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Revisions to the Strategic Petroleum Reserve Well Grading System

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ABSTRACT

This report presents revisions to the Strategic Petroleum Reserve (SPR) well grading framework. The well grading framework is composed of multiple components and was developed as a guide in application of well remediation and monitoring resources. The revisions were applied to enhance the efficiency and consistency of the well grading process across the four SPR sites. Documentation of the revisions and any significant impact from these revisions are also discussed. The current general workflow for the application and updating of the well grades is also provided.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
DOE	Department of Energy
LAS	log ASCII standard
MAC	multi-arm caliper
MIT	mechanical integrity test
OD	outer diameter
SNL	Sandia National Laboratories
SPR	Strategic Petroleum Reserve

1. INTRODUCTION

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 well casings provide critical isolation of cavern fluids from the surface environment and groundwater.

Periodically, these wells display integrity issues which compromise their critical isolation function. These integrity issues are most commonly associated with deformation of the casing caused by geomechanical stresses or leaks through the threaded connections of the casing. In 2012 the Department of Energy SPR leadership requested that Sandia National Laboratories (SNL) develop a process to access the condition of all the SPR cavern access wells. The goal of this process would be to provide information to prioritize well remediation resources. In early 2013, SNL organized the first of four meetings to establish a remediation priority framework and to establish initial remediation assessments for each SPR cavern access well. Each of these four meetings covered one of the SPR sites. The first meeting focused on the Big Hill site and it was in this meeting that the majority of the remediation priority, or 'grading' framework was developed. The final grading framework incorporated components that are applicable at all the SPR sites and cover the unique characteristics of each of the sites.

The goal of this report is to document revisions to the original well grading framework. These revisions do not change the general framework but do simplify the application of the grading process and confirm consistency of the process across each of the SPR sites. In addition, revisions to some of the supporting processes for the grading framework will also be presented. Finally, this report will act as additional documentation of the grading procedure and as a guide to application of the grading process.

2. GENERAL WELL GRADING FRAMEWORK

The well grading framework was developed in order to set priorities for well monitoring and remediation based on the important phenomena at each of the sites. During development of the framework, it was determined that a two-dimensional space was required to convey the key information. Highest priority was ranking according to need for remediation. Second priority was ranking for monitoring intensity. An illustration showing this principle is given in Figure 2-1.

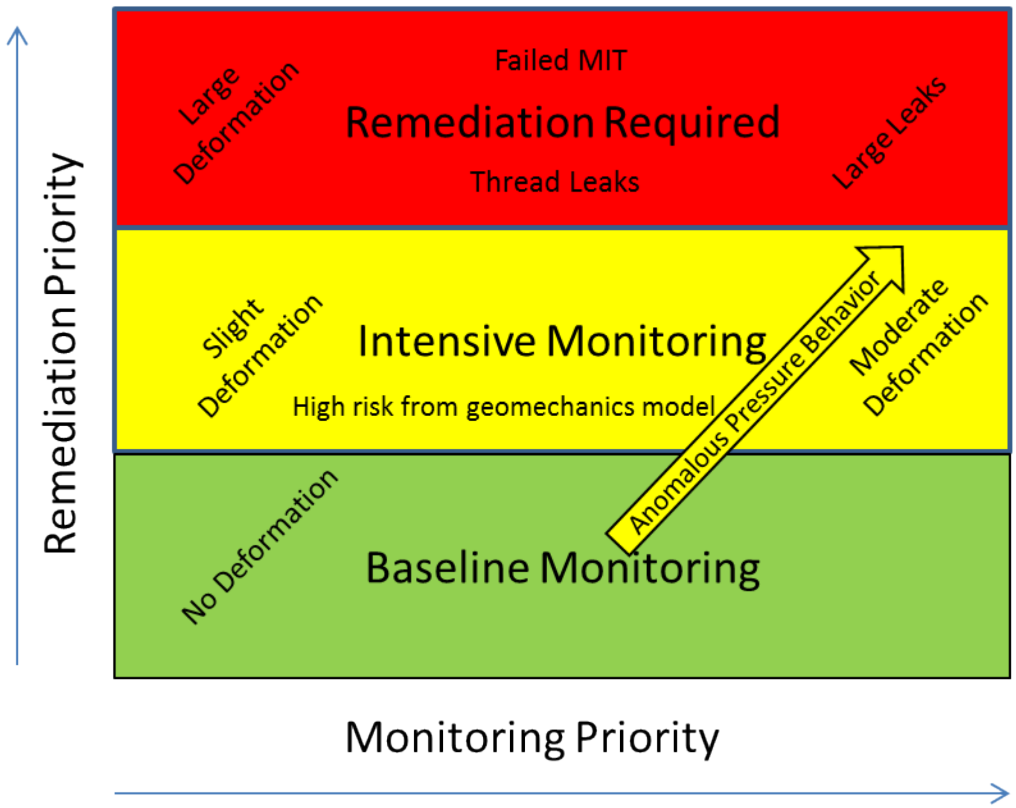

Figure 2-1. Illustration of two-dimensional SPR well grading framework.

Any cavern that exhibited technically defensible evidence of loss of pressure integrity or showed significant casing deformation would be categorized as high priority (red zone), requiring remediation. Caverns that did not display loss of pressure integrity, but showed elevated risk due to moderate casing deformation, anomalous pressure behavior, or were identified in geomechanics modeling as high risk, would be categorized as medium priority (yellow zone) and placed under intensive monitoring. Caverns showing no specific problems would be categorized as low priority (green zone) and set to a baseline monitoring schedule.

The developed well grading framework consists of seven main grading components. These seven main components are listed in Table 2-1.

Table 2-1. Listing of main well grading components.

Main Component	Explanation
Multi-arm caliper (MAC) survey results	Information on casing deformation
Cavern pressure history	Direct information of pressure integrity
Geomechanical simulation results	Indication of stress fields acting on well casings
Geological considerations	Geologic factors impacting casing integrity
Composite well information	Well history and other well specific information
Cavern geometry	Height, width, depth, and other cavern shape factors
Offsite activities	Any non-SPR activities that may impact SPR well casings

These seven components were then combined to generate two final grades; one for remediation priority and one for monitoring priority (see Figure 2-1). Grading values range from 1 to 5 with 5 normally representing the highest priority; in extreme cases, where several factors indicate a very high remediation priority, grading values of 6 are assigned to the remediation grade.

In order to provide the grading framework in a form that is readily accessible and familiar to the SPR community, a standard Excel workbook format was adopted. A separate workbook is maintained for each SPR site and each well at that site has an entry in the workbook. Each of the main components listed in Table 2-1 is represented on a separate tab in the spreadsheet. Each of these components is then combined in a weighted fashion to create the final monitoring and remediation grades.

Details of the main components are provided in the next section of this report.

3. DETAILS OF WELL GRADING COMPONENTS

This section presents the methodology of assigning well grade values for the various components listed in Table 2-1. These individual grade values are then combined to derive single values for remediation and monitoring priorities. The process for combining the grade values from these individual components and the weighting values used in this process are presented in [1].

3.1. MAC Grade Component

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. Deformation of this type is typically the result of rock mass movements from the surrounding geology. Deformations seen from these logs can be indicative of potential future casing failures. The MAC tool makes a determination of this deformation by measuring the inner radius of the well as the tool is raised up the well casing. The number of radial measurement arms varies as a function of the tool manufacturer but typically is in the range of 56 to 80 individual measurements. These measurements are then collected as a function of depth. Early SPR MAC logs had a vertical depth spacing of 0.1 feet; more recent MACs use a much finer vertical spacing of 0.025 feet. The data from these MAC surveys is received as raw radial arm measurements which is then processed using SNL-developed software to obtain a final MAC component well grade.

3.2. Cavern Pressure History Component

Cavern pressure history is used as a fundamental indicator of well integrity at the SPR; wells that don't exhibit expected pressure values typically have some type of integrity issue. The pressure history component of the well grading is determined by examination of the well pressure values as a function of time. Unexplained deviations from the expected pressure increases provide information to the grading process. Under some circumstances, nitrogen is injected into the well casing to evaluate the well's integrity. This can happen as part of a standard Mechanical Integrity Tests (MIT), or as part of an ad hoc well investigation/isolation procedure. Results from ad hoc nitrogen injection and MITs are also considered in the pressure history component. The level of grade assigned to different pressure and MIT conditions are listed in Table 3-1; all cavern pressure history grade values are integers between 1 and 5 with 5 indicating highest level of concern.

Table 3-1. Pressure grades for differing conditions.

Grade	Conditions
5	Confirmed hydraulic leak through cemented casing or around shoe in excess of what can be offset by nitrogen injection. Failed MIT.
4	Pressure trending anomalies such as flattening or loss of pressure. Apparent nitrogen leak yet leak zone may or may not be identified. Cemented annulus pressure tracks with oil pressure. Leak can be contained with nitrogen.
3	Pressure trending anomalies such as flattening or loss of pressure. No problems under last MIT or nitrogen test with detailed pressure trending analysis. OR, has been remediated and does not yet have an adequate pressure history/MIT.
2	Some discrepancy in the pressure history curves.
1	No known problems with pressure trending analysis, or under nitrogen/MIT.

Annular pressure is considered as a sub-component of the pressure history. Annular pressure represents pressure in the cemented annular spaces between the concentric well casing installations. The presence and response of annular pressure to changing cavern pressures provides information included in the well grading process. Annular pressure is treated as a sub-component of the cavern pressure history grade component as follows:

$$\max\left[cav\ press\ grade,\ (ann\ press\ grade\ when > 3)\right]$$

Effectively, the final pressure grade component is only driven by the cavern pressure, unless the annular pressure grade is greater than 3; when the annular pressure grade is greater than 3, then the final pressure grade is taken as the maximum of the cavern and annular pressure grades. The annular pressure grades are determined using the criteria shown in Table 3-2.

Table 3-2. Annular pressure grading conditions.

Grade	Condition
5	Annulus pressure similar in magnitude and time response to the wellbore pressure.
4	Annulus pressure less than the wellbore pressure. The annulus pressure responds ‘similarly’ to changes in the wellbore pressure.
3	A large pressure (100’s of psi) is present in the annulus but it does not respond to changes in the wellbore pressure. OR well has been remediated and does not yet have an adequate pressure history for a determinate grade.
2	A small positive pressure (smaller than 100 psi) is present in the annulus but it does not respond to changes in the wellbore pressure.
1	No positive pressure in the cemented annulus

3.3. Geomechanics Component

Currently, because of the differing site details and model implementations, the geomechanics grading component is assigned based on the expert opinion of the geomechanics modelers. The grades for each site are determined by the modeler for that site based on their most recent simulation results. All geomechanics grade values are integers between 1 and 5 with 5 indicating highest level of concern.

3.4. Geology Component

The geology component of the well grading criteria encompasses those aspects of the site geology which may affect cavern well integrity. This well grading component is composed of several sub-components. These include aspects such as subsidence, salt spines, and caprock concerns. Because the geologic concerns related to well integrity at the SPR sites are diverse and complex, a set of fixed grade-mapping rules was not developed. Instead, the expert opinion of SPR project geologists was used to assign a 1 – 5 grade to the geology grade sub-components. These sub-components were then equally weighted to obtain the final geology grade which was incorporated into the final site grade for each well.

Table 3-3 lists the sub-components of the geology grading component and a brief explanation of its inclusion. Additional details regarding these sub-components can be found in [1].

Table 3-3. Sub-components of geology grading component.

Sub-Component	Explanation
Salt Fall Count	Relative number of salt falls in the associated cavern
Spine/Fault Distance	Relative distance to nearest fault or salt spine boundary
Uplift/Subsidence	Relative amount of uplift or subsidence in area of well
Salt Overhang	Relative proximity to overhanging salt margin
Caprock Issues	Relative significance of any caprock issues impacting well integrity

3.5. Composite Well Information Component

The composite well information component of the well grading system is composed of the seven sub-components listed in Table 3-4. These sub-components are combined using equal weighting averaging into the final composite well information component. These sub-components use relative or deterministic grading criteria as described in [1].

Table 3-4. Sub-components of composite well information component.

Sub-Component	Explanation
Age	Time since initial well installation or well remediation
Gas Regain	Relative rate of gas accumulation in the well casing
Fluid in Cement Annulus	Relative amount of fluid in the cemented annulus
Well Deviation	Relative deviation of the well bore from true vertical
Leak History	Any substantiated leak history
Well Pair History	Accounts for events or leaks for wells in close proximity
MAC Age	Time since last multi-arm caliper survey

3.6. Cavern Geometry Component

The cavern geometry well grading component relates those aspects of the cavern's shape, spatial location within the salt dome, and relative location to adjacent caverns which have an impact on cavern well integrity. The sub-components of this term are associated with cavern stability which has a direct impact on well integrity. Table 3-5 lists the sub-components of this grading component; details regarding these sub-components can be found in [1].

Table 3-5. Sub-components of cavern geometry component.

Sub-Component	Explanation
Shape	Relative term for cavern deviation from ideal shape
Pillar-to-Diameter	Term capturing proximity of adjacent caverns relative to cavern size
Salt Roof Thickness	Relative term relating thickness of salt above cavern roof

3.7. Offsite Activities Component

The offsite activities component of the well grading system captures any non-SPR activities which can affect SPR cavern well integrity. The most common offsite activity impacting SPR well integrity is the injection or extraction of subsurface fluids, but this component is not limited to only those concerns. This component is given a relative ranking ranging from 1 to 5 depending on the interpreted potential impact of the offsite activity based on best available information.

4. IMPLEMENTATION OF THE WELL GRADING PROCESS

The goal of the SPR cavern access well grading process is to provide guidance on the relative priority of each well with respect to its need for remediation and enhanced monitoring. This is done by assigning each well a numeric grade ranging from 1 to 5; a value of 1 indicating the lowest need for remediation and/or enhanced monitoring and 5 indicating the greatest need. In rare cases, where there is extreme casing deformation and immediate pressure concerns, a well can be given a grade of 6.

The 1 through 5 grading scheme is implemented using an Excel workbook framework. This framework was chosen because:

1. It is based on a widely available software platform
2. It allows for the inclusion of self-documenting features
3. It provides necessary data structures
4. It has internal computational capabilities
5. It is user friendly and familiar to most scientists and engineers

The grading framework is represented by a single workbook for each of the four SPR sites; each workbook is identical in its functionality, but only includes wells for that specific site. Each workbook contains 10 individual tabs or spreadsheets. The names and purpose of each tab is listed in Table 4-1.

Table 4-1. Name and purpose of tabs in grading workbooks

Tab Name	Purpose
Revisions	Records revisions to grading data by date and person
Final Grades	Contains status flag, final remediation and monitoring grades and values of individual grading components
Mac	Holds MAC grade component as computed in separate MAC workbook
Pressure	Holds separate cavern pressure and annular pressure grades and combines these for the final pressure grade
Well	Holds age, gas regain rate and other well specific information
Geomech	Records the grades determined from geomechanical modeling
Geology	Contains relevant information on salt falls, salt, and caprock characteristics
Cavern Geometry	Holds grades reflecting cavern shape, spacing, and depth
Offsite Act.	Allows for inclusion of impacts from off-site activities
CavGeom Detail	Contains details used for calculations on the Cavern Geometry tab

Each individual grading component worksheet may have a number of sub-components. Typically, these sub-components are combined via a weighting function to derive a final component grade which is then used on the "Final Grades" tab to compute the final remediation and monitoring grades.

For most of the grading components, everything is computed and recorded in the site-specific workbook. The one exception is the MAC grade. Because the MAC grade is computed from a series of complex calculations involving a very large data set, these grades are determined in a separate workbook and then transferred to the well grading workbooks. The MAC workbooks are fairly complex and are typically tens of megabytes in size. They contain various values computed from the original MAC radial arm data, various graphs, and computations of the MAC grade component. Because of the complexity and integral nature of this workbook, the details of its functionality and data content are described in the following section.

4.1. MAC grading workbook

The multi-arm caliper logs collected from the SPR wells provide fundamental information regarding the status of the inner-most casing string. These are direct measurements of the inside geometry of the casing and show where the casing may be experiencing deformation due to geologic forces. The data from MAC logs is received as raw Log ASCII Standard (LAS) files. The current vertical sampling interval for these logs is nominally 0.025' and with 60 to 80 individual radial measurements over a 2000' length of casing, these files can be fairly large. To aid and automate the processing of these files a Python script is used to read the LAS file, compute a series of depth varying values, and record these values along with graphs of the data to an Excel workbook.

Several of the values computed in these workbooks are directly used in computing the MAC grade component used in the well grading, other values are computed for reference or investigative purposes. Details regarding these variables and their use in the analysis of casing deformation can be found in [2]. The parameter values computed by the Python script and included in the MAC workbooks are listed in Table 4-2. All of these values are computed from the raw radial arm data as received in LAS format, the only additional data used is the expected inner diameter of the casing.

Table 4-2. Values computed by Python script and recorded in MAC spreadsheets.

Parameter	Description
XY Center Location	XY of centroid of polygon described by radial values
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
Diameter coefficient of variation	Normalized diameter standard deviation
Diameter Delta	Difference between the maximum and minimum diameters
Max. ID Delta	Largest difference between measured and nominal diameters
Relative wall displacement	Casing wall displacement relative to wall thickness

5. GRADING FRAMEWORK REVISIONS

This section of the report describes the details of the revisions to the SPR well grading framework. This includes changes to the main grading workbooks as well as revisions to the MAC workbooks. This discussion is intended to document these revisions as an aid in using the grading framework.

5.1. Revisions to the Site-Specific Well Grade Workbooks

These revisions were applied to the four site-specific well grade workbooks. The main objectives were to: 1) remove unnecessary complexities, 2) enhance for automated data processing, 3) assure consistency, and 4) clean up and simplify formatting. A listing of the primary revisions is provided below.

1. <u>Removal of unnecessary macros</u>: During the initial creation of the workbooks a series of macros were used to assist in populating new well entries. With all the current SPR wells having entries in the grading workbooks these macros are no longer needed.
2. <u>Changes to Revisions Worksheet</u>: The Revisions worksheet holds an entry for each time the data in the workbook is updated. No changes were needed for the Revisions worksheet.
3. <u>Revisions to the Final Grades worksheet:</u>
    a. Worksheet renamed from "Final_Grades" to "Final Grades".
    b. MAC grade column renamed from "FULL MAC-FINAL" to "MAC".
    c. Renamed "Pressure for Monitoring" column to "Pressure"
    d. Renamed "MAC for Monitoring" column to "MAC"
    e. Applied conditional formatting to final remediation grade column to highlight high remediation grades.
    f. General cleanup of formatting.
4. <u>Revisions to MAC grades worksheet:</u>
    a. Renamed worksheet from "Full MAC Only" to "Mac". This change is related to a realignment of the view of the MAC data and potential casing deformation. The initial version of the MAC grade worksheet only considered the depth area around the salt-caprock interface for the Remediation MAC grade component and the entire casing length for the Monitoring MAC grade component. Experience has shown that is not an appropriate approach and that the entire casing length should be considered in both grading components and this name change reflects this.
    b. Consistent with 4.a above, extraneous text and columns were removed to reflect the fact that only the full casing length is now considered in the MAC grade component.
    c. Removal of M&O contractor grade component. When the grading framework was initially developed there was an effort to include the Management and Operations (M&O) contractor's well grading into the MAC grade component.

Over the years it has been recognized that this is not appropriate as this grade is not directly comparable to the other values in the grading framework and so the M&O contractor grade has been removed from the grading workbook.

   d. Updates to worksheets referencing the Mac grade spreadsheet.

5. Revisions to Pressure grades worksheet:

   a. Changes were made to simplify columns to reflect direct consideration of annular space pressure issues and assure consistency. During the evolution of the site well grading workbooks the consideration of annular space pressure was implemented in differing formats; the computations were consistent, but the implementation differed. A single format was applied to all of the workbooks.

6. Revisions to Well information worksheet:

   a. Changed the FLUIDANU column so that it automatically pulls the annular pressure grade from the Pressure worksheet; previously this value was entered manually.

   b. Updated the formula in the Remediated Age column so that it only generates values for wells that have been remediated.

   c. Changed formula in Effective Age column to be consistent with changes in Remediated Age column.

   d. General cleanup of formatting.

7. Revisions to Geomech information worksheet:

   a. This worksheet holds grade values which are populated by the geomechanical modeling personnel based on their expert opinion. Only minor formatting changes to gain more consistency were applied to this worksheet.

8. Revisions to Geology grades worksheet:

   a. Dropped the subsurface temperature considerations from the Bryan Mound grading workbook to make it consistent with the other sites. Although the Bryan Mound site does have elevated subsurface temperature due to historic liquid injection sulfur mining, this is unique to this site. The consideration of temperature was dropped to enhance consistency with the other sites. The information for this term is retained in historic copies of the grading workbook if it is needed in the future.

   b. Other minor changes to enhance consistency.

9. Revisions to Cavern Geometry information worksheet:

   a. Removal of unused columns.

   b. Addition of SHOEDIA column to the Big Hill site grading workbook to be consistent with the other site workbooks.

10. Removal of Offsite Activities worksheet:

   a. The original grading workbook contained a worksheet that represented any offsite activities that could impact SPR well integrity. The only driver for this was a suspicion that offsite injection into the caprock at the Big Hill site may impact subsidence and have some impact on the Big Hill wells. Since the original framework was developed the concern of the offsite injection with respect to well integrity has diminished. In addition, information about the injection activities and how they may impact individual wells is difficult to quantify with any certainty. For these reasons, and to add consistency across the individual site grading workbooks, this term has been dropped. This was one of the weighted components used in computing the Monitoring Grade; the weight from this component has been shifted over to the Geology component raising its weight from 0.1 to 0.15.

11. Revisions to the CavGeom Detail worksheet:
    a. This worksheet contains detail information about each cavern's geometry. These parameters are used in calculations performed on the Cavern Geometry worksheet. The only revision done was to add this worksheet to the Big Hill workbook as it was missing from the original version.

The above revisions were applied to the current copes of the grading workbooks and saved as new copies. The grading values themselves were not updated in this process except for those cases where a given grading element was dropped from consideration.

5.2. Revisions to the MAC Grading Workbook

As discussed in Section 4.1, a separate workbook is generated from the LAS MAC data. This workbook handles the computing of the MAC component of the well grade. This process is kept separate from the main grading spreadsheets to reduce their size and complexity.

An individual MAC grade workbook is generated for each MAC survey performed on any of the SPR cavern access wells; therefore, each well can have multiple MAC grade workbooks. Each workbook is identified uniquely by the well name and date of the MAC survey.

In addition to computing the MAC component of the well grade, the MAC grade workbooks also provide a means to examine the MAC data in detail and to compare the current MAC data to previous surveys. This gives a mechanism to determine if there is any increase in casing deformation. The process of computing summary variables from the LAS files, generating comparative graphs, and computing the MAC component grade is time consuming and a process that lends itself well to automation. During the early stages of the well grading process a Python script was developed to automate this process. As our examination of the MAC data has matured, it has become evident that this process can be improved even more. The following discussion covers improvements to this process. Although these revisions manifest themselves as changes in the resulting workbook, most of the revisions actually involve changes to the Python script which generate the workbooks.

5.2.1. SMACLAST

The initial version of the Python script used to generate the MAC grading workbooks was named SMACLAST_v1 for Sandia Multi-Arm Caliper Log Analysis Tool version 1. This initial version of the script read the MAC LAS file, computed the variables listed in Table 4-2, generated graphs of several of the variables, computed the MAC grading component, and recorded this information to an Excel workbook. This functionality was adequate during the initial period of MAC survey collection. But as multiple MAC surveys started to be collected through time, comparing these earlier surveys to the current MAC became necessary and the existing code was not designed with this in mind. Instead, a manual process of accessing the previous MAC workbooks was necessary. This process is cumbersome and time consuming. Therefore, a new version of the SMACLAST software was developed to overcome these shortcomings. This new version will be referred to as SMACLAST_v2 for version 2 of the code. It uses the original SMACLAST code as its starting point but add additional modules to meet the required functionality. In addition, some minor reformulation of the existing code was implemented for improved efficiency.

To confirm that there are no significant differences in the computed values between the two versions of the code a comparison between the computed values was made for a randomly selected MAC survey. The results from the comparison showed that all the computed variables had a difference of less than 10^{-10} percent when compared against the newer version of the code and most were identical within the computational accuracy of Excel. This provides confidence that the two versions of the code are generating comparable values and that values from the new code can be compared against the prior code.

5.2.1.1. SMACLAST v1 workflow

To better understand the differences between SMACLAST version 1 and version 2, it is helpful to first present the operational workflow of version 1. SMACLAST uses a simple graphical user interface (GUI) during operation. The general workflow of version 1 is shown in Figure 5-1. After starting the script in a Python interpreter, the user is presented with the main window as shown in Figure 5-2. This window allows the user to designate if the MAC LAS data represent radius (most common) or diameter (very rare) measurement values. The next step is to click the appropriate button indicating whether a single LAS file or multiple LAS files will be processed during this session. The multiple LAS file selection requires a separate listing of the files to process and is rarely used in practice. To exit SMACLAST the Quit button can be used.

Assuming one clicks the Single LAS File button, then the workflow proceeds as shown in Figure 5-1. The first step presents a file selection window as shown in Figure 5-3. The initial file selection is filtered to only show LAS file extensions. After the MAC LAS file is selected, the code reads in the entire file and presents a listing of the individual curve values contained in the file as shown in Figure 5-4. The individual curve values represent the different measurements or computed values held in the LAS file; there is a measurement value for each of these for each depth interval listed in the file. This selection window allows the user to select which curves represent the radial arm measurement curves; only the radial arm measurement curves should be selected at this time. The user can use the Shift key to select contiguous sections of the curve listing. In the example Figure 5-4, the radial arm curves are those that start with 'R' and are followed by a sequential number. Following the section of the radial arm curves, the user is presented with a similar window which allows for the selection of the depth curve (Figure 5-5). Manual selection of the depth curve is needed due to rare occurrences when the depth curve naming convention is not adhered to in the LAS file. After selection of the depth curve, the code proceeds with the processing of the radial arm data.

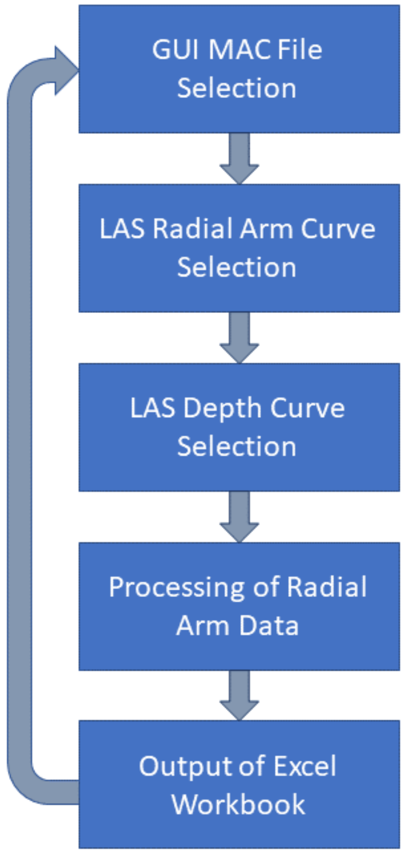

Figure 5-1. General workflow for Version 1 of SMACLAST.

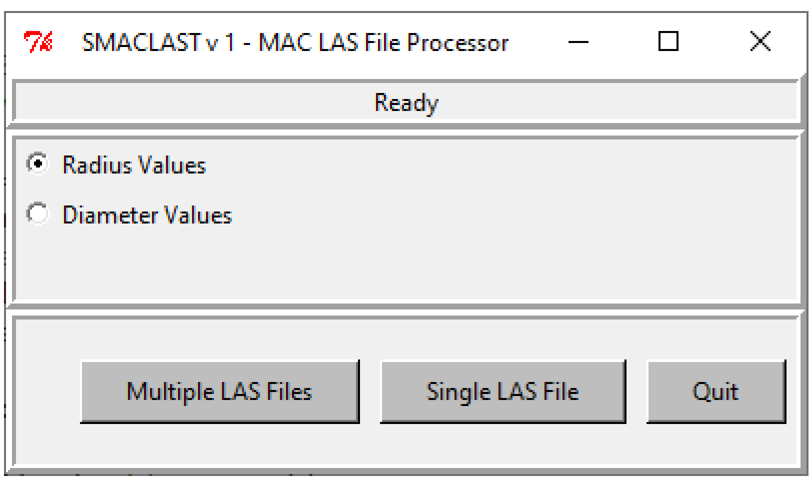

Figure 5-2. Main SMACLAST version 1 window.

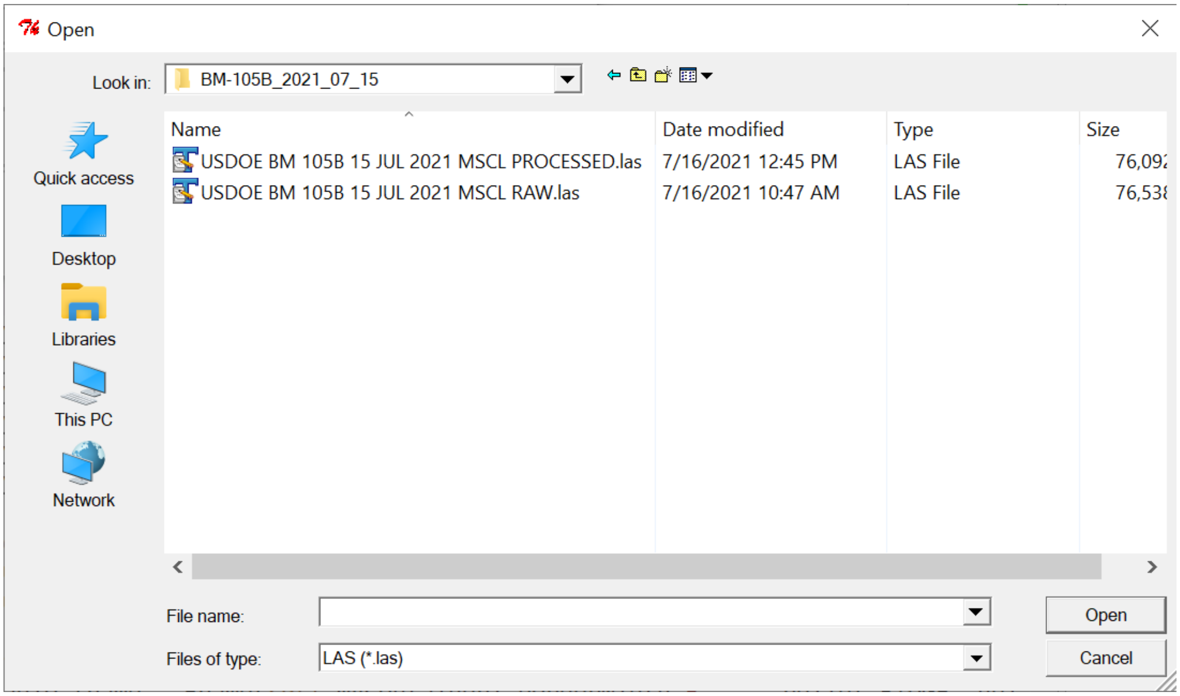

Figure 5-3. SMACLAST file selection window.

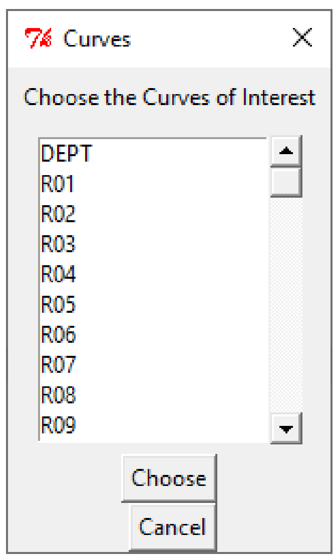

Figure 5-4. Listing of curve values from the MAC LAS file.

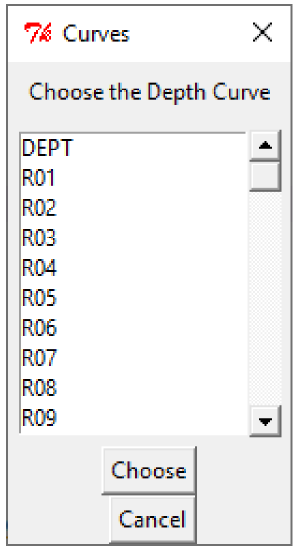

Figure 5-5. Depth curve selection window.

The processing of the radial arm data consists of the computation of the variables listed in Table 4-2, generation of graphs of several of the variables, computation of the MAC grading component, and writing all this information to an Excel workbook. The final step in the workflow is the output of the final Excel workbook. This workbook consists of six individual tabs or worksheets. The names of these worksheets and their purpose are listed in Table 5-1.

Table 5-1. Worksheets contained in the MAC grading workbook.

Worksheet Name	Purpose
Data	Contains the computed summary values for each depth station
Graph	Location for graphs of summary values
Casing	Holds a graph of the mean casing diameter with depth. Used to assess the actual installed casing sizes. A median filter is applied to diameter data to remove spikes caused by collar connections. Also compares measured diameter to diameter listed in Scalers worksheet.
Scalers	Contains scaler values used for various computations in the workbook.
Metadata	Records information regarding the processing of the MAC LAS data including the input file, processing date, curves used, and number of radial arms curves.
Grading	Holds graphs and data columns used in computing the MAC grading component. The two components used in this grading are the diameter coefficient of variation and the relative wall displacement (Table 4-2). A median filter is applied to these data to remove spikes caused by casing collars. Manual inspection of the data is also necessary to remove any other casing features that do not represent deformation, this would include float collars or similar features that can impact the MAC grade.

After creation of the MAC analysis workbook using SMACLAST, analysis of the MAC data would proceed to a manual phase where the summary variables in the workbook are used to determine if the well casing is experiencing deformation. Typically, this manual analysis would involve manually setting several of the scaler values, creating comparative graphs using data from a previous MAC survey, and filtering the MAC grading worksheet to remove features not related to casing deformation. These steps can be time consuming. The automation and enhancement of these steps are what are represented by the revisions leading to SMACLAST version 2.

5.2.1.2. SMACLAST v2 revisions and workflow

This section covers the revisions to SMACLAST and the new workflow resulting from these revisions. Enhancing the automation of SMACLAST has significantly increased the efficiency of the MAC data analysis but does require an additional data file with associated maintenance.

This additional data file is an index of well and MAC history for each well at each site. This data is implemented as four Excel workbooks, one for each site. The workbooks contain an index worksheet which lists each well at that site, its depth to the top of the salt, and the depth to the top of caprock; these values are referenced to the Braden Head Flange and are in feet. The workbooks also have a separate worksheet for each well at the site. These individual well worksheets have an entry for each MAC survey run for that well and list the date of the MAC, when the MAC LAS file was received by SNL, and the expected casing outer diameter for that well. Using these data components, it is possible to automate many of the manual analysis tasks associated with version 1 of the software.

Figure 5-6 shows the new general workflow for version 2 of SMACLAST.

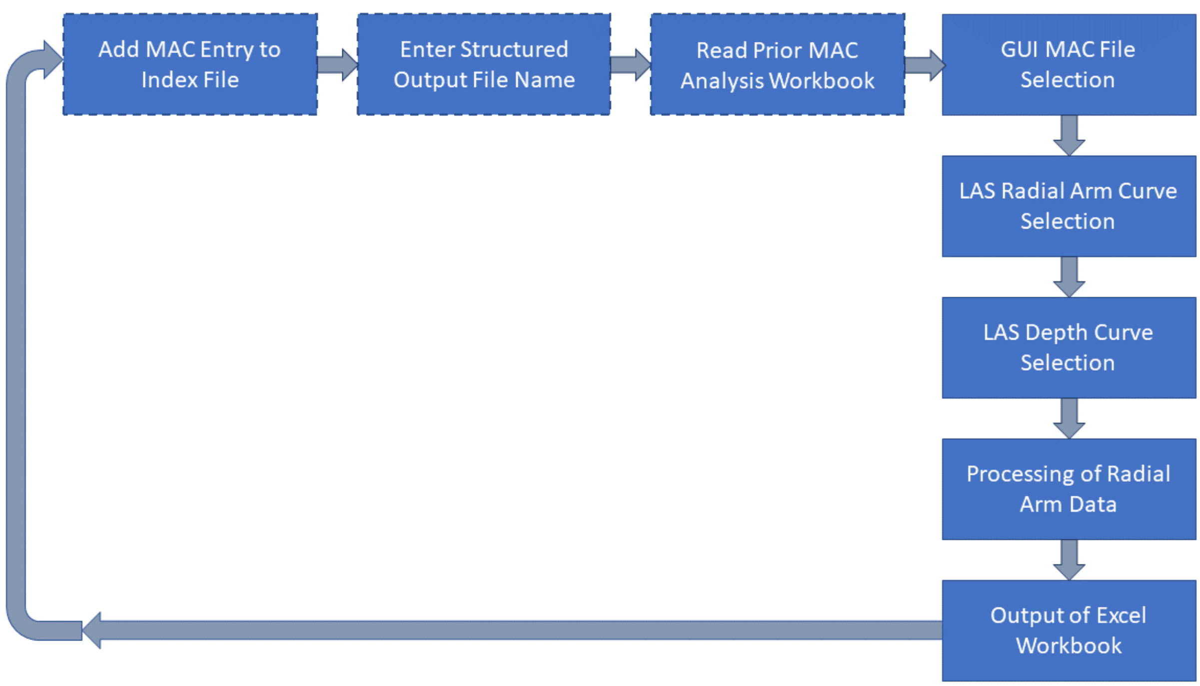

Figure 5-6. General workflow for Version 2 of SMACLAST.

The right-hand side of Figure 5-6 is identical to the workflow for version 1 of the software. The new components are represented by the new workflow boxes with dashed outlines added to the upper left side of the figure. These will be discussed along with other enhancements in the workflow description below.

The first step in processing a MAC file using the workflow for SMACLAST version 2 is to create an entry for the new MAC in the MAC index workbook for that site. This new entry would be made on the worksheet for the well under consideration and would consist of the date of the new MAC, when the MAC LAS file was received at SNL, and the current casing outer diameter (OD) for that well; note that the casing OD may change if a liner is installed in the well. Adding an entry to the MAC index workbook is performed manually outside of the SMACLAST code.

Once the new MAC entry is added to the MAC index workbook, then the SMACLAST version 2 code can be run. The main screen of the version 2 code is shown in Figure 5-7. As shown in this figure, the options for running multiple LAS files has been removed. This was done because this option has not proved to be useful; the underlying code for this option has also been removed from SMACLAST. In addition, there is now a text entry box for the name of the output Excel workbook.

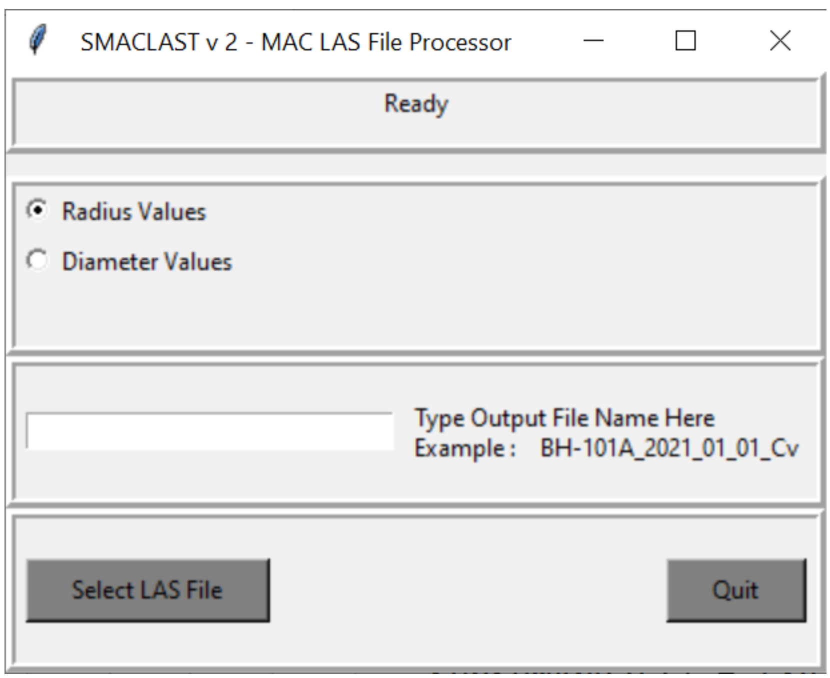

Figure 5-7. Main SMACLAST version 2 window.

The output Excel workbook file name should be entered following the structured naming convention shown in Figure 5-8. In this convention, the red text in Figure 5-8 would be replaced with appropriate information while the black characters would be entered as shown. An example of a valid entry would be "BH-101A_2021_01_01". In version 1 of the code the output file name was automatically generated from information in the LAS file. However, lack of a consistent well naming and date convention in the LAS files led to unpredictable output file names. Note that the well name field can be composed of from 1 to 4 characters. Examples of the expected two-character site abbreviations and well names can be found in the site index files. Using this structured naming convention is a fundamental requirement of the automation in version 2 as it allows for the code to find previous MAC analysis workbooks in an automated fashion. Note that no period or file extension should be entered in the text field.

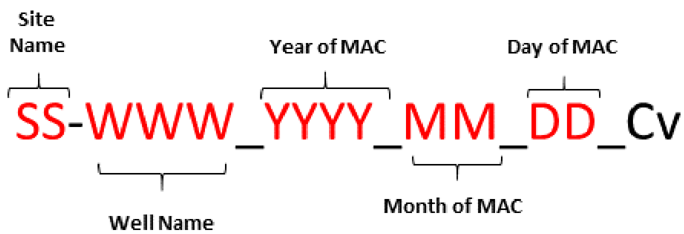

Figure 5-8. Structured naming convention for MAC workbooks.

Once a valid file name is entered, then the user may proceed to click on the Select LAS File button. Clicking on this button will actually perform several tasks before the file selection window is presented, these include reading scalar values from the appropriate site well index workbook and reading in the MAC analysis variables from the previous MAC run on this well if available. This ingestion of prior data may add a slight delay to the appearance of the MAC LAS file selection dialog box.

Once the current MAC LAS file is selected in the file dialog box, then the code proceeds in a fashion similar to version 1 (see section 5.2.1.1) with the selection of radius arm and depth curve names. The revisions that have been discussed so far have been related to automation of the analysis process, primarily focused on reading in previous MAC analysis results, a process that was previously performed manually.

The other revisions to SMACLAST are represented in the output workbook. These appear typically as additional graphs and enhancements to the graphs. Although these revisions are realized in the output workbooks, the implementation of the revisions are in the SMACLAST code that creates the workbooks. These revisions are presented in the listing below.

1. Addition of a prior MAC analysis data worksheet:
    a. One of the primary activities in analyzing the MAC data is to compare against any prior MAC data. The automated addition and population of a worksheet to hold this data increases the efficiency of the process dramatically. This new worksheet is named 'Prior_Data' and holds a select subset of the prior MAC analysis variables.
2. Addition of prior MAC data curves to comparison graphs:
    a. This revision uses the data from the Prior_Data worksheet to add comparison curves to the analysis graphs; previously this was done manually.
3. Addition of data range names:

    a. Named ranges were added to the Data and Prior_Data worksheets to streamline reference to these data columns.
    b. This revision also added named cells to various important cell locations. This will aid in additional automation of the MAC data processing.

4. Addition of a 'Grade Validity' flag:
    a. To automate future extraction of the MAC component grade from the MAC analysis spreadsheets, an indicator that the MAC grade is valid is needed. This would indicate that the MAC analysis variables had been examined for any irregularities that would invalidate the grade value. This flag is initially set to zero and should be changed to a non-zero number once the grading data are validated.
5. Removal of depth zone filter:
    a. A depth zone filter was created in version 1 of the grading worksheet to highlight the area around the salt-caprock interface. The special grade treatment of this zone has been dropped because it was not useful and was somewhat biased, so this filter is no longer needed.
6. Flag maximum values on grading worksheet:
    a. In the grading worksheet, graphs of the diameter coefficient of variation and relative wall displacement variables (see Table 4-2) are used to assist in the manual removal of portions of these data curves which should be excluded from the MAC grading process. These would be sections that have well casing components that cause spikes in these variables, but don't represent casing deformation and so should be excluded from analysis. In this revision, an additional component was added to the graphs that flags locations on the curves representing the top 5% of values. This allows easy identification of these points so they can be examined to determine if they should be filtered.
    b. An additional revision was added to the grading worksheet to color code the top 2% of the values in the data columns contained in this worksheet. This was done using Excel's conditional formatting capabilities and so will dynamically update as values are filtered. The top 2% of data values are shaded with a red background.
7. Addition of graphs highlighting areas of interest:
    a. This revision adds additional graphs to the Graph worksheet. These additional graphs are centered (depth-wise) on particular sections of the casing to allow a more detailed view of these areas. Specifically, these areas are the depth location of the smallest minimum diameter value and the area around the salt-caprock interface.
8. Set appropriate X-axis scaling:
    a. This revision automatically sets the X-axis scaling of the graphs to values most appropriate for the data curves. This is particularly pertinent to the curves showing casing diameter related values.
9. Write computed variable in consistent depth increasing order:
    a. This revision sorts and filters the computed variables (Table 4-2) so that they are written to the Data worksheet in a consistent depth-increasing order. In version 1 of SMACLAST the data and variables were written in the same order as encountered in the LAS file which were sometimes depth-increasing and

sometime depth-decreasing. In addition, often the LAS file would include negative depth values from measurements above the Braden Head Flange; these values are not useful, and this revision filters these values out.

In addition to the specific revisions listed above, the revisions of SMACLAST also included general cleanup, minor refactoring, and additional commenting of the code.

6. APPLICATION OF THE WELL GRADING PROCESS

This section provides a brief explanation of the application of the well grading process and discusses the review frequency of the various well grading components. It does this from the perspective of the revised well grading framework and so does not include those components that were dropped during the revision. The goal is to provide a guide on the process and how frequently this process is typically applied for each grading component.

Figure 6-1 shows a general schematic of the current SPR well grading process. It shows how the multiple grading components are mapped to the two grading dimensions, remediation and monitoring. Each of the grading components and mapping arrows are color-coded as a guide to the frequency of reviews and updates. These frequencies are provided as a general guideline and are not absolute; more or less frequent reviews and updates may be necessary depending on specific circumstances.

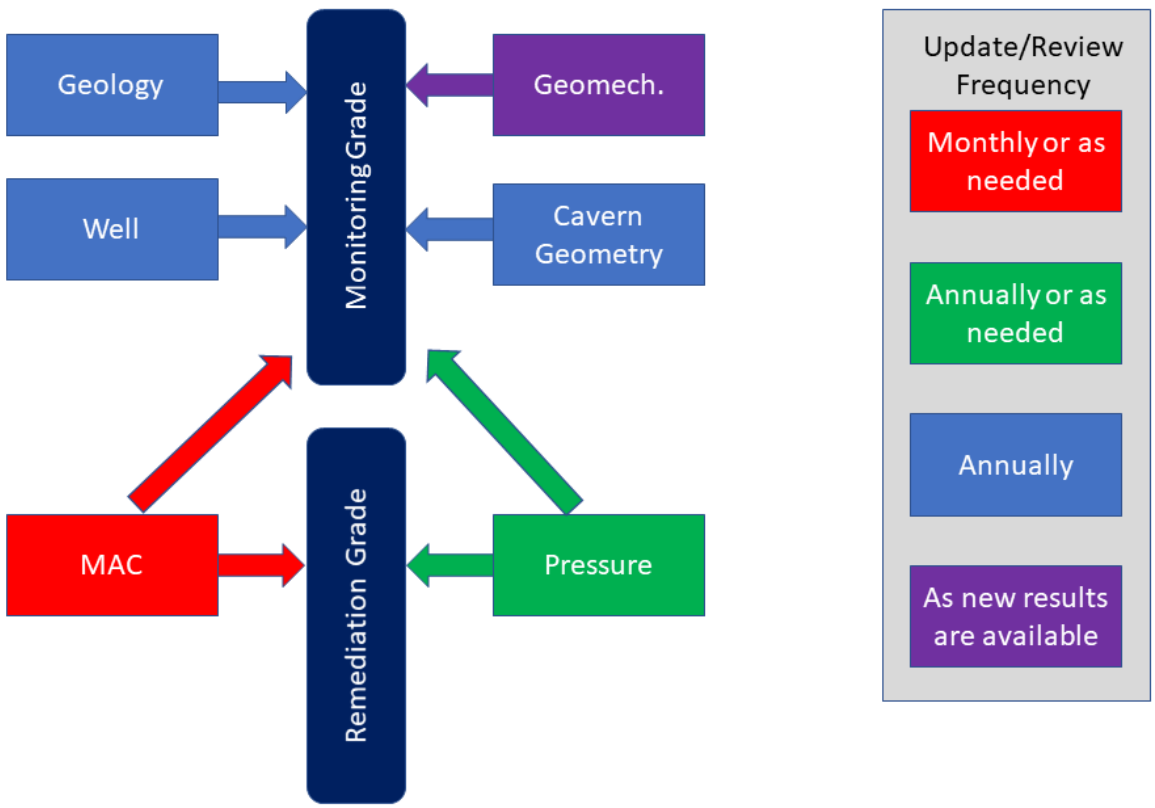

Figure 6-1. Schematic showing guidelines for review and update frequency for the well grading components.

In Figure 6-1, the right-hand side shows the color code key that explains the suggested update and/or review frequency. For many components, such as the Geology component, there is not expected to be significant changes on an annual basis, so for these components an annual review is typically all that is needed. Reviews of this type are just are a quick check to confirm nothing has changed significantly. Conversely, the MAC component is updated more frequently, typically as new data are available. The frequency of new MAC data is highly variable, anywhere from multiple

MACs per week, to every other month depending on the field schedule for MAC acquisitions. Intermediate to these is the pressure component which is typically reviewed annually or as needed. The geomechanical modeling component is a special case in that the grading values are updated typically only as new results are available. The frequency of these types of updates are highly variable but typically no more frequently than every-other year.

For most of the components show in Figure 6-1 the updates are applied directly in the site well grading workbook. The one exception to this is the MAC grade which requires processing outside of the grading workbooks as discussed in Section 5.2 of this report. Updates for this component first require that the MAC analysis workbook be generated, the grading worksheet in the MAC analysis workbook reviewed, and then the MAC grade transferred to the appropriate well grading workbook.

After any individual well grading component is updated, the final Remediation and Monitoring grades are automatically updated on the Final Grades worksheet. After an update has been entered, an appropriate entry to the Revisions worksheet should be added.

7. SUMMARY

This report presented the various components of the SPR well grading framework developed at SNL and the recent revisions applied to those components and the well grading data structure. The final well grades are computed from the individual components using an Excel workbook data structure. Each of the separate grading components are represented by an individual worksheet in the workbook, and each component may be comprised of multiple sub-components. All of these components are combined using a weighted average to devise a well monitoring grade while the remediation grade is determined from the maximum of the MAC and pressure components. All grades range in value from 1 to 5 with 5 representing conditions of greatest concern for well integrity.

The main objectives of the revisions to the grading framework were to: 1) remove unnecessary complexities, 2) enhance for automated data processing, 3) assure consistency, and 4) clean up and simplify formatting. The grading framework revisions were applied to the four individual SPR site grading workbooks to assure grade consistency across all four of the sites. In addition to the revisions of the final grading workbooks, revisions were also made to the separate MAC analysis workbooks that feed into the final grading workbooks. More specifically, since the MAC analysis workbooks are programmatically created using a Python script, the revisions were to the code itself which then manifests itself as changes in the generated workbook output. These changes enhanced the final output as well as increased the efficiency of the MAC analysis process. These revisions also slightly changed the overall workflow for the MAC analysis processing.

Finally, the report presents the general application of the well grading process and the typical update/review frequency of the individual components. This is provided as documentation to assist in the application of the SPR well grading framework.

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[2] Roberts, Barry L, 2015, Analysis of Multi-Arm Caliper Data for the U.S. Strategic Petroleum Reserve, SAND2015-2212, Sandia National Laboratories, Albuquerque, New Mexico.

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