_{ijk} - \bar{Y}_{ij.})^2}$$  \hspace{1cm} (8)

$$\bar{Y}_{ij.} = \frac{1}{k} \sum_{k=1}^{k} Y_{ijk}$$  \hspace{1cm} (9)

Where $S_{ijk}$ is the standard deviation of the $k^{th}$ measurement on the $i^{th}$ part, by the $j^{th}$ operator. $(k-1)$ is the degrees of freedom. Squaring the standard deviation will give the variation of the particular measurement.

### 3.2.2.3 Precision-to-Tolerance (P/T) Ratio of GR&R

Once the variance is calculated, the P/T ratio can be calculated. The P/T ratio addresses the percent tolerance of the variation and can determine the suitability of the
measurement system. The percent tolerance must be $\leq 10\%$ of process variability for critical response variables, between 10% and 30% variability for non-critical response variable and unacceptable for $> 30\%$ of process variability.

The P/T ratio uses the formula:

$$P/T = \frac{K \sigma_{R&R}}{USL - LSL}$$

(10)

The K value can be associated with two different values. The value $K = 6$ corresponds to the number of standard deviations between “natural” tolerance limits of a normal process. The value $K = 5.15$ corresponds to the limiting value of the number of standard deviations between bounds of a 95% tolerance interval that contains at least 99% of a normal population [12]. The K value of 5.15 will be used for this GR&R since a 95% confidence interval is used in the dimensional inspection data at LANL. The $\sigma_{R&R}$ is the total repeatability and reproducibility variation in the process. USL and LSL are the upper and lower specification limits of the part. Minitab® calculates the P/T ratio percentage for all factors and interest points, but the total process variation and total GR&R P/T ratios will be the main interest point.

### 3.2.3 QUINDOS 7

QUINDOS metrology software is an open architecture software package that can be used to measure virtually anything. QUINDOS is a metrology/measuring software from Brown & Sharpe© and is designed for both CMM and PMM machines. With different analysis packages it is possible to measure anything from machined parts, gears, turbine blades, camshafts and many other parts. LANL’s purpose for using QUINDOS and not other metrology software (i.e. PC-DMIS) is because it is more mathematically
capable for the types of geometries encountered in LANL’s WR quality components. Older versions of QUINDOS are currently being implemented on WR components, but QUINDOS 7, the newest version of the software, will be implemented on the inspection program.

QUINDOS programs can be created directly from CAD models (offline programming) or manually probing parts on the CMM. Various CAD software models can be imported into QUINDOS and part geometries can be generated, so that the CMM can measure the produced geometry through DCC. With offline programming, QUINDOS can be used from a remote location without having to be connected to a server or a CMM. QUINDOS can also be “taught” to measure parts geometry. Like all physical metrology machines, CMMs can manually collect points on a part; QUINDOS can then store the location of the data point, relative to the machine and part coordinate systems and retrace those points to measure the part. The QUINDOS 7 routine for the s will be produced by both methods.

3.2.3.1 Measuring Routine with Code

The QUINDOS 7 program will be structured around collecting measurement points from the shell in the polar (0° to 88°) and azimuth (0° to 360°) directions. The reason for the polar direction only being measured up to 88°, is that the rounding ring used for holding the shell only allows travel up to 88° for stability purposes. The azimuth direction can be measured entirely at the equator of the shell.

The shell’s measuring routine callouts in the engineering drawing shall be measured for “the inside radial distance, inner contour, and for the radial wall thickness
in the 360° circumferential, spiral, or planar sweeps in two degree increments from the theta angle of zero degrees to 86° and eight points at the theta angle for 88° [16]. This inspection process collects approximately 44000 data points on a single shell. This rotary contour measuring routine is stated from the design agency, but for the GR&R a similar but shorter program will be used. The reason for a shorter program is the processes are still in preliminary stages, time is a constraint and there is no immediate need for a high-point data density program for the.

This program is built around a scanning routine and not a touch trigger routine because of shorter time duration during the measuring process. Though touch trigger probing is more accurate, time becomes a factor for the amount of data recorded from each shell. If the same scanning routine were implemented with touch trigger probing, the measuring routine would be significantly longer, thus violating one of the purposes for researching this project, time constraints.

The QUINDOS 7 program will measure the polar direction of the shell in two degree increments. This data will be collected every two degree from 0° to 88°, including 0°, which will result in 45 data points in the polar direction. In the azimuth direction, every 30° degrees will consist of a polar band measure, the polar direction measurement. This will equate to 12 polar bands of data from the azimuth angle. The reason every 30° is, if needed, to have a direct comparison to the rotary contour machines data. A total of 540 data points is collected from a single shell. This method will measure the inner contour and the outer contour of the shell, which the radial wall thickness can then be calculated. The radial wall thickness is the main interest of LLNL, so the analysis will be done with respect to the radial wall thickness.
Figure 2 demonstrates the measuring directions of the shell program:

![Figure 2: Measuring Direction of Shell.](image)

With an agreed data density, the following measuring methodology will be implemented on the shell for the GR&R study. The PMM-C will calibrate all the measuring probes before any measurement is taken. First is the reference probe. A reference probe is what the PMM-C will reference to the machine coordinate system. Once the PMM-C is referenced, the next probe calibration is the Datum A, Datum B and inner contour probe. After calibrating this probe, the outer contour probe is calibrated.

Once probe calibration is done, then a simple quality check sub-routine is implemented into the code. This sub-routine will measure the inside diameter of a ring gauge, to ensure that the probes are aligned and calibrated correctly. If the probes are not calibrated correctly, then the PMM-C will prompt the inspector for another probe calibration until they are correct.

In the program, there is a commented out sub-routine that can be used if the holding fixture for the shell is moved. This sub-routine will ask the user to take a few measurements of the rounding ring base and inner contour and relate those two coordinate systems to the machine coordinate system. This sub-routine comes in handy when another component needs to be measured and the fixture has to be moved to another portion of the working volume.
After the ring gauge test, then the measurement process can begin. First is Datum A. Datum A relates the machine coordinate system to the part coordinate system with a plane. Datum A is measured, 36 points, on the bottom surface of the rounding ring holding the shell. After Datum A is set, Datum B is measured. Datum B keeps the coordinate system on the Datum A plane from translating. Datum B is measured, 16 points, near the equator of the inner contour, approximately at 88°. After Datum B, Datum C is used to fix the rotation of the coordinate system on Datum A plane. Datum C is not actually measured on the shell, but is set when the shell is fastened onto the mounting fixture base. Further explanation of the measuring process fixtures will be discussed in section 3.4. After all constraints are set, the measuring of the inner contour of the shell will begin. The measuring of the inner contour will use the same probe that measured Datums A and B. After the inner contour is measured, the next probe will measure the outer contour of the shell. Once the outer contour is measured, the program is complete. From these measurements, QUINDOS will then calculate the radial wall thickness.

All the probes in the program will be qualified by a 30 mm calibration sphere and all probe changes will be done by DCC on a probe holding rack. Further discussion of the probing setups will be discussed in section 3.4.

An unclassified program of the shell will be documented in a text file for security purposes in Appendix A.
3.2.4 Minitab®

Minitab® is a statistical analysis package that can be used to analyze many types of data sets. Minitab® 16 has built in GR&R capabilities. The GR&R capabilities include from a GR&R worksheet where a randomized testing order or testing matrix can be generated. The testing matrix can be seen in Appendix B. GR&R run charts; linearity and bias studies can also be done. There are three different categories for running a GR&R study in Minitab®. The three categories are GR&R (Nested), GR&R (Crossed) and GR&R (Expanded). The crossed GR&R is a typical GR&R study, using ANOVA or control charts to display variability of the data. The nested GR&R uses the same methods as the crossed, but can be used if there is data missing. It will compensate for missing the data and display variability for the data at hand. The expanded GR&R will be the method of choice because more options for displaying data are available. This expanded version displays the variability in individual terms of the ANOVA method and graphical representation of the data.

3.2.4.1 Analysis Method for Shell

In a GR&R study, the variation is calculated from a single data point or a sub-group of data points and measured numerous times to get an appropriate amount of data. The PMM-C measures the inner contour and outer contour of the shell, and then the radial wall thickness is calculated from these two measured values. The radial wall thickness is controlled by both the inner contour and outer contour. This means that the inner contour and outer contour are independent measurements and the radial wall thickness is a dependent measurement. There will actually be only two separate
measurements of the shell. The measured data and calculations will be gathered and for security purposes, the unclassified deviations and graphical displays of the deviations will be documented in this report.

The measurement of interest will be the radii for the inner contour and outer contour, which can then calculate the radial wall thickness. The shell design adds more constraints to the analysis of the data. Since the tolerances are averages for the radial wall thickness, slices of data will be analyzed from different sections of the shell. Slices from the equator, 88°, the midpoint of the shell, 44° and the pole, 0°, will be analyzed for variation. If all the data were analyzed, then there would be 45 different GR&R results, which would not be reasonable for presenting to the customer. Taking into account customer needs and preliminary purposes, these three different slice analyses will be adequate. For future endeavors, a more rigorous analysis method will be implemented, if needed.

As stated previously, a single data unit measured multiple times is the driving factor of a GR&R. For the shell, from a customer’s stand point, the data set that is most crucial is the radial wall thickness. The inner contour is more rigorous to measure, considering the setup, and the specifications are tighter, but the customer is more interested in radial wall thickness data. The specifications of the radial wall thickness are based-off of averages from the inner and outer contours, so there is more variability associated with the data. With customer needs, the radial wall thickness will be the data set that will be used for the analysis and documentation of the GR&R on the shell. The radial wall thickness, for different slices, will be documented for the repeatability,
reproducibility, part-to-part variation, operator variation, operator*part variation and P/T ratio. The variability of the total process will then be quantified for the shell.

The outputted graphical data will demonstrate all the sources of variation and inconsistency within the total process. These graphs will tell if the PMM-C is in need of a re-calibration or how a new operator compares to an experienced operator. These graphs can give a visual on where the process could be improved for future use. These graphs will be documented in section 4.

3.3 Government Specification 9900000 “General Requirements” for Shell

3.3.1 4:1 Testing Ratio

For the shell’s features that are measured, inner contour, outer contour and radial wall thickness, the tolerances specified are: inner contour = ± 25 µm and radial wall thickness (average) = ± 30 µm. These values are documented because they are deviations from the actual measurement. The radial wall thickness is LLNL’s main interest but, the inner contour has a tighter tolerance and would give a smaller 4:1 ratio, so the inner contour 4:1 ratio will be used, to get the best results from the PMM-C. With tolerances set and applying the 4:1 rule, the PMM-C must be calibrated to measure within ± 6.25 µm or 25% of the required tolerances for the inner contour. Minitab® will calculate this value as the repeatability of the GR&R and this value will be analyzed and documented for detecting how much variability can be attributed to the PMM-C.
3.3.2 Surface Finish

Surface finish is another source of potential variability. The shells are Computer Numerically Controlled (CNC) machined to reduce surface roughness and have a better surface finish. The shells are lathe based fabricated to ensure a continuous cutting process for a better surface finish. The notes on the engineering drawing callout a surface finish of 1.6 µm all over. For this GR&R, only parts with a surface finish of ≤ 1.6 µm will be used.

After machining, the transfer of the shells to the inspection lab must go through a thorough process, so that nicks and dings do not accumulate. The drawing specifications account for imperfections, knowing that the part is not ideal, but good enough. For further information on surface finish, including instruments accuracies for measuring surfaces and the techniques that are utilized for measuring, reference ASME B46.1-2009 [7].

3.3.3 Laboratory Temperature

Uncertainty is the most critical portion of the measurement process [8], but was little understood in the early portion of the 20th century. Uncertainty applies to all measurement types, including thermal, physical or electrical. Temperature is a major influence on work being conducted at LANL. For critical components, a regulated temperature must be set forth for various types of work. With a practical approach, a reference temperature for laboratory measurement of 20°C was drafted in the early 1900’s. After numerous testing, scientists approached a temperature of 20.63°C for an
exact measurement of a 100 mm gage block. From this research a conclusion was drawn that a 20°C laboratory temperature would be the new standard for dimensional measuring.

Following this research and confidence of 20°C for laboratory measurements, LANL has set forth this temperature as its reference for dimensional measurements. This reference temperature is also a recognized standard by NIST.

From this determination, government specification 9900000 “General Requirements’ states, under section 3.3.5.1 (physical measurement temperature), “physical measurements of a product are considered to apply only at a temperature of 20°C. If referee measurements are required, the measurement shall be made at 20°C or adjusted to 20°C to account for differences in thermal expansions or contractions in the material of the gage and/or part. The tolerance of the 20°C temperature is controlled by the degree of accuracy required for the measurement being made.”[6]. From a dimensional metrology stand point, temperature can be assumed to be 20°C because the measurement lab controls the environment to 20 ± 1°C.

3.3.4 Assumptions

To comply with the government specification 9900000 “General Requirements”, LANL has assumptions in place for dimensional measurements, knowing that it cannot control every aspect of the measurement processes. For surface finish, surface profiles and flatness, variability is assumed negligible compared to other sources and only parts that meet drawing specifications are used.

Temperature is a bit more general, with only the labs ambient temperature having a specified value. The CMMs and PMMs also have built in temperature compensations.
With fluctuating changes in ambient temperature, the resistance thermometer circuitry must be compensated. The resistors that are used in the measuring circuitry are selected so that their resistance will remain constant over the range of temperature expected. The PMM-C accounts for these fluctuations in the lab, so the assumption of constant temperature is induced and variability from this source can be neglected.

3.4 Hardware

3.4.1 Precision Measuring Machine (PMM-C)

LANL has adapted CMMs and PMMs to research and development projects for WR quality components. Shell Inspection is the most recent development of WR processes. A preliminary test has shown positive results considering the development machine, Brown & Sharpe® Xcel 765 CMM, was never intended to run a scanning routine, but was modified through controller upgrades to accommodate fast scanning inspection routines. The data is acceptable, but not as accurate as that of Sheffield and SMM machines.

With inaccuracy being a major source for error, the Dimensional Inspection (DI) group is now tasked with finding and testing a new CMM, or PMM, to meet the same performance specifications as the Sheffield and SMM. The new machine of choice is an ultra-accurate and precise version of a shop floor CMM. The machine is a PMM-C.

The PMM-C, “C” in PMM-C stands for third generation machine, has similar stated performance specifications as Sheffield and SMM. The PMM-C has a similar type of setup, but differs slightly from a shop floor CMM. Like CMMs, PMMs use Cartesian coordinates, but differs slightly on the direction of the coordinates. The CMMs
coordinate system directions can be seen in Figure 3. For the PMM-C, the x-axis and y-axis are switched around. The bridge on a PMM-C, the rail that the machine moves about, is the y-axis, the granite table, where the parts or components are measured from, is the x-axis and the probing head is the z-axis. The PMM-C coordinates can be seen in Figure 4. All axes are designed with air bearings, so that the machine moves with as little resistance as possible. Along these axes are electro-optical incremental lengths measuring devices called glass scales, which read off actual position of the machine.

There is another coordinate system the CMM/PMM-C utilizes. The part coordinate system is also referenced on the CMM/PMM-C for measuring routines. Both coordinate systems are right-handed and all axes are perpendicular to each other. Figure 3 displays the part coordinates system.

Figure 3: CMM and Part Coordinate Systems.
From a performance point of view, the PMM-C differs from regular shop floor CMMs in that the probing head does not articulate but rather stays fixed in one position. Figure 5 shows the differences between a CMM and PMM probing head.
The probing head of the PMM-C is a true three dimensional measuring system, which records the surface normal, together with each probing point. This design reduces dynamic measurement error because of less moving parts. Instead of the head moving, the bridge and granite table move. With a non-articulating probing head, the PMM-C’s moving features have less error than a floor CMM. CMMs rest on granite holding blocks, while a PMM-C uses air bags under the machine. This ensures that the system reaches equilibrium before a point is measured.

Another differing feature is the weight balance. Weight balance stabilizes the CMM/PMM-C probing head before it can collect data or run a program. This feature helps reduce additional machine error. Shop floor CMMs are equipped with this feature, but is not as apparent as a PMM-C. A PMM-C actually has an option on the hand control.
for weight balance and the air bearing systems pneumatically adjust the probe in the measuring head. CMM’s weight balance is internally built with kinematic coupling. The manual weight balance of the PMM-C shows a more statistically controlled process. The weight balance of the PMM-C can handle styli and extensions up to 800 mm in length and a weight of 1000 g without creating a bending moment and adversely affecting the data.

The PMM-C’s technical specifications are similar to that of rotary contour machines. The rotary contour machines can measure up to within 1 µm of stated accuracy of the measured value. The PMM-C has more performance specifications, considering it not only scans but it can also touch-trigger measure. The performance specifications are different for both touch-trigger and scanning. The rotary contour machines can only scan a hemi-shell, so it accuracy is only stated for scanning. The specification for the PMM-C scanning accuracy is 1.9 µm [18]. PMM-C probing accuracy is 1.2 µm [17]. Volumetric accuracy is the main specification for CMMs/PMMs. Volumetric accuracy is the position accuracy within the working volume. The volumetric accuracy of the PMM-C is $1.2 + \frac{L}{400} \mu m$ with $L$ as the length of the measurement in mm [18]. 400 is a value from the ISO standard and changes for different working volumes. The working volume of the PMM-C is 1200 mm (X) x 1000 mm (Y) x 700 mm (Z). If measuring a 10 mm part, the volumetric accuracy would be 1.225 µm.

### 3.4.2 Measuring Probes for PMM-C

The measuring probes for the GR&R study are specially designed and ordered for the PMM-C. The purpose of the specialized measuring probes is to reduce the weight of
the probe itself. The probing setups are quite large in design and concerns of creating a bending moment that would clearly affect the data. A light weight material is introduced to solve this problem. The measuring probe extensions are fabricated out of carbon fiber, the rotary knuckles, connectors and styli are fabricated out of light weight aluminum and the styli tip is made of ruby to reduce friction during measurement. These probing setups are designed to accommodate measuring different portions of the shell. There will be three different probing setups for the shell measurements: Reference Probe, Datum A/ Datum B/Inner Contour Probe and Outer Contour Probe.

A drawback to the light weight of these probes is the stiffness of the probe setup. The stiffness is affected when the measuring portion is being conducted. The PMM-C generates a much higher contact force than a shop floor CMM. A shop floor CMM generates a force in the range of 6 to 18 grams-force. The PMM-C generates a force in the range of 80 grams-force. The stability of the probes could be affected by this higher force. After some investigation, the problem pointed to the connections of the probes. The connecting portions are fastened by threaded shafts. Thread glue, or Teflon, will be used to stiffen up the threads and reduce movement along the connecting points.

### 3.4.2.1 Probing Setup

The probe setups are arranged in order of use. Datum B must be measured before the inner contour is measured, so the order of probes is as follows: Reference probe, Datum A, Datum B, Inner Contour and Outer Contour. Also documented will be the 30 mm calibration sphere for qualifying all the measuring probes. Pro/Engineer drawings of these probes setups can be referenced in Appendix C.
**Figure 6:** 30 mm Calibration Sphere

**Figure 7:** Reference Probe
The probing setups were designed so that the PMM-C will not be obstructed when reaching all surfaces of the shell.
3.4.3 Six Hemi-Shells

The shell will not be documented. The main difference between this shell and other hemi-shells is, but not limited to, the material, size, shape and drawing specifications. About a dozen shells were fabricated, but only six will be used for the GR&R. More tests will be conducted on the shells, but LLNL chose to use these six specified parts as prototypes for possible design changes.

3.4.3.1 Unclassified Mock Hemi-Shell

The following hemi-shell is an unclassified mock that will be used to represent the shell. This artifact is made of stainless steel. Pro/Engineer drawings can be referenced in Appendix C.

Figure 10: CMM Artifact (Unclassified Mock Component)
3.4.4 Mounting Fixture Base, Rounding Ring and Rounding Ring Plate

The mounting fixture base is a fixture designed to be mounted on the granite table, through bolt holes, of the PMM-C. The rounding ring is a uniquely fabricated circular holding fixture for hemi-shells. The shell is then set on a specified rounding ring. The rounding ring will hold, round and stabilize the shell in place so that it does not move during the measuring process. The rounding ring plate is designed to connect the rounding ring and the mounting base together. When the mounting fixture base and rounding ring plate are set on the granite table, the rounding ring with the shell is then placed on the mounting fixture base with the rounding ring plate and fastened down with clamps. These clamps are used to hold the rounding ring in place and so that it does not slip off the fixture and to lock Datum C into place. The whole measuring fixture is designed so that the rounding ring and shell are 45° from the horizontal of the granite table. This design is a replicate of the positioning of a hemi-shell on a rotary contour machine. It was also designed so that the PMM-C probes can access all the surfaces of the shell. Figure 11 demonstrates the mounting fixture base and the rounding ring plate.
Figure 12 demonstrates a mock rounding ring with a mock hemi-shell mounted on it. This hemi-shell is an artifact from the United Kingdom and the rounding ring was uniquely fabricated for it. The hemi-shell is made out of hard plastic and is used to monitor the Sheffield and SMM for any type of unusual errors. Both the hemi-shell and rounding ring are unclassified.
Figure 12: Mock Hemi-shell and Mock Rounding Ring Setup (Unclassified)

Figure 13 demonstrates the entire measuring process setup with mock hemi-shell, mock rounding ring, rounding ring plate and mounting fixture base. Pro/Engineer drawings of all the fixtures and mock hemi-shells are documented in Appendix C.
3.4.5 Setup of Measuring Process

The mounting fixture base is not mounted in a specific location on the granite table. The entire mounting fixture is not on a large scale, so the smaller the operating volume, the less uncertainty over the measurements. The QUINDOS 7 program accounts for changing position of the mounting fixture, if necessary. With this setup, the PMM-C will able to access all the necessary surfaces for measuring. This positioning of the mounting fixtures can be seen in Figure 14.
Each probe will be mounted on a change rack that is mounted on the PMM-C. The probing changes will be DCC to eliminate any unnecessary additional error. An example of the probe change rack can be seen in Figure 15.
The entire measurement process, from part setup to qualification to radial wall thickness calculations, takes approximately one hour for completion. This is much faster than initially estimate of four hours, but the measuring routine is shorter with a smaller point density and only used for preliminary purposes.

The following figures show the measuring process of a hemi-shell. Figure 16 demonstrates the inner contour probe measuring and collecting data near the pole of the hemi-shell.
Figure 16: Datum A, Datum B and Inner Contour Probe Measuring (Unclassified)

Figure 17 demonstrates the outer contour probe measuring data near the equator of the hemi-shell.
4.0 Experimental Evaluation

4.1 Testing Parameters

For test evaluation, six hemi-shells, two inspectors and three trials of each shell will be used for the GR&R. Table 1 represents the methodology for the GR&R:

**Table 1:** Parameters for GR&R on a shell using a PMM-C

<table>
<thead>
<tr>
<th>Parameters for GR&amp;R on Shells</th>
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</thead>
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<td><strong>System</strong></td>
</tr>
<tr>
<td>PMM-C</td>
</tr>
</tbody>
</table>

From these parameters for the GR&R, Minitab® is used to randomly generate a testing order for process. This method adds the randomization to the data, so every element can be incorporated. The testing matrix can be seen in Appendix B.
Using ANOVA techniques, Minitab® will first generate a table with interactions (i.e. operator*part) and if the P-value, the probability of obtaining a test statistic at least as extreme as the one that was actually observed assuming that the null hypothesis is true, is ≥ 0.25, Minitab® will generate another ANOVA table without interactions. If the P-value reaches 0.25 or greater, then there is not a significant effect from operator*part variation, in terms of tolerances, and will be incorporated into the error component of the linear statistical model. This P-value ANOVA technique is used only for the interaction term in the GR&R because it must treat all the other terms individually. In Minitab®, the default value of 0.25 is used because of the 95% confidence interval, so this alpha value will be used.

ANOVA also uses statistical hypothesis testing. A statistical hypothesis is a statement either about the parameters of a probability distribution or the parameters of a linear statistical model. With the linear statistical model used in the GR&R, the null hypotheses, original guess, states that the interaction between the operators and part has a significant impact on the total process variation. This hypothesis can be accepted or rejected from the P-value of ANOVA tables generated in Minitab®. The P-value will be used for justification purposes.

From these ANOVA calculations, a great deal of total process variation will be pinpointed to where most of the variation is generated and possible ideas can be drawn from on how to improve not only individuals points, but the total process in general.
4.2 Results and Analysis for Pole Location

First measurement will be the pole location, 0°, of the shell.

Table 2: ANOVA Results for 0°

Factor Information

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<th>Factor</th>
<th>Type</th>
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<td>1, 2, 3, 4, 5, 6</td>
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<tr>
<td>Operators</td>
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ANOVA Table with All Terms

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Alpha to remove interaction term = 0.25

The P-value is below the 0.25 value. This means that the null hypothesis cannot be rejected. There is a detectable effect from the operator*parts interaction variability. The operator*parts interaction will not be consumed into the error component of the statistical model and will be treated as a significant source for process variation. Table 3 shows the GR&R results.
Table 3: Variance Components and Gauge Evaluation at 0°

Variance Components

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<td>Total Gage R&amp;R</td>
<td>0.338457</td>
<td>67.03</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.338333</td>
<td>67.00</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>0.000123</td>
<td>0.02</td>
</tr>
<tr>
<td>Operators</td>
<td>0.000123</td>
<td>0.02</td>
</tr>
<tr>
<td>Part-To-Part</td>
<td>0.166481</td>
<td>32.97</td>
</tr>
<tr>
<td>Parts</td>
<td>0.000000</td>
<td>0.00</td>
</tr>
<tr>
<td>Parts*Operators</td>
<td>0.166481</td>
<td>32.97</td>
</tr>
<tr>
<td>Total Variation</td>
<td>0.504938</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Process tolerance = 60

Gage Evaluation

<table>
<thead>
<tr>
<th>Source</th>
<th>StdDev (SD)</th>
<th>Study Var (5.15 * SD)</th>
<th>%Study Var (%SV)</th>
<th>%Tolerance (SV/Toler) (P/T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Gage R&amp;R</td>
<td>0.581770</td>
<td>2.99612</td>
<td>81.87</td>
<td>4.99</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.581664</td>
<td>2.99557</td>
<td>81.86</td>
<td>4.99</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>0.011111</td>
<td>0.05722</td>
<td>1.56</td>
<td>0.10</td>
</tr>
<tr>
<td>Operators</td>
<td>0.011111</td>
<td>0.05722</td>
<td>1.56</td>
<td>0.10</td>
</tr>
<tr>
<td>Part-To-Part</td>
<td>0.408021</td>
<td>2.10131</td>
<td>57.42</td>
<td>3.50</td>
</tr>
<tr>
<td>Parts</td>
<td>0.000000</td>
<td>0.00000</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Parts*Operators</td>
<td>0.408021</td>
<td>2.10131</td>
<td>57.42</td>
<td>3.50</td>
</tr>
<tr>
<td>Total Variation</td>
<td>0.710590</td>
<td>3.65954</td>
<td>100.00</td>
<td>6.10</td>
</tr>
</tbody>
</table>

From table 3, it is apparent that there is a significant effect on the variation from the interaction. The PMM-C induces about 67.03% of the variation and the shell/inspector combination introduces about 32.97%. Ideally, it would be better for the shell and inspector interaction to harbor all the variation. The % Total GR&R is somewhat surprising, the repeatability accounts for 81.86%, while the reproducibility is almost negligible at 1.56%. This can be accounted for from the shell setup. The shell was placed on the rounding ring, and then a quality check was used to ensure that the shell was sitting correctly on the rounding ring. A calibrated height master gauge was used to measure the pole height of the shell and rounding ring combination. This helped stabilize the pole measurement. The % Total GR&R for the P/T ratio is almost 5%, so the PMM-C and shell variability’s are under the 10% Total Variability for critical response.
variables. The repeatability is under 25% for the 4:1 testing ratio, so the PMM-C is well calibrated and can measure within 6.25 µm accuracy. The P/T ratio is under the 10% of Total Process Variation. It is actually 6.10%, so the total process of measuring the pole location on a shell, on a PMM-C is acceptable.

Better representation of the sources of variability will give a better indication of possible process improvement. Graphical output of the data of the 0° measurement will also demonstrate the variability of the total process with average deviations, measured in micrometers, and ranges of these deviations for the pole location of the shell.

### Components of Variation

![GR&R (ANOVA) for 0 Degree (Radial Wall Thickness)](image)

**Figure 18:** Components of Variation (0°)

Figure 18 shows the exact parentage of the variation components at the pole location of the shell. The PMM-C accounts for most of the variation, while the setup and the actual shell account for a smaller portion of the total system variation. It would be more ideal for the percentages to be vice versa.
Figure 19: Operator by Part Interaction (0°)

Figure 19 definitely shows that there is a difference, but very little. The effect is apparent in the ANOVA tables, but with the tolerances of ± 30 µm, the inspectors look almost identical. The scaling shows about four µm max average deviation, so not critical. From the graph, it is clear that it doesn’t depend on which part is being measured and which operator measures a certain shell. This can be attributed to the placing of the shell/rounding ring on the fixture base. Since the shell is placed on the rounding ring first, then the base, the error is reduced drastically compared to placing the rounding ring on the base first then the shell on the rounding ring. There is only a scribe line on the shell and mounting fixture for alignment, but with single digit micrometer misalignment, there is not a significant cause for concern.
Figure 20: Measurements by Operator (0°)

Figure 20 shows that the inspectors are on average measuring the parts in a similar fashion. If the x-axis is parallel to one another, then both would be close to making the same measurement. The measurements by the inspectors are only off by possibly a single micrometer or less, and the variability is almost nonexistent. There are two points lying on the outside of the plots, they can be possible outliers, but with a one micrometer difference, the effect of this possible outlier is negligible. The measurements are appropriate for the results.
**Figure 21:** Measurements by Part (0°)

Figure 21 shows more of the same, with the parts meeting up with averages. The average spread seems to be about one to two micrometers. The variation is almost negligible between the parts. The setup is eliminating significant amounts of variation in the measurements.

The graphical output shows relatively no variation, but with large tolerance of ± 30 µm and good part setup, the amount of variation should be very small and rely mostly on the PMM-C for variation, as the results show. The measurement of the pole location is a qualified process.
4.3 Results and Analysis for Midpoint Location

For the 44° location, using the same methodology, the results are as follow:

Table 4: ANOVA Results for 44°

Factor Information

<table>
<thead>
<tr>
<th>Factor</th>
<th>Type</th>
<th>Levels</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parts</td>
<td>random</td>
<td>6</td>
<td>1, 2, 3, 4, 5, 6</td>
</tr>
<tr>
<td>Operators</td>
<td>fixed</td>
<td>2</td>
<td>1, 2</td>
</tr>
</tbody>
</table>

ANOVA Table with All Terms

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parts</td>
<td>5</td>
<td>15.088</td>
<td>15.088</td>
<td>3.018</td>
<td>1.98</td>
<td>0.236</td>
</tr>
<tr>
<td>Operators</td>
<td>1</td>
<td>0.903</td>
<td>0.903</td>
<td>0.903</td>
<td>0.59</td>
<td>0.476</td>
</tr>
<tr>
<td>Parts*Operators</td>
<td>5</td>
<td>7.626</td>
<td>7.626</td>
<td>1.525</td>
<td>0.58</td>
<td>0.714</td>
</tr>
<tr>
<td>Repeatability</td>
<td>24</td>
<td>63.020</td>
<td>63.020</td>
<td>2.626</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>35</td>
<td>86.636</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Alpha to remove interaction term = 0.025

ANOVA Table with Terms Used for Gage R&R Calculations

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parts</td>
<td>5</td>
<td>15.088</td>
<td>15.088</td>
<td>3.018</td>
<td>1.24</td>
<td>0.317</td>
</tr>
<tr>
<td>Operators</td>
<td>1</td>
<td>0.903</td>
<td>0.903</td>
<td>0.903</td>
<td>0.37</td>
<td>0.547</td>
</tr>
<tr>
<td>Repeatability</td>
<td>29</td>
<td>70.646</td>
<td>70.646</td>
<td>2.436</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>35</td>
<td>86.636</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The P-value for parts*operator is > 0.25. This means that the null hypothesis can be rejected. So the parts*operator interaction is incorporated into the error component of the linear statistical model and another ANOVA table is recalculated without the interaction of the operator*part. This P-value shows that a not a significant amount of variation that comes from the interaction. Since 44° is the midpoint between the shell polar directions, the measurements aren’t significantly affected by the pole location quality check or the rounding ring. This measurement can be considered to be measured in a Free State. A Free State measurement is when a measurement is taken with as little constraint as
possible. An assumption can be made that this measurement should not be affected from the fixturing or positioning and the variation should most only be from the PMM-C.

Table 5: Variance Components and Gauge Evaluation at 44°

Variance Components

<table>
<thead>
<tr>
<th>Source</th>
<th>VarComp</th>
<th>%Contribution of VarComp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Gage R&amp;R</td>
<td>0.0246113</td>
<td>96.21</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.0243606</td>
<td>95.23</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>0.0002507</td>
<td>0.98</td>
</tr>
<tr>
<td>Operators</td>
<td>0.0002507</td>
<td>0.98</td>
</tr>
<tr>
<td>Part-To-Part</td>
<td>0.0009692</td>
<td>3.79</td>
</tr>
<tr>
<td>Parts</td>
<td>0.0009692</td>
<td>3.79</td>
</tr>
<tr>
<td>Total Variation</td>
<td>0.0255806</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Process tolerance = 60

Gage Evaluation

<table>
<thead>
<tr>
<th>Source</th>
<th>StdDev (SD)</th>
<th>Study Var (5.15 * SD)</th>
<th>%Study Var (%SV)</th>
<th>%Tolerance (SV/Toler) (P/T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Gage R&amp;R</td>
<td>0.156880</td>
<td>0.807932</td>
<td>98.09</td>
<td>1.35</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.156079</td>
<td>0.803806</td>
<td>97.59</td>
<td>1.34</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>0.015833</td>
<td>0.081542</td>
<td>9.90</td>
<td>0.14</td>
</tr>
<tr>
<td>Operators</td>
<td>0.015833</td>
<td>0.081542</td>
<td>9.90</td>
<td>0.14</td>
</tr>
<tr>
<td>Part-To-Part</td>
<td>0.031133</td>
<td>0.160334</td>
<td>19.47</td>
<td>0.27</td>
</tr>
<tr>
<td>Parts</td>
<td>0.031133</td>
<td>0.160334</td>
<td>19.47</td>
<td>0.27</td>
</tr>
<tr>
<td>Total Variation</td>
<td>0.159939</td>
<td>0.823687</td>
<td>100.00</td>
<td>1.37</td>
</tr>
</tbody>
</table>

From table 5, as stated previously, the PMM-C is almost entirely the source of the variation in the process. 95.23% of the variation is from the repeatability, with only a small percentage from reproducibility and part-to-part variation. The % Total GR&R, 1.37%, indicates that the P/T ratio of the PMM-C and shell is well under 10%. The 4:1 ratio, repeatability, at 44° also indicates that the PMM-C is well calibrated and can easily measure within 6.25 µm accuracy. For the % Total Process Variation, the P/T ratio is 1.37%, well under the 10% for critical response variables. Initial thoughts were that the midpoint measurement would be much closer to the limit of 10%, because of the Free State. Possible effects could be from both the pole quality check and rounding ring,
causing both to stabilize the setup from pole to equator. More thought will be looked at for future endeavors. The analysis indicates that the setup was good and the PMM-C can measure a shell at midpoint location of a polar band, so the total process of measuring the midpoint location on a shell on a PMM-C is acceptable.

Better representation of the sources of variability will give a better indication of possible process improvement. Graphical output of the data of the 44° measurement will also demonstrate the variability of the total process with average deviations, measured in micrometers and ranges of these deviations for the midpoint location of the shell.

<table>
<thead>
<tr>
<th>GR&amp;R (ANOVA) for 44 Degree (Radial Wall Thickness)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gage name: PMM-C</td>
</tr>
<tr>
<td>Date of study: 12-15-2010 to 3-7-2011</td>
</tr>
<tr>
<td>Misc: Percentage</td>
</tr>
</tbody>
</table>

![Components of Variation](image)

**Figure 22:** Components of Variation (44°)

Figure 22 shows that variation is due mostly from the PMM-C, but the shell and inspector add in more variation then at the pole location. This shows that the shell does slightly move during the measuring routine, but the PMM-C does not lose contact with the shell. The probing force on the PMM-C can be a cause for the shell to move slightly.
Considering the higher force on a PMM-C and the small tolerances of the shell, there is a possibility for movement. Another cause can be an outlier. It also reiterates that the PMM-C is associated with the most process variability.

![GR&R (ANOVA) for 44 Degree (Radial Wall Thickness)](image_url)

**Figure 23: Operator by Part Interaction (44°)**

Figure 23 shows that the parts*operator interaction of both the operators are measuring consistently with each other. The average is shifted in the positive direction about 16 to 18 micrometers from the nominal value. This can potentially be caused by an outlier or could be that a foreign object (i.e. lint, dust, etc) could have possibly been detected by the probe head. The average values are still within the tolerances, so no too much cause for concern. A more in-depth analysis or possible re-measurement of this measurement could lead to better results.
Figure 24: Measurements by Operator (44°)

Figure 24 shows that the shells were not being measured similarly on average because the averages on the x-axes do not match up, but the variation is consistent. This could be pointed back to the positive shift of the measurements. The max average deviations seem to be between three to four micrometers. Even with a shift in data, the measurements are acceptable.
Figure 25: Measurements by Part (44°)

Figure 25 shows little variation between measurements, with the most variation on the sixth shell. The max average deviations seem to be about five micrometers. Again a further investigation can be done on the shifted data.

The graphical output shows shifted variation from the nominal, but still within the tolerances of ±30 µm. A further look into the measurement, or the Free State setup could possibly tell of why the data is shifted up by 16 to 18 micrometers. The measurement of the midpoint location is a qualified process.
4.4 Results and Analysis for Equator Location

For the equator, 88°, using the same methodology, the results are as follow:

Table 6: ANOVA Results for 88°

Factor Information

<table>
<thead>
<tr>
<th>Factor</th>
<th>Type</th>
<th>Levels</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parts</td>
<td>random</td>
<td>6</td>
<td>1, 2, 3, 4, 5, 6</td>
</tr>
<tr>
<td>Operators</td>
<td>fixed</td>
<td>2</td>
<td>1, 2</td>
</tr>
</tbody>
</table>

ANOVA Table with All Terms

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parts</td>
<td>5</td>
<td>147.76</td>
<td>147.76</td>
<td>29.55</td>
<td>0.99</td>
<td>0.506</td>
</tr>
<tr>
<td>Operators</td>
<td>1</td>
<td>16.95</td>
<td>16.95</td>
<td>16.95</td>
<td>0.56</td>
<td>0.486</td>
</tr>
<tr>
<td>Parts*Operators</td>
<td>5</td>
<td>150.00</td>
<td>150.00</td>
<td>30.00</td>
<td>1.13</td>
<td>0.370</td>
</tr>
<tr>
<td>Repeatability</td>
<td>24</td>
<td>635.70</td>
<td>635.70</td>
<td>26.49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>35</td>
<td>950.40</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Alpha to remove interaction term = 0.25

ANOVA Table with Terms Used for Gage R&R Calculations

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parts</td>
<td>5</td>
<td>147.76</td>
<td>147.76</td>
<td>29.55</td>
<td>0.99</td>
<td>0.386</td>
</tr>
<tr>
<td>Operators</td>
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<td>16.95</td>
<td>16.95</td>
<td>16.95</td>
<td>0.63</td>
<td>0.435</td>
</tr>
<tr>
<td>Repeatability</td>
<td>29</td>
<td>785.70</td>
<td>785.70</td>
<td>27.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>35</td>
<td>950.40</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The P-value for parts*operator is > 0.25. This means that the null hypothesis can be rejected. So the parts*operator interaction was incorporated into the error component of the linear statistical model and another ANOVA table was recalculated without interaction. This P-value shows that a not a significant amount of variation came from the interaction. There was no quality check for this measurement, since it was closest to the equator of the shell. However, the rounding ring rounded out the equator of the shell, so as to restrict the rotation and translation degrees of freedom. This kept the equator rounded and should show that most of the variation should come from the PMM-C.
Table 7: Variance Components and Gauge Evaluation at 88°

Variance Components

<table>
<thead>
<tr>
<th>Source</th>
<th>VarComp</th>
<th>%Contribution (of VarComp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Gage R&amp;R</td>
<td>0.275638</td>
<td>98.54</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.270930</td>
<td>96.85</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>0.004707</td>
<td>1.68</td>
</tr>
<tr>
<td>Operators</td>
<td>0.004707</td>
<td>1.68</td>
</tr>
<tr>
<td>Part-To-Part</td>
<td>0.004098</td>
<td>1.46</td>
</tr>
<tr>
<td>Parts</td>
<td>0.004098</td>
<td>1.46</td>
</tr>
<tr>
<td>Total Variation</td>
<td>0.279735</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Process tolerance = 60

Gage Evaluation

<table>
<thead>
<tr>
<th>Source</th>
<th>StdDev (SD)</th>
<th>Study Var (5.15 * SD)</th>
<th>%Study Var (%SV)</th>
<th>%Tolerance (SV/Toler) (P/T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Gage R&amp;R</td>
<td>0.525012</td>
<td>2.70381</td>
<td>99.26</td>
<td>4.51</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>0.520510</td>
<td>2.68063</td>
<td>98.41</td>
<td>4.47</td>
</tr>
<tr>
<td>Operators</td>
<td>0.068611</td>
<td>0.35335</td>
<td>12.97</td>
<td>0.59</td>
</tr>
<tr>
<td>Part-To-Part</td>
<td>0.064013</td>
<td>0.32967</td>
<td>12.10</td>
<td>0.55</td>
</tr>
<tr>
<td>Parts</td>
<td>0.064013</td>
<td>0.32967</td>
<td>12.10</td>
<td>0.55</td>
</tr>
<tr>
<td>Total Variation</td>
<td>0.528900</td>
<td>2.72384</td>
<td>100.00</td>
<td>4.54</td>
</tr>
</tbody>
</table>

The PMM-C is again the main source for variation at 96.85%. At 88°, the part-to-part variation is at its smallest which indicates that the rounding ring corrected out most of the variation. The % Total GR&R, 4.51%, indicates that the P/T ratio < 10% with almost no variation from reproducibility, .59%. The 4:1 ratio at 88° also indicates that the PMM-C is well calibrated and can measure within 6.25 µm accuracy. The % Total Process Variation is 4.54%, < 10% for critical response variables. This indicates that the setup was good and the PMM-C can measure a shell at the equator of a polar band, so the total process of measuring at equator on a shell on a PMM-C is acceptable.

Better representation of the sources of variability will give a better indication of possible process improvement. Graphical output of the data of the 88° measurement will
also demonstrate the variability of the total process with average deviations, measured in micrometers and ranges of these deviations for the midpoint location of the.

**GR&R (ANOVA) for 88 Degree (Radial Wall Thickness)**

<table>
<thead>
<tr>
<th>Component</th>
<th>% Contribution</th>
<th>% Study Var</th>
<th>% Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gage R&amp;R</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Repeat</td>
<td>90</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>Reprod</td>
<td>10</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Part-to-Part</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Figure 26: Components of Variation (88°)**

Figure 26 indicates that most of the variation comes from the PMM-C and a small portion from the shell and inspector. At the equator, the part-to-part and reproducibility variation is small; mainly due to the rounding ring restricting movement. The tolerances were consumed a bit more in this measurement then the midpoint and pole locations, possibly from the rounding ring.
Figure 27: Operator by Part Interaction (88°)

Figure 27 indicates both operators are consistently measuring the shells similarly, except for shell number three. The data is shifted up from the nominal, so further investigation is needed. Shell number three looks to be on the nominal value, while the other shells are shifted by about 12 micrometers. This could be just a random occurrence or outlier, but further investigation will be needed.
Figure 28: Measurements by Operator (88°)

Figure 28 indicates for the most part; the inspectors are measuring the shells similarly on average, except for the possible outlier, which is skewing the data. The variation is consistent; looking more into the possible outlier could potentially fix the skewed data.
**FIGURE 29:** Measurements by Part (88°)

Figure 28 indicates constant and little variation between measuring parts, except for the possible outlier. There is a max average deviation, excluding the outlier, of about six to seven micrometers. This spread is no cause for concern.

The graphical output shows shifted variation from the nominal, but still within the tolerances of ± 30 µm. A further look into the measurement, or the possible outlier of shell three could possibly tell of why the data is shifted up about 12 micrometers. The measurement of the equator location is a qualified process.

The graphical output shows most variation in the PMM-C for all three locations, but the amount of variation shown, there is no cause for concern. The shifted data on the midpoint and equator locations need to be investigated further on why they are off significantly from the nominal. More thought will go into the shell number three measurement, if needed. The three measurements are qualified processes.
Overall the process gives promising results for measuring a shell on a PMM-C. The setup of the shell was much better than anticipated and seems to of helped control the variation between the different inspectors.

For more graphical representation, the $\bar{X}$ and R charts for each operator at each measurement can be seen in Appendix B.

5.0 Conclusions

From the resulting three studies, the total process variability was captured for each of the measurements. These three studies captured most of the concerns of variability when using a PMM-C to measure a hemi-shell. The fixturing and quality checks helped out with minimizing the variation in the process. Fixturing helped out tremendously with the data collection and the results. If all the measurements were taken in a Free State, no fixturing to hold the shell steady, then the quality of the measurements and results would be lower.

A summary of the measurements and the main percent variation can be seen in Table 8.

Table 8: Summary Chart of Measurements

<table>
<thead>
<tr>
<th>Source</th>
<th>Pole (0°)</th>
<th>Midpoint (44°)</th>
<th>Equator (88°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Total Variation</td>
<td>6.1</td>
<td>1.37</td>
<td>4.54</td>
</tr>
<tr>
<td>% GR&amp;R</td>
<td>4.99</td>
<td>1.35</td>
<td>4.51</td>
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<tr>
<td>% 4:1 Ratio (Repeat)</td>
<td>4.99</td>
<td>1.34</td>
<td>4.47</td>
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From Table 8, the summarized results show that at each measurement location, the PMM-C and inspector variability are acceptable for measuring a hemi-shell. The 4:1
measurement uncertainty ratio is well under the 25% value for measuring instruments used in LANL’s production process. Overall, the measuring process of a hemi-shell on a PMM-C is acceptable for WR quality work done at LANL.

Each time a shell was measured; there was 540 data points, broken up into polar bands and azimuth bands. This gives approximately 9720 data points for measuring all six shells; three times each. That amount of data would take weeks to analyze and could possibly lead to diminishing returns. The analysis will be done for the non-included data sets, but will not be documented in this report for preliminary purposes.

The GR&R was a success, with a few minor discrepancies. The analysis method was a bit more tedious than initially thought. The radial wall thickness has averaged tolerance values. The data collected is the inner and outer contours of the shell, which the radial wall thickness is calculated from. So as stated previously from the measurement process, each shell is measured from pole to equator, collecting a data point every two degrees, which in total is 45 points. This measurement is done at every 30 degrees on the shell, so in all there is 12 pole to equator measurements for each shell. From these 12 measurements, the average value is used for the analysis. The average value is then used in the Minitab® analysis

After the analysis was completed, the results showed that the PMM-C and inspector variability is less than 10% and the 4:1 ratio is under 25%, which shows a successful study. After the conclusion of the GR&R study, LANL and LLNL will accept that a CMM can be used to measure WR products, and can eventually become a replacement for rotary contour machines.
6.0 Future Work Recommendations Endeavors

Future work from this GR&R study is to implement a similar methodology on a new machine that LANL has purchased for War Reserve (WR) processes. LANL purchased a Leitz CMM reference machine, a hybrid between a shop floor CMM and PMM, which is stated to be more accurate and have better CAD capabilities. With better CAD capabilities, the new Leitz machine can support various CAD software, which can be used to import solid models into QUINDOS. From these models, better programming techniques can be used to help the programmer with writing measuring routines. These measuring routines can be generated in QUINDOS on a solid model, without having to physically probe the part or hard coding parameters into the routine. LANL will conduct a similar GR&R study and ISO standard tests on the new machine to validate its specifications and check for variability. The GR&R is a building block for the CMM reference and other CMMs for developing WR processes.

The PMM-C is on a one year calibration cycle. The calibration cycle is due to end on March 2011. This GR&R was conducted toward the later part of the calibration cycle, so if another GR&R is conducted at the beginning of the cycle, then the results could potentially be different. Further investigations will be done.

A more specialized QUINDOS 7 program will be developed for Shell Inspection Process WR work. The current program only takes 540 total points, a polar band scan at every 30 degrees, 12 bands, and two degree increments from zero to eighty eight degrees. The enhanced program will take the same point from zero to eighty eight, but will now take polar band scans every one and a half degrees. Once the program is modified and deemed satisfactory, it will be implemented on the WR work. Another feature to be
added to the program is to use a high-speed-scan (HSS) routine instead of an open-loop program. Open-loop programs search the surface of the part, picking up a data point as it can. This is good for writing a short concise program and for preliminary purposes. The HSS program uses a defined path that does not search the surface for points, and collects at specified locations. HSS is more difficult to implement, but would reduce error in collecting data and could potentially reduce more variability in the process.

With the probe stiffness becoming an issue during this study, new probes of different materials will be researched for best possible results on being light weight and stiff. Some preliminary research has been done with a specific vendor, ITP Styli, as to what is the best option LANL should consider for solving these problems. The best options available now would be a single piece, light weight titanium probe. Another path could still involve carbon fiber with a single piece like the titanium, but with welded knuckles. ITP Styli also has carbon fiber ‘filled’ options on probes. A more in-depth look into these filled probing setups could also potentially solve these problems also.

The material became an issue when the measuring process was conducted. The ruby styli that were used in this GR&R were adequate, but occasionally the styli lost contact with the shell. With the ruby probes, a bit of oil was used to lubricate the ruby tip and shell so that the coefficients of friction of the two materials would not affect the data by losing contact with the shell. Another solution to this is using a zirconium styli tip. The zirconium has a smoother surface and glided along the shell, with the occasional slip. Another option is to try diamond finish styli, but the expense is about five times that of a ruby styli.
The analysis method for the data was acceptable enough for the preliminary purposes, but a more rigorous method could possibly help with quantifying all the data. A numerical method could be implemented to run an algorithm for loading the data in analysis software and have quality checks to ensure that the data is appropriate. These thoughts could use further investigation.
7.0 References

8.0 Appendices

8.1 Appendix A: Code

8.1.1 Hemi-shell Inspection Program
Figure A-1: QUINDOS Program for Shell (Unclassified)
8.2 Appendix B: Minitab® GR&R

8.2.1 Minitab® GR&R Testing Matrix

<table>
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<th>C3-T Operators</th>
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Figure B-1: Randomized Testing Matrix for GR&R
8.2.2 Minitab® Control Charts

**GR&R (ANOVA) for 0 Degree (Wall Thickness)**

- **Gage name:** PMM-C
- **Date of study:** 12-15-2010 to 3-7-2011

**Xbar Chart by Operators**
- Mean Deviations (um)
  - **X̄:** -0.006
  - **UCL:** 1.012
  - **LCL:** -1.024

**R Chart by Operators**
- Range Deviations (um)
  - **R:** 0.783
  - **UCL:** 2.016
  - **LCL:** 0

**Reported by:** Lucas M. Valdez
**Tolerance:** USL=30, LSL=-30
**Misc:** Micrometers

---

**Figure B-2:** Control Charts for 0°
**GR&R (ANOVA) for 44 Degree (Wall Thickness)**

Gage name: PMM-C  
Date of study: 12-15-2010 to 3-7-2011  
Reported by: Lucas M. Valdez  
Tolerance: USL=30, LSL=-30  
Misc: Micrometers

**Xbar Chart by Operators**

![Xbar Chart](image)

- TG: UCL=20.256, LCL=14.583, X=17.419
- LV: UCL=20.256, LCL=14.583, X=17.419

**R Chart by Operators**

![R Chart](image)

- TG: UCL=6.865, LCL=0, R=2.667
- LV: UCL=6.865, LCL=0, R=2.667

**Figure B-3:** Control Chart for 44°
Figure B-4: Control Chart for 88°
8.3 Appendix C: Pro/Engineer Drawings

8.3.1 Reference Probe

Figure C-1: Reference Probe Pro/Engineer Drawing (Unclassified)
8.3.2 Datum A, Datum B and Inner Contour Probe

Figure C-2: Datum A, Datum B and Inner Contour Probe Pro/Engineer Drawing

(Unclassified)
8.3.3 Outer Contour Probe

Figure C-3: Outer Contour Pro/Engineer Drawing (Unclassified)
8.3.4 CMM Artifact

Figure C-4: CMM Artifact (Mock Hemi-shell) Pro/Engineer Drawing (Unclassified)
8.3.5 Rounding Ring Plate (Redesign)

Figure C-5: Rounding Ring Plate (Redesign) (Unclassified)
8.3.6 Mounting Fixture Base

Figure C-6: Mounting Fixture Base (Unclassified)