BW - ______35________

Cavern Characterization Plan

2017

Chavez, Carl J, EMNRD

From: danny@pwllc.net
Sent: Monday, March 6, 2017 8:01 AM
To: Chavez, Carl J, EMNRD
Cc: Marvin Burrows; Bill Prichard
Subject: Discharge Permit BW-35 Cavern Characterization Plan Submittal
Attachments: Siringo Cavern Characterization with Cover Letter 0306117.pdf

Carl,
Attached is Llano Disposal, LLC's Cavern Characterization Plan submittal for the Siringo ACS State BW #1 (30-025-30701). If you have any questions or need additional information, please let me know.
Thank you,

Danny J. Holcomb
Pueblo West, LLC
Cell: 806-471-5628
Email: danny@pwllc.net

Pueblo West, LLC
6900 Spring Cherry Lane
Amarillo, Texas 79124

March 6, 2017

New Mexico Oil Conservation Division
Environmental Bureau
1220 South St. Francis Drive
Santa Fe, New Mexico 87505
Attn: Mr. Carl Chavez

Re: Discharge Plan Permit (BW-35)
Llano Disposal, LLC
UIC Class III Brine Well - Siringo ACS State BW #1 (30-025-30701)
UL 'D', Sec 26, T17S, R36E, 660 FNL x 660 FWL, Lea County, New Mexico

Dear Mr. Chavez,

Per Discharge Permit BW-35 approval conditions dated September 8, 2016, Llano Disposal, LLC is required to submit the following plans to the NMOCD Environmental Bureau within 180 days:

- Surface Subsidence Monitoring Plan
- Solution Cavern Characterization Plan

Llano submitted the proposed surface subsidence monitoring plan in the original discharge permit application dated April 28, 2016. Please see pages 18 – 19 and Attachment 'P'. The survey monument contractor is currently preparing to start installation of the three monuments and wellhead survey point.

Attached, Llano hereby submits our proposed solution cavern characterization plan. This plan demonstrates that a 280 foot diameter salt solution cavern at the referenced well exceeds the NMOCD's safety factor guidelines for a stable cavern roof structure.

Since the time of discharge permit approval last September, Llano has been working to recomplete the well and build the surface facilities. Llano anticipates the well and facilities should be ready for first production during the 2nd quarter of 2017.

If you need any additional information concerning either the surface subsidence monitoring plan or the attached solution cavern characterization plan, please let us know. Thank you in advance for your consideration.

Sincerely,

Danny J. Holcomb
Pueblo West, LLC
Agent for Llano Disposal, LLC
Cell: 806-471-5628
Email: danny@pwllc.net

Attachments

Llano Disposal, LLC
Siringo ACS State #1
API # 30-025-30701
Solution Cavern Characterization Plan

This plan characterizes the size and shape of the proposed solution cavern at the referenced well using geophysical methods approved by the OCD.

1. Well Configuration and Lithology

The Siringo ACS State BW #1 (API # 30-025-30701) is located at 660 FNL x 660 FWL, Unit Letter D, Section 26, T17S, R36E, Lea County, New Mexico. Exhibit 1 illustrates the final well completion and the well lithology. The well has two casing strings with the smallest casing string shoe at 2043'. A dual-string packer will be set at ~1993' with 3-1/2" steel IPC production tubing to surface. Fresh water will be pumped down the tubing-casing annulus, through an open port in the packer and then through approximately 400' of fiberglass tailpipe below the packer. Fresh water will enter the salt formation at a depth of approximately 2393' which is 350 feet below the smallest casing shoe. The solution cavern will be allowed to grow from the bottom up, creating an inverted conical cavern. See proposed cavern conceptual shape in Exhibit 2. Insolubles embedded within the salt will drop to the bottom of the cavern. Cavern development will be controlled by the depth of injection tubing and by varying the flow rates through the initial, development and production process stages.

Below is a summary of formation lithology based on drilling records and Llano's experience while drilling out cement plugs and testing (circulating) the well:

Lithology	Depth
Surface Fill	0-40'
Water Zone	50-70'
Red Beds/Anhydrite	40-1040'
Red Beds/Anhydrite/Salt	1040-1330'
Red Beds/Anhydrite	1330-1547'
Anhydrite	1547-2043'
Salt	2043-3034'
Salt/Anhydrite	3034-3500'
Anhydrite/Dolomite	3500-3651'

E-W and N-S cross-sections diagrams are included in Exhibits 3a and 3b. They demonstrate that lithology is relatively consistent across the area of review. The lithology at the Siringo ACS State BW #1 provides for approximately 496 feet of anhydrite overlying the anticipated solution cavern area.

2. Cavern Roof Stability Calculations Using Cantilever Beam Theory

Llano developed a steady state model to calculate the maximum safe cavern diameter based on ultimate stresses developed in a cantilever beam that is uniformly loaded. A minimum safety factor of 2.0 was utilized. The maximum compressive, tensional and shear stress can be assessed using general flexure bending formulas. Similar studies conducted by organizations such as DOE (WIPP) and the National Labs have determined that the uniformly loaded cantilever beam method is the most conservative approach to determine salt cavern roof stability.

Formulas:

$\sigma = My/I$ Maximum flexure stress at the outer most fibers of the beam, which are in compression and tension.

$\tau = VQ/It$ Maximum transverse shear stress, generally found near the supported end of the beam.

Definitions of Stress Elements and Units:

M = moment (foot-lbs)
I = second moment of inertia beam (inch^4)
y = distance from the center of the beam to the outer fibers (inches)
V = shear on beam, connection end (lbs)
Q = first moment of beam, end view, center axis (inches)
t = thickness (width) of the beam (inches)

Model Assumptions:

1 - The beam is considered a stiff anhydrite material of homogenous and isotropic properties. Since compressive strength properties of anhydrite are substantially larger than the tensile strength, tensional properties are utilized for the most conservative results.
2 – The cantilever beam theory assumes the highest stress occurs near the supported end of the beam.
3 – Slippage due to shearing between layers within the anhydrite beds is discounted and therefore, not considered.
4 – Physical properties of anhydrite were obtained from various sources. Average figures for these properties are utilized.
5 – The beam was selected to be a rectangle with a width of 12 inches to allow for uniform loading. The length and height (i.e. thickness) are variable inputs.
6 – The density of the overburden rocks and soil were set at 156.1 lbs/ft^3.[i]
7 – A general rule of thumb states that the maximum shear stresses are estimated as one half of the difference between the maximum and minimum normal stresses$(\sigma\,\max - \sigma\min)/2$. Since the ultimate tensile strength of anhydrite is used as the limiting property, the maximum shear force would be one-half of the normal stresses.[ii]
8 – The total lifetime brine production estimate was calculated based on cylinder volume then reduced by 25% to compensate for insolubles within the salt formation.
9 – Ultimate tensile strength for anhydrite was determined to be 8 Mpa or 1160 psi.[iii]
10 – The cantilever beam uniformly loaded approach presents a very simple and friendly method of modeling the stresses. However, this method can cause some error in the

calculations. The outer fibers of the anhydrite are in pure bending under tension and the shear forces are zero.

The model equations include the counter hydrostatic forces generated by the well bore hydrostatic head on the cavern formation. These forces actually push upward and help support the roof beam. The model outputs provide stress calculations on the beam with and without these hydrostatic forces.

See Exhibit 4 for a summary of the model inputs and outputs. See Exhibit 5 for an explanation of the stress equations utilized within the model.

Model Inputs (Best Case):

1) Beam length in feet (i.e. radius of cavern) – 140 feet (found to be the largest allowable radius).

2) Beam width was kept constant at 12 inches

3) Beam height (thickness of the anhydrite layer) – 496 feet

4) Depth of the overburden (i.e. depth of the casing shoe/top of salt) – 2043 feet

5) Thickness of the salt production zone – 991 feet

Model Output Results:

1) Maximum tensional stress on the beam when the cavern pressure is maintained. A maximum allowable tensile stress of 1160 psi was utilized. Any output number above this threshold would be considered unsafe. Model results were 275 psi for inputs referenced above.

2) Maximum tensional stress on the beam when the cavern pressure is not maintained. A maximum allowable tensile stress of 1160 psi was utilized. Any output number above this threshold would be considered unsafe. Model results were 529 psi for inputs referenced above.

3) Ratio of cavern diameter/depth of casing shoe. An allowable threshold of <0.5 has been established by the NMOCD Environmental Bureau. Any output number above this threshold would be considered unsafe. Model results were 0.14 for inputs referenced above.

4) Bending safety factor when the cavern pressure is maintained. A threshold of > 2.0 was utilized. Any output number below this threshold would be considered unsafe. Model results were 4.2 safety factor for inputs referenced above.

5) Bending safety factor when the cavern pressure is <u>not</u> maintained. A threshold of > 2.0 was utilized. Any output number below this threshold would be considered unsafe. Results were 2.2 safety factor for inputs referenced above.

6) Shear safety factor when the cavern pressure is maintained. A threshold of > 2.0 was utilized. Any output number below this threshold would be considered unsafe. Model results were 5.2 safety factor for inputs referenced above.

7) Bending safety factor when the cavern pressure is <u>not</u> maintained. A threshold of > 2.0 was utilized. Any output number below this threshold would be considered unsafe. Model results were 2.7 safety factor for inputs referenced above.

8) Estimated brine production volume over the life of the brine well was calculated. This estimate was conservatively calculated based on 75% of the cylinder volume. Model results were 13.2 million barrels.

9) Maximum surface static or test pressure on the cavern. Maximum allowable pressure was 300 psig.

10) Maximum cavern diameter. Model results were 280 feet.

Based on the optimum model results, the safe cavern design for this solution mined salt cavern was 280 feet maximum diameter.

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[i] Physical Properties of Salt, Anhydrite, and Gypsum – Preliminary Report by Eugene C. Robertson, Richard A. Robie, Kenneth G. Books, August, 1958, US Geological Survey.

[ii] Formulas for Stress and Strain by Raymond J. Roark, Third Edition, McGraw-Hill Book Company, Inc.

[iii] Applied Salt-Rock Mechanics 1 by C. A. Baar Copyright 1977, Elsevier Scientific Publishing Company.

WELLBORE DIAGRAM AND LITHOLOGY

Configured for Brine Source Well

Llano Disposal, LLC
Siringo ACS State BW #1
API # 30-025-30701
660' FNL x 660' FWL, UL 'D', Sec 26, T17S, R36E, Lea County, NM

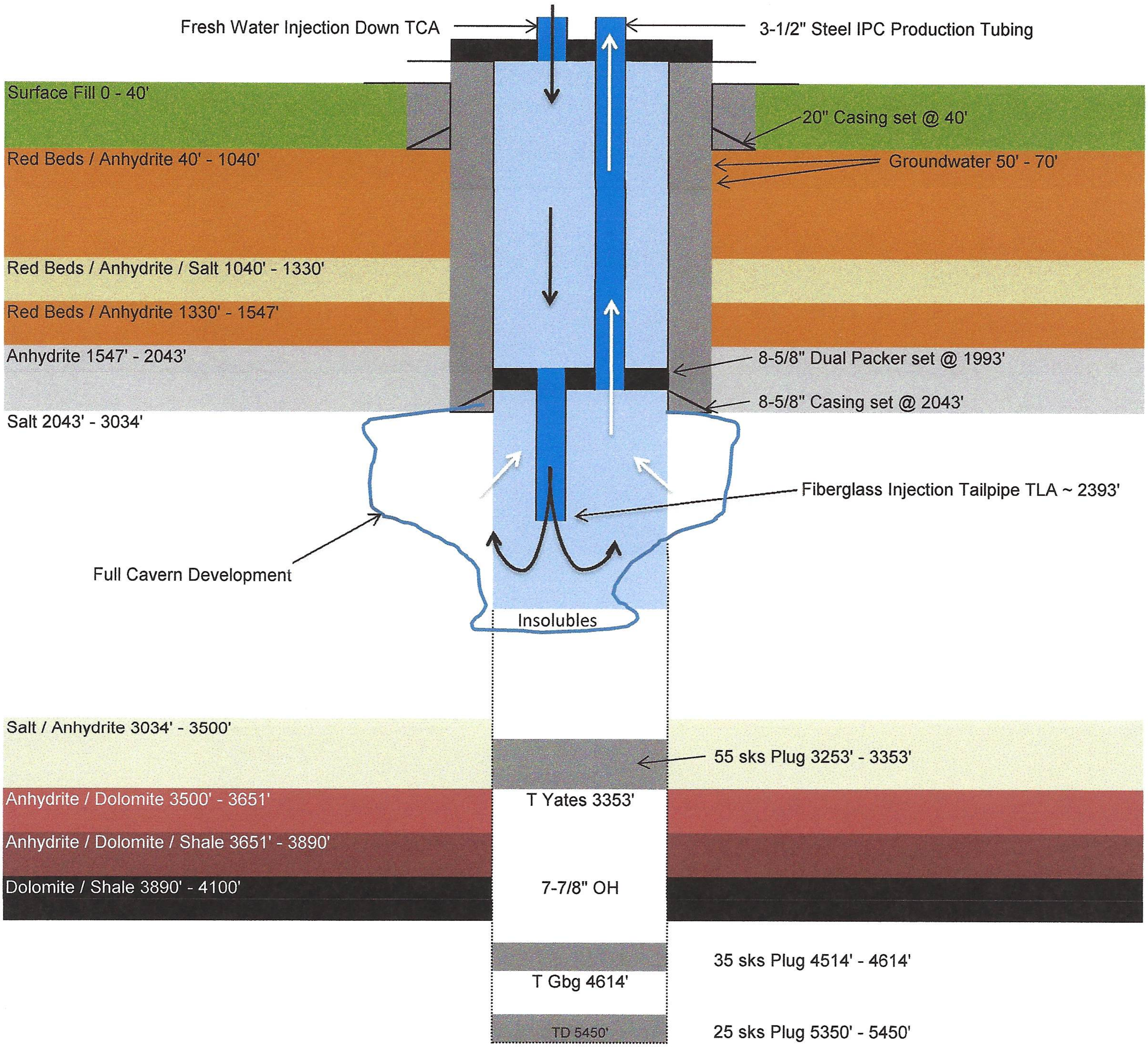
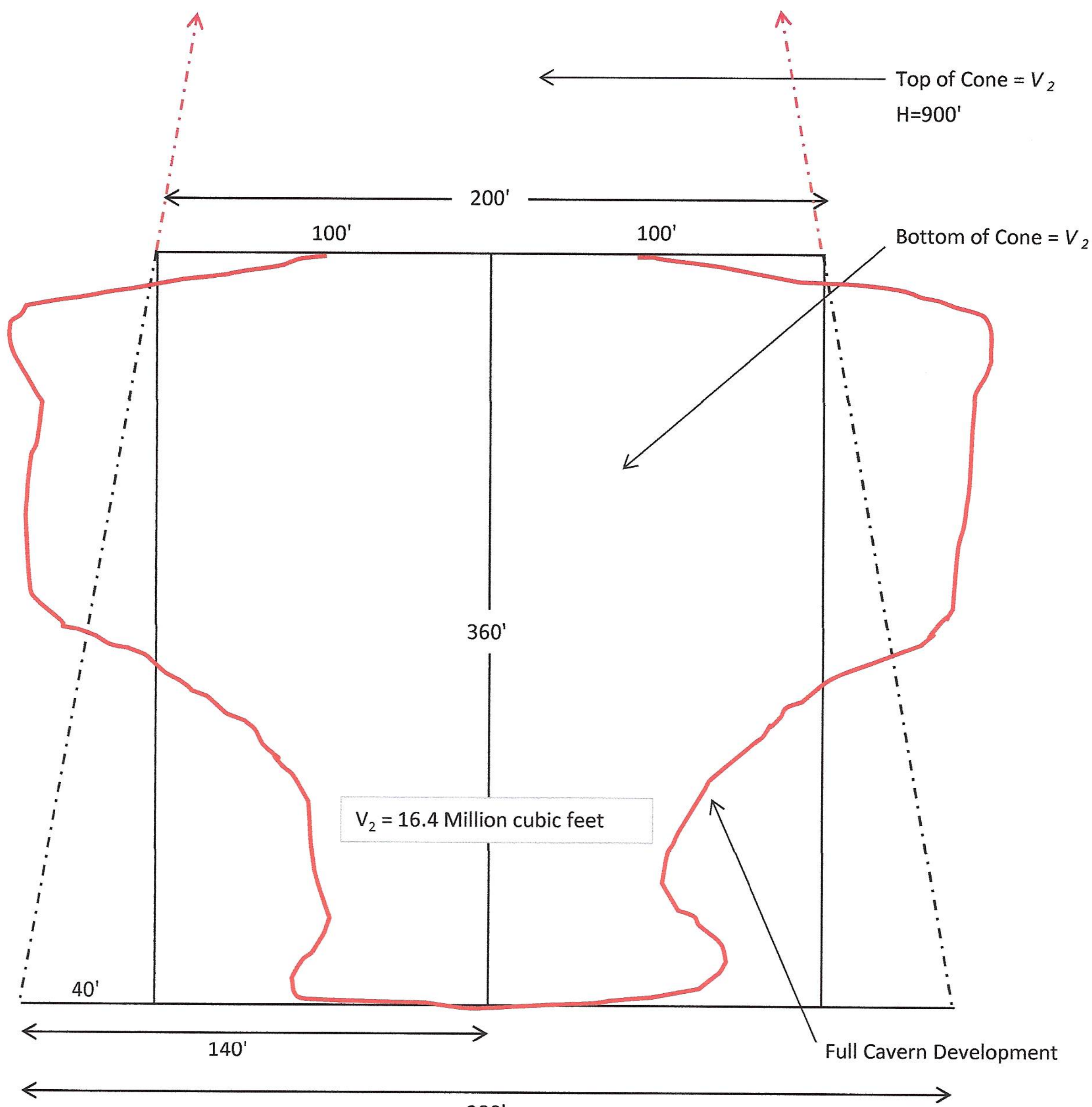


Exhibit 1
Drawing Not to Scale

Siringo ACS State BW #1
Cavern Volume Calculation

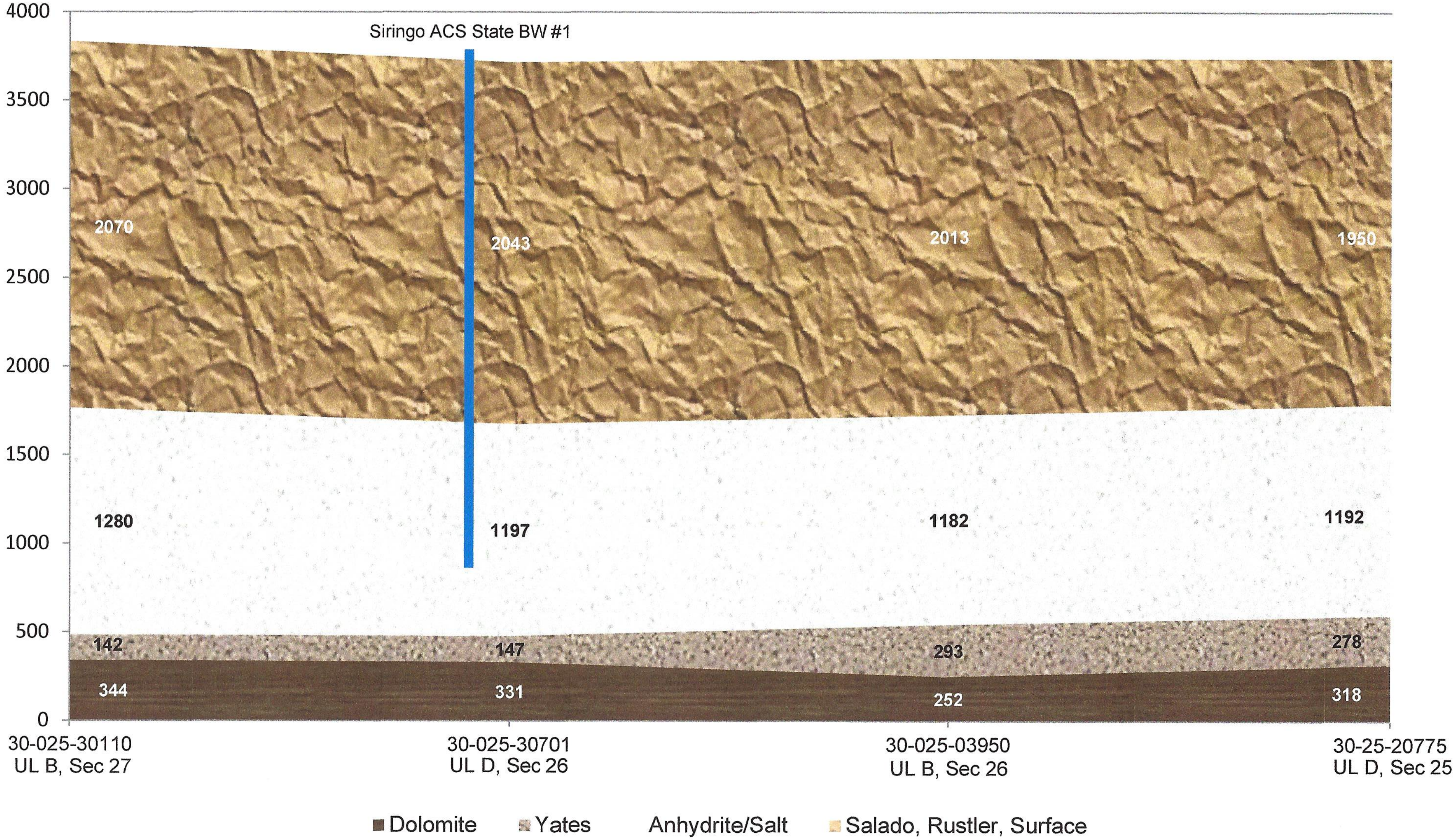


Cylinder Volume:		
$V_T = \frac{1}{3}\pi r^2 * H$	$V_1 = \frac{1}{3}\pi r^2 * H$	$V_2 = VT - V_1$
$V_T = \frac{1}{3}\pi 140^2 * 1260$	$V_1 = \frac{1}{3}\pi 100^2 * 900$	$V_2 = 25.848\ M - 9.420\ M$
$V_T = 25.848\ M$	$V_1 = 9.420\ M$	$V_2 = 16.428M$

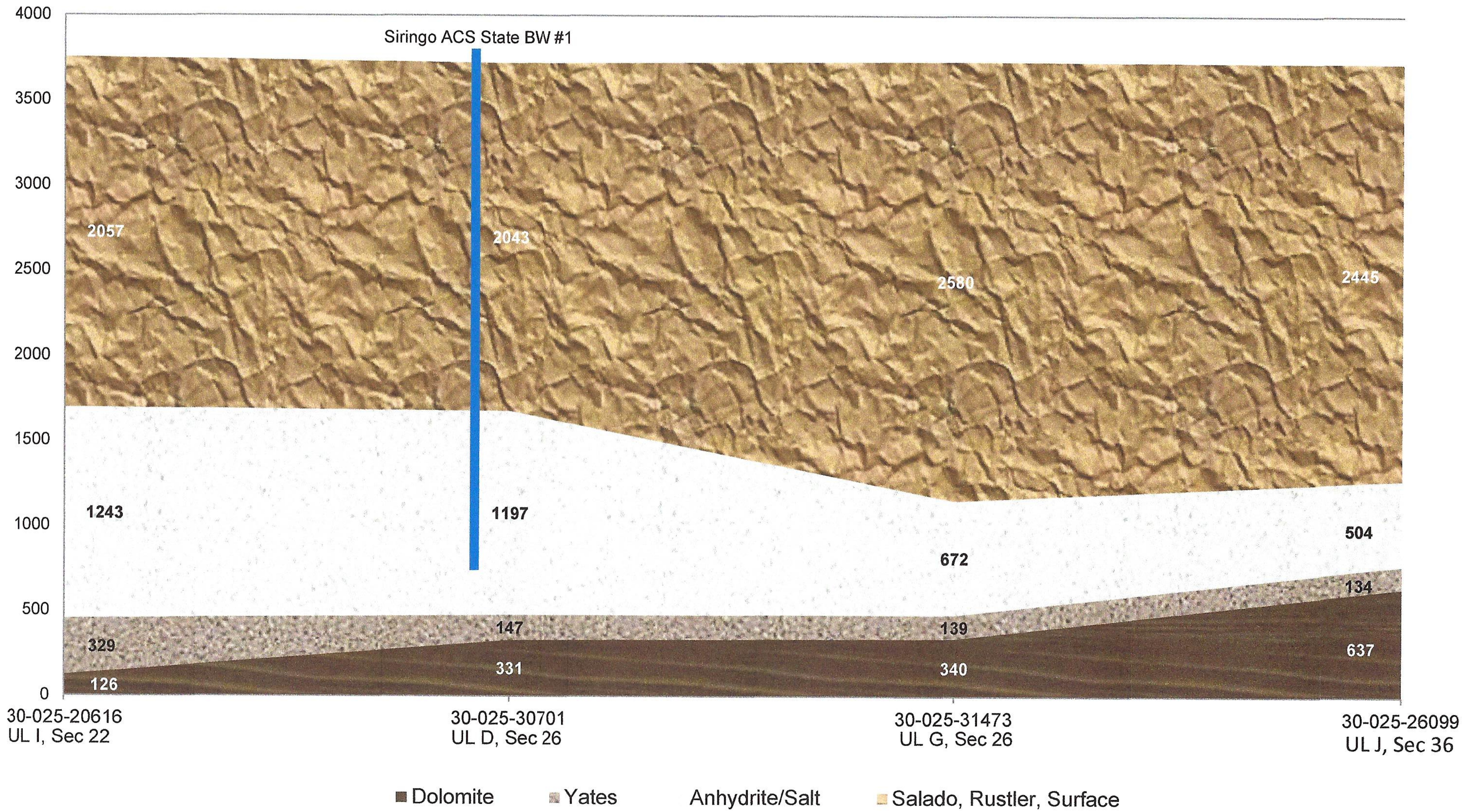
Brine Production Volume:	
$Vcyl = \pi r^2 h = \pi(100ft)^2(360ft)$	Brine = 88.59% of vol H_20 + 11.41% NaCl by volume
$Vcyl = 11{,}304{,}000\ ft^3$	Vol_{Brine} = 99.03 mft^3 brine
$Vcyl = 11.3\ M\ ft^3\ of\ salt$	Vol_{Brine} - 17.63 m bbls brine x 75% = 13.2 m bbls

Exhibit 2
Drawing Not to Scale

Siringo ACS State #1
East to West Cross Section
Exhibit 3A



Siringo ACS State #1
North to South Cross Section
Exhibit 3B



Siringo ACS BW #1 Well Roof Stability Steady State Model

Cantilever Beam Design when Anhydrite Separates from Casing

Exhibit 4

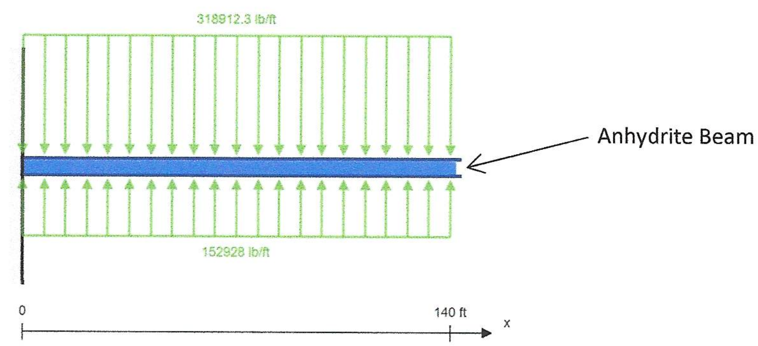
Function	Value	Unit	Method
$\sigma = My/I$ - Equation For Flexure Stress (Normal Tension/Compression Stress	275.4	psi	
$\tau = VQ/It$ - Equation For Transverse Shear Stress	3751	psi	
Inputs			
Beam Length in Feet (ie. Radius of Cavern)	140	feet	input value
Beam Width	12	inches	input value
Beam Height (Anhdyrite Thickness)	496	feet	input value
Depth of Casing Shoe Below GL	2043	feet	Depth to top of salt
Estimated Thickness of Salt Production zone	991	feet	input value
Model Calculations			
M = Moment	1626138108	ft-lbs	calculation
y = Distance From Center To Outer Fibers	2976	inches	calculation
I = Second Moment of Inertia Beam	2.10857E+11	inches4	calculation
w = Total Uniform Load of Beam (Wob-wc)	165932	lbs/ft	calculation
wc = Counter Uniform Load Generated by Hydrostatic Cavern Pressure	152980	lbs/ft	calculation
Wob = Uniform Load on Beam From Overburden	318912.3	lbs/ft	calculation
V = Shear From Total Load on Beam (Connection End)	44647722	lbs	calculation
Q = First Moment of Beam - End View, Center Axis	212557824	inches	calculation
t = Thickness (Width) of Beam	12	inches	fixed value
P = Cavern Hydrostatic Pressure Calculated Directly Below Anhydrite or at Shoe	1062	psi	calculation (w/brine wtr)
Outputs			
Maximum Bending Stress When Cavern Pressure Is Maintained	275	psi	Passed - Stable Roof
Maximum Bending Stress When Cavern Pressure Is Not Maintained	529	psi	Passed - Stable Roof
Ratio of Cavern Diameter/Depth of Casing Shoe (D/H <0.5)	0.14		Passed - Within Limits
Bending Safety Factor When Cavern Pressure is Maintained (must be > 2.0)	4.2		Passed - Within Limits
Bending Safety Factor When Cavern Pressure is Not Maintained (must be > 2.0)	2.2		Passed - Within Limits
Shear Safety Factor When Cavern Pressure is Maintained (must be > 2.0)	5.2		Passed - Within Limits
Shear Safety Factor When Cavern Pressure is Not Maintained (must be > 2.0)	2.7		Passed - Within Limits
Estimated Brine Production Volume (75% of cylinder)	13.2	mmbbls	See Figure 2
Maximum Surface Static or Test Pressure (psig)	300	psig	
Maximum Cavern Diameter (ft)	280	feet	

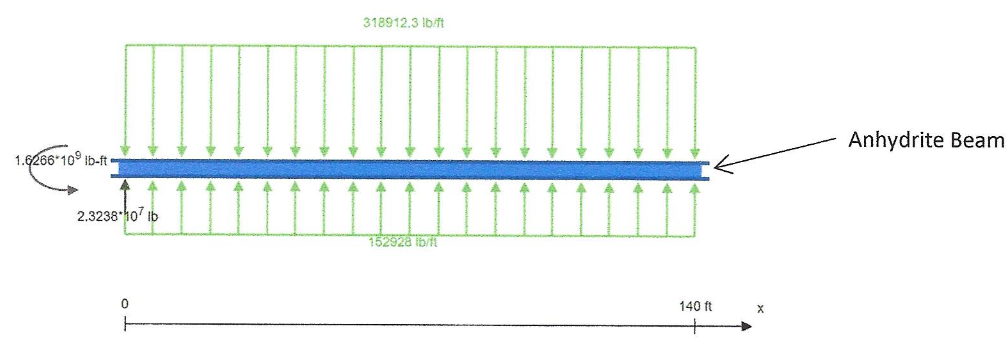
Siringo ACS State BW #1
Beam Stress Calculations
Exhibit 5

$$\sigma_T = \frac{My}{\bar{I}_x}$$

Where: $\sigma_T = tensile\ stress,\ M = bending\ moment,$

$y = distance\ from\ the\ neutral\ axis, \quad \bar{I}_x = second\ moment\ of\ intertia$





To calculate M:

Overburden (OB) is the weight of the anhydrite beam and the earth above it. Since anhydrite is the densest material in the lithography above the beam, the conservative approach is to calculate the weight of the overburden using anhydrite's density. $\rho_{Anh} = 156.1\,{}^{lb}/_{cu\ ft}$

$$F_{OB} = \rho_{Anh} lwh = \left(156.1\,{}^{lb}/_{cu\ ft}\right)(140ft)(1ft)(2043ft)$$

$$\underline{F_{OB} = 44{,}647{,}722\ lbs}$$

$$F_{brine} = P_{brine} lw = 1062\ lbs/sq\ in\,(140ft)(1ft)$$

$$\underline{F_{brine} = 21{,}409{,}920\ lbs}$$

$$F_{total} = F_{OB} - F_{brine} = 44{,}647{,}722\ lbs - 21{,}409{,}920\ lbs$$

$$F_{total} = 23{,}237{,}802\ lbs \approx 23.24\ million\ lbs$$

$$M = F_{total}\left(\tfrac{1}{2}l\right) = 23.24 million\ lbs\ \left(\tfrac{1}{2}140ft\right)$$

$$\underline{M = 1{,}626{,}800{,}000\ lb - ft}$$

To calculate $\bar{I}_x$:

$$\bar{I}_x = \frac{1}{12}bh^3 = \frac{1}{12}(1ft)(496ft)^3$$

$$\bar{I}_x = 10{,}168{,}661.3\ ft^4\ \text{(2.10857E+11 in}^4\text{)}$$

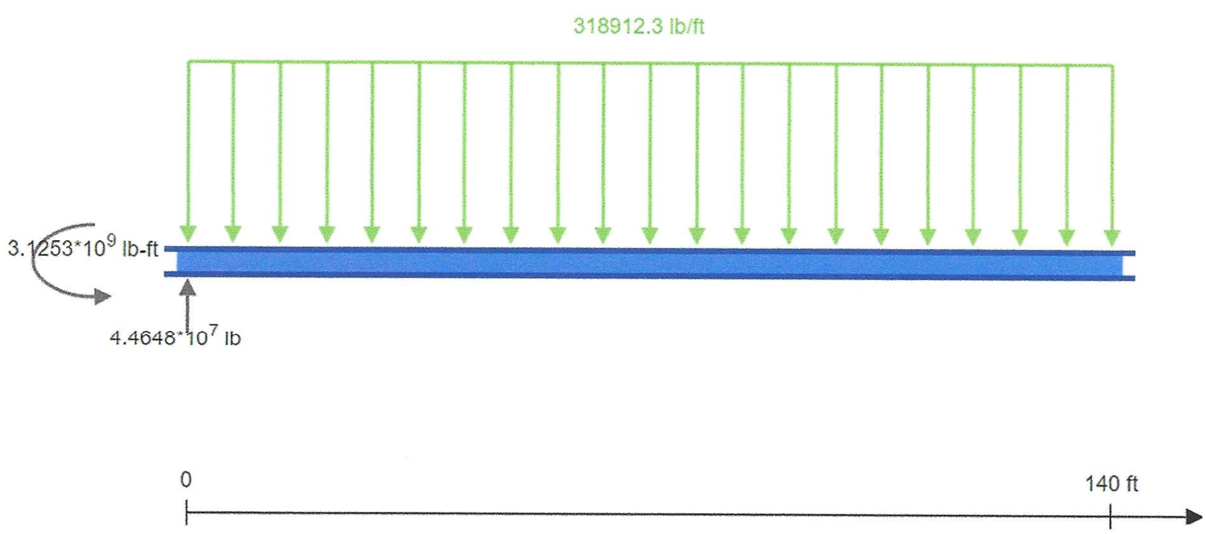
Thus:

$$\sigma_T = \frac{My}{\bar{I}_x} = \frac{(1{,}626{,}800{,}000\ lb - ft)(\frac{496ft}{2})}{10{,}168{,}661.3\ ft^4}$$

$$\sigma_T = 39{,}675.46\ {}^{lb}/_{sq\ ft} = 275.52\ {}^{lb}/_{sq\ in}$$

$$S.F. = \frac{\sigma_{UTS}}{\sigma_T} = \frac{1160psi}{276\ psi} = \underline{4.2}$$

Calculating the same bending stress if the brine is <u>NOT</u> present:



$$M = F_{OB}\left(\frac{1}{2}l\right) = 44.65million\ lbs\ \left(\frac{1}{2}140ft\right)$$

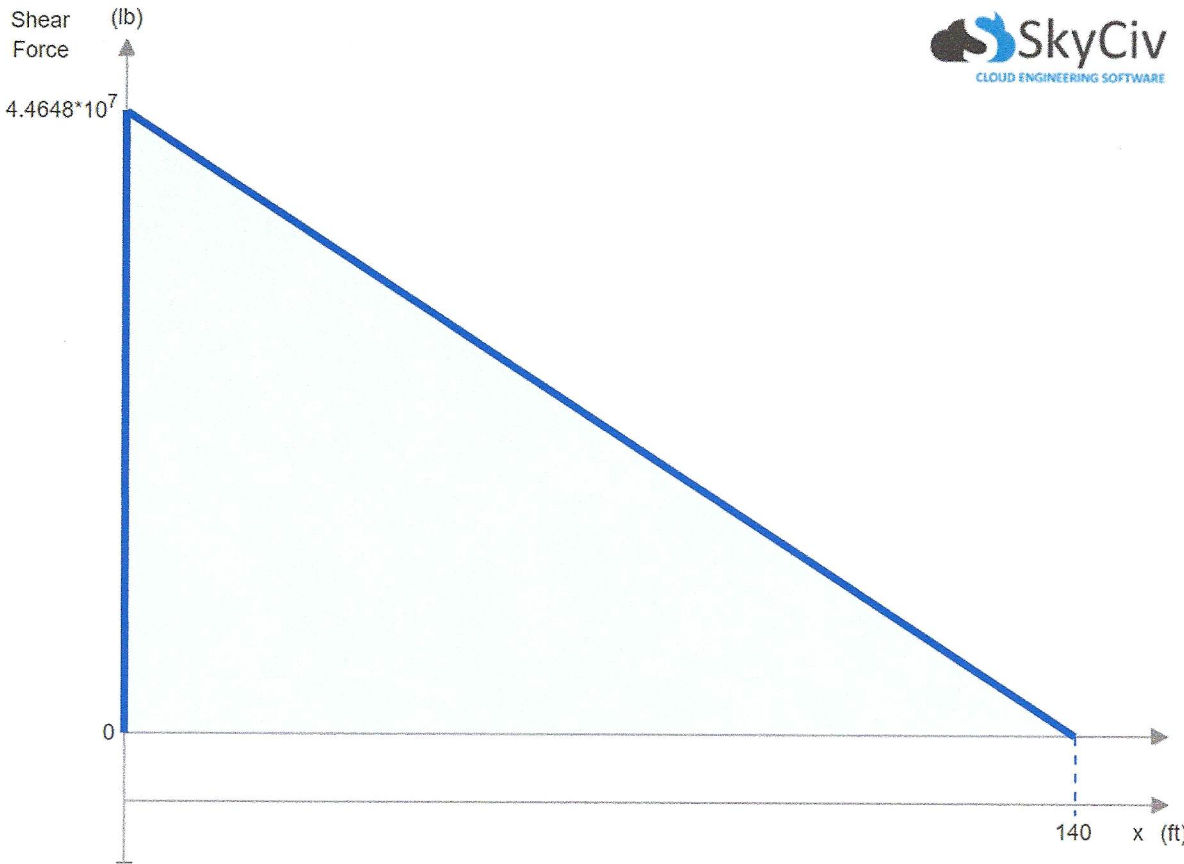
$$\underline{M = 3{,}125{,}500{,}000\ lb - ft}$$

$$\sigma_T = \frac{My}{\bar{I}_x} = \frac{(3{,}125{,}500{,}000\ lb - ft)(\frac{496ft}{2})}{10{,}168{,}661.3\ ft^4}$$

$$\sigma_T = 76{,}226.75\ {}^{lb}/_{sq\ ft} = 529.35\ {}^{lb}/_{sq\ in}$$

$$Safety\ Factor = \frac{\sigma_{UTS}}{\sigma_T} = \frac{1160psi}{529.35\ psi} = \underline{2.2}$$

Checking Shear:



$$\tau = \frac{VA'z'}{\bar{I}_x b} = \frac{F_{OB}\, A_{cross\ section}\frac{h}{2}}{\bar{I}_x\, w} = \frac{(44{,}647{,}722\ lbs)(496ft * 1ft)(\frac{496ft}{2})}{(10{,}168{,}661.3\ ft^4)(1ft)}$$

$$\tau = 540{,}096\ \frac{lb}{sq\ ft} = 3{,}751\frac{lb}{sq\ in}$$

Calculating τ_{max} using Mohr's Circle:

$$Safety\ Factor = \frac{\tau_{max}}{\tau} = \frac{10152\ psi}{3{,}751\ psi} = \underline{2.71}$$

Source: Free body diagrams from SkyCiv Software