STRENGTH REQUIREMENTS AND CHARACTERISTICS OF PIPE AND WELL SCREEN FOR DEEP WATER WELL APPLICATIONS

Prepared for
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REPORT

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INTRODUCTION

This report summarizes the strength requirements applicable to well casing and screens used by the Los Alamos National Laboratory (LANL) in deep water wells on the Pajarito Plateau. This information has been prepared to provide needed Quality Assurance/Quality Control (QA/QC) guidelines for the R-well drilling program component of the Hydrogeologic Work Plan (HWP) at Los Alamos.

The information presented here is divided into three sections. First, formulas are presented for computing key strength properties of pipe and pipe base well screens. Second, strength requirements for deep well installation are described. Finally, calculations are presented comparing the requirements on the Pajarito Plateau to the properties of the materials being used there.

COMPUTING STRENGTH PROPERTIES

Designing pipe and screen for deep wells must consider both horizontal and vertical strength properties. Horizontal stresses can cause collapse of the pipe or well screen while vertical stresses can cause yield or tensile failure. The pipe and screen must have sufficient horizontal strength to resist collapsing/crushing forces and sufficient vertical strength to withstand tensile stresses. Each parameter is evaluated separately below.

Collapse Strength

Calculating collapse strength of pipe is a complex process and can require different formulas for thin-wall tubes than for thick-wall tubes. Thin-wall tube collapse is dependent primarily on the *modulus of elasticity* of the pipe material, whereas the collapse strength of thick-wall tubes is related to the *yield strength* of the pipe material. Thus, different formulas are sometimes used, depending on the ratio of the pipe outside diameter (D) to the wall thickness (t).

The American Petroleum Institute (API) proposes using four different formulas for computing the collapse strength of pipes. They are:

1. Yield Strength Formula (for low D/t ratios)

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2. Plastic Collapse Formula (for medium-low D/t ratios)
3. Transition Collapse Formula (for medium-high D/t ratios)
4. Elastic Collapse Formula (for high D/t ratios)

The first and last formulas on this list were derived on a theoretical basis. The two intermediate formulas that bridge the gap between yield-related collapse and elastic collapse were derived empirically. Unfortunately, the empirical constants used in the intermediate formulas, as well as the D/t threshold criteria that determine which of the four formulas to use, vary from one kind of casing to the next (e.g., H-40 versus J-55 versus N-80, and so on). Furthermore, these various empirical formulas have been worked out only for certain grades of oil field pipe, and not for common water well materials. As a result, using the API approach to compute collapse strength for water well completion materials is problematic.

A better and more general approach for water well applications is the use of the Main Formula (Main, 1939). This formula incorporates both elastic effects and yield effects and, thus, covers a broad range of D/t ratios.

The Main Formula is as follows:

$$P = 3E + 4bE + Sa - \sqrt{(3E + 4bE + Sa)^2 - 16abSE} \qquad (1)$$

where,

P = collapse strength of blank pipe, in pounds per square inch (psi)
S = yield strength, in psi
E = modulus of elasticity, in psi

In this expression, yield strength (S) is considered to be 35,000 psi for typical steel water well materials and 30,000 psi for Type 304 stainless steel. The modulus of elasticity (E) generally ranges from 2.8 x 10^7 to 3.0 x 10^7 psi.

In the above expression, a and b are defined as:

$$a = 2(1 - \mu^2)\left(\frac{D}{t} - 1\right)^3 \qquad (2)$$

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$$b = \sqrt{\frac{2(1+\mu)k^4 + 2(1-\mu)}{(k^2-1)^2}} \qquad (3)$$

where,

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μ = Poisson's ratio (approximately 0.30)
D = outside diameter of pipe, in inches
t = wall thickness, in inches
k = ratio of pipe outside diameter to inside diameter

It can be shown that in the limit as the ratio D/t becomes large, the Main Formula approaches one of the commonly used thin-wall cylinder elastic collapse formulas:

$$P = \frac{2E}{1-\mu^2} \frac{1}{\left(\dfrac{D}{t}-1\right)^3} \qquad (4)$$

The API recommends applying a safety factor of 0.7125 (0.95 x 0.75) to collapse calculations in the elastic range. It recommends no safety factor for the other ranges, because the other formulas are already conservative. A prudent approach to use in applying the Main Formula is to apply the 0.7125 safety factor to all calculated results for blank pipe. This is a highly conservative approach, ensuring safe designs.

For well screens, however, as described later, an empirical formula has been derived based on strength calculations without the safety factor applied. Thus, the safety factor is already indirectly incorporated empirically and a separate safety factor need not necessarily be applied to well screens.

Bending Strength

A strength parameter that plays a role in describing the performance of well screens is the resistance to stress applied to opposite sides of the screen. This relates to the failure that can occur when the screen is loaded along two vertical lines, parallel to the axis of the screen and 180 degrees apart. This

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stress, referred to here as bending stress, is expressed in pounds per inch of screen length. For blank pipe, the bending strength is calculated as follows:

$$B = \frac{\pi}{3} S \frac{t^2}{D} \qquad (5)$$

where,

B   = bending strength of blank pipe, in pounds per inch
S   = yield strength, in psi
D   = outside diameter, in inches
t   = wall thickness, in inches

Vertical Strength

The vertical strength of pipe is calculated as the product of the yield strength of the material and the cross-sectional area of the wall of the pipe:

$$V = \pi S (D - t) t \qquad (6)$$

where,

V   = vertical strength of blank pipe, in pounds
S   = yield strength, in psi
D   = outside diameter, in inches
t   = wall thickness, in inches

This is a measure of the stress threshold that will cause permanent deformation of the pipe in tension.

Open Area Correction For Pipe Base Well Screens

The base pipe used in fabricating stainless steel pipe base screens is perforated by drilling several longitudinal rows of round holes. The original base pipe used at LANL had 14 staggered rows of holes, with 6 half-inch holes per lineal foot of pipe in each row. The new design, effective April 2002, will have 14 staggered rows, with 12 half-inch holes per lineal foot of pipe in each row, double the previous number.

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The holes reduce the collapse strength in proportion to the ratio of the diameter of the drilled hole to the hole spacing vertically along the pipe:

$$P_p = P\left(1 - \frac{d}{s}\right) \qquad (7)$$

where,

P_p = collapse strength of perforated pipe, in psi
P = collapse strength of blank pipe, in psi
d = hole diameter, in inches (0.5-inch for LANL screens)
s = hole spacing in a particular row, in inches (2 inches for original LANL screens, 1 inch for updated design)

Offsetting this, the collapse strength of the well screen is enhanced somewhat by the presence of the wire wrapped screen jacket on the exterior of the perforated pipe. However, the jacket is relatively lightweight compared to the base pipe and the additional strength it provides is usually ignored. This constitutes a small additional safety factor.

The holes drilled in the pipe reduce the bending strength by the same factor applicable to the collapse strength. Thus, the bending strength of the perforated pipe is:

$$B_p = B\left(1 - \frac{d}{s}\right) \qquad (8)$$

where,

B_p = bending strength of perforated pipe, in pounds per inch
B = bending strength of blank pipe, in pounds per inch
d = hole diameter, in inches (0.5-inch for LANL screens)
s = hole spacing in a particular row, in inches (2 inches for original LANL screens, 1 inch for updated design)

The bending strength of the well screen is enhanced somewhat by the presence of the wire wrapped screen jacket on the exterior of the pipe. Again, this effect is usually ignored, thus providing a slight safety factor.

For a base pipe with a limited number of holes, the vertical strength of the perforated pipe is reduced by the number of holes drilled at the same vertical position on the base pipe. For hole patterns with staggered rows, the number of holes located at the same vertical horizon is equal to half the number of rows of drilled holes. The resulting vertical yield strength of the perforated pipe is:

$$V_p = St\left[\pi(D-t) - \frac{Nd}{2}\right] \tag{9}$$

where,

V_p = vertical strength of perforated pipe, in pounds
S = yield strength, in psi
D = outside diameter, in inches
t = wall thickness, in inches
d = hole diameter, in inches (0.5-inch for LANL screens)
N = number of rows of drilled holes (14 for LANL pipe base screens)

This equation is based on the failure location consisting of a circumferential line, perpendicular to the axis of the pipe, passing through holes at the same elevation, i.e., every other row. If the density of holes is sufficient, however, the failure zone will pass through all rows of holes in a zigzag pattern. This will occur when the lineal length of parted metal is shorter in the zigzag pattern passing through all rows than in the straight pattern involving only half the rows. Under these circumstances, the vertical yield strength declines to the following:

$$V_p = StN\left(\sqrt{\left(\frac{6}{M}\right)^2 + \frac{\pi^2(D-t)^2}{N^2}} - d\right) \tag{10}$$

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where,

V_p = vertical strength of perforated pipe, in pounds
S = yield strength, in psi
D = outside diameter, in inches
t = wall thickness, in inches
d = hole diameter, in inches (0.5-inch for LANL screens)
M = number of holes per lineal foot of pipe in each row (6 for original screens, 12 for updated design)
N = number of rows of drilled holes (14 for LANL pipe base screens)

The presence of the outer screen jacket adds to the vertical strength of the completed screen assembly because of the presence of the vertical rods used in manufacturing the jacket. The resulting vertical yield strength of the screen assembly, including the rods, is:

$$V_s = St\left[\pi(D-t) - \frac{Nd}{2}\right] + SnA \qquad (11)$$

$$V_s = StN\left(\sqrt{\left(\frac{6}{M}\right)^2 + \frac{\pi^2(D-t)^2}{N^2}} - d\right) + SnA \qquad (12)$$

where,

V_s = vertical strength of pipe base screen, in pounds
S = yield strength, in psi
D = outside diameter, in inches
t = wall thickness, in inches
d = hole diameter, in inches (0.5-inch for LANL screens)
M = number of holes per lineal foot of pipe in each row (6 for original screens, 12 for updated design)
N = number of rows of drilled holes (14 for LANL pipe base screens)
n = number of vertical rods (36 for recent LANL screen shipments)
A = area of each vertical rod, in square inches (0.0085 square inches for recent LANL shipments)

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In practice, the actual strength will be the minimum value calculated from these two equations. In these formulas, if the yield strength of the pipe material is different than that of the screen jacket rods, this can be accounted for by using the appropriate yield strength parameter in each portion of the equation.

STRENGTH REQUIREMENTS

In deep well installations, the vertical strength requirements are the same for both the well casing and the well screen. However, the horizontal strength requirements are very different. The reason for this is that the well casing is subject to hydraulic collapse that can occur when the fluid level outside the pipe is higher than that inside the pipe. In general, well screens are less susceptible to hydraulic collapse because they "leak", thus relieving fluid pressure buildup outside the screen. The requirements that should be incorporated into the design of each well component, for both vertical and horizontal stresses, are described below.

Horizontal Strength Requirements For Blank Pipe

In any well design, the horizontal collapse strength of the blank casing installed in the well should be sufficient to withstand a hydraulic load equal to the depth of the well subjected to the applicable fluid, i.e., water or grout.

For example, in conventional water supply wells in which the grout seal is relatively shallow, the fluid of concern is water. In such wells, the casing should have a strength, after application of the safety factor of 0.7125, equal to the pressure exerted by a column of water equal in height to the entire depth of the well. This design criterion guards against collapse that could occur if the pressure inside the casing were reduced to atmospheric (by pumping the well dry, or by surging vigorously) while the outside of the casing was fully submerged in water.

There are other stresses on the well casing associated with natural formation pressures and the impact of solids against the pipe that occurs during filter pack installation and well development. However, these stresses are minor compared to the potential fluid pressure and, thus, the hydrostatic pressure criterion becomes the driver for strength design.

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If water is the primary fluid of concern, the collapse strength requirement of the blank pipe is that it must exceed the hydrostatic load corresponding to the well depth. For water, this is 0.4335 psi per foot of depth. If grout is the fluid of concern (for example, if the entire length of the casing will be grouted), the hydrostatic forces associated with the more dense grout material must be used. For example, cement grout can commonly have densities that exert pressures ranging up to about 0.8 psi per foot. High solids bentonite grouts are less dense than this, but substantially more dense than plain water.

Horizontal Strength Requirements for Well Screen

Selecting safe depths for well screens is trickier than for blank pipe because hydraulic loading is not usually a problem for screens. The primary loads on the well screen are related to natural formation pressures, which are fairly low, and transient stresses associated with filter pack placement and movement of solids around the screen during well development. Because these stresses are not readily quantifiable, it is necessary to rely on empirical methods to select appropriate strength characteristics for well screens.

In the 1980's, David Schafer performed an extensive analysis of existing deep well screen designs, including both successful installations and failed screens. The data from hundreds of actual deep well installations were correlated to develop an empirical approach to selecting suitable well screen strength. No other such analysis has been performed in the groundwater industry.

The results of the analysis showed that both collapse strength and bending strength influenced the success or failure of well screen installations, with bending strength having the greater effect. An empirical safe depth formula was developed based on both parameters. The result of the empirical study was the following equation for safe installation depth for well screens:

$$d_s = \left[\left(B_p\right)^{\frac{3}{4}} \left(P_p\right)^{\frac{1}{4}} \right]^{1.5} \qquad (11)$$

where,

d_s = safe installation depth, in feet
B_p = bending strength of perforated base pipe, in pounds per inch
P_p = collapse strength of perforated base pipe, in psi

Vertical Strength Requirements For Blank Pipe And Well Screen

The vertical strength requirement for pipe and screens is a function of the hanging weight of the completion string. Any joint of pipe or screen in the completion string must have sufficient vertical strength to support the hanging weight (and other induced stresses) of the materials below it.

Besides the hanging weight, there are additional transient vertical stresses frequently imposed on the casing string. These can be caused by such things as 1) successively lowering and stopping the casing string during installation, 2) occasionally pulling upward on stuck pipe and 3) the downward frictional forces imparted to the completion string during filter packing and well development. These latter stresses are not readily quantifiable and, therefore, experience and empirical observation must be relied on to guide the design process.

It is advisable that the vertical yield strength of a given section of casing or pipe base well screen be at least two times the calculated hanging weight of the underlying materials. This design provides a sufficient safety factor to allow successful installation, completion and development.

For rod base well screens, the vertical yield strength should be *two to three times* the calculated hanging weight of the underlying materials. In the manufacture of rod base screens, the end fittings are welded to the screen rods by hand. Often, these welds are not 100 percent effective, resulting in a joint strength less than the theoretical expectation. Thus, the larger safety factor is used for rod base screens.

The ultimate tensile strength properties of construction materials provide some additional safety factor to prevent parting of the casing string under adverse conditions. For Type 304 stainless steel, for example, the completion design is based on the yield strength of the material – 30,000 psi for fully annealed Type 304 stainless steel. This is the stress required to permanently deform the metal. The ultimate tensile strength of 60,000 psi provides an additional safety factor against separation failure of the metal.

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The ultimate tensile strength is the stress required to cause a complete separation of the metal.

EXAMPLE STRENGTH CALCULATIONS AND DESIGN FOR THE DEEP WELLS AT LANL

This section examines the horizontal and vertical strength characteristics of the 5-inch pipe and pipe base screens presently being used for completing the LANL R-wells in support of the HWP. Specifications previously in use called for 5-inch OD, 0.247-inch wall thickness Type 304 stainless steel blank casing and 5-inch pipe base wire wrapped screens manufactured using the same pipe by slipping a lightweight, wire wrapped stainless steel screen jacket over the pipe, which has been pre-drilled with 14 staggered rows of ½-inch holes on two-inch centers (84 holes per lineal foot of pipe). Recently, the specification was changed, calling for ½-inch holes on 1-inch centers (168 holes per lineal foot of pipe). Strength characteristics will be computed below and depth guidelines established for these designs.

Fully annealed (dead soft) Type 304 stainless steel material has a yield strength of 30,000 psi and a tensile strength of 60,000 psi. Recent purchases of stainless steel casing for the HWP R-wells have been supplied with non-annealed material having greater yield and tensile strength than this. As a conservative measure, however, strength calculations and design guidance will be based on fully annealed material. This will ensure that the current designs will work for any Type 304 stainless steel pipe purchased in the future.

There is no assurance that high tensile materials will continue to be supplied in the future. Also, it is possible that, from time to time, small "fill-in" quantities of pipe may have to be procured from various alternative sources with little control over the choice of material hardness. Furthermore, on occasion it may be necessary to "custom build" components of the casing string for various reasons (to facilitate installation, for example). Any such custom fabrication that employed welding would anneal the material in the area of the weld, reducing its strength to the nominal dead soft levels. Thus, a conservative approach assuming that the material strength would be limited to that of a fully annealed condition will ensure that designs are adequate and that installations will be safe as long as dimensional specifications are met and the required American Society for Testing and Materials (ASTM) specifications apply.

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LANL Pipe Strength Characteristics

The casing specified for the R-wells is 5-inch OD, having a nominal wall thickness of 0.247-inch. The required minimum wall thickness is 87.5 percent of the nominal value, or 0.216-inch. Therefore, horizontal and vertical strength must be computed using this minimum value.

Applying Equations (1), (2) and (3), and the API safety factor of 0.75 x 0.95, the calculated collapse strength of the blank pipe is 1680 psi. Based on a hydraulic load of 0.4335 psi per foot of depth, the maximum application depth, based on collapse strength, is approximately 3880 feet.

For sections that are grouted, the grouted length is limited by the density of the grout and the continuous length of pipe that is grouted at one time (without allowing the grout to set up). For example, for cement grout having a density of 1.8 (15 pounds per gallon), the hydraulic force exerted on the casing is 0.78 psi per foot of depth. This would limit the continuous grout length to 2150 feet. Regardless of the fluid density applied (water or grout), it is clear that the strength of the pipe used at LANL is adequate for the projected well depths of 1000 to 2000 feet.

The vertical yield strength of the casing (in tension) is computed from Equation (6) to be 97,400 pounds. The hanging weight of the material should be limited to half this, or 48,700 pounds. To determine the pipe footage that can be suspended from the uppermost pipe section (i.e., the maximum allowable well depth) it is necessary to determine the weight of the casing string.

The 5-inch OD, 0.247-inch wall pipe specified for the R-wells has a theoretical weight of 12.5 pounds per foot. Thus, the permissible casing string length is calculated to be 3900 feet (48,700 divided by 12.5). The actual pipe weight can vary slightly from the theoretical value. For example, seamless pipe can vary in weight from 10 percent over to 3.5 percent under the nominal weight. Thus, seamless pipe could weigh up to 13.8 pounds per foot, reducing the permissible string length to 3530 feet (48,700 divided by 13.8).

It is more common for Type 304 stainless steel pipe to be at or under the nominal weight, rather than over it, because the high cost of stainless steel provides manufacturers with incentive to target the minimum allowable

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weight rather than the maximum allowable weight during the manufacturing process. The depth limitation may be adjusted if the actual pipe weight is verified to be different from the theoretical. It may be possible to determine the pipe weight from the manufacturer, from shipping records or by direct measurement, if a precise determination of actual weight is required.

LANL Pipe Base Screen Strength Characteristics

Computing the safe depth of installation for the pipe base screens requires calculating both the collapse strength and bending strength. Equations (1), (2) and (3) were used to determine the collapse strength of blank pipe to be 2360 psi (without safety factor). Equation (7) can be used to correct this value for the presence of the perforations in the pipe. The resulting collapse strength is 1770 psi for the original design and 1180 psi for the new design with 168 drilled holes per lineal foot of pipe.

The bending strength was computed using Equations (5) and (8), yielding 220 pounds per inch for the original design and 147 pounds per inch for the new design. Finally, Equations (11) and (12) were used to determine the safe installation depth. The resulting guidelines of 7120 feet for the original design and 3880 feet for the updated design confirm that pipe base screens are very rugged and generally over-designed from a horizontal strength standpoint for water well applications.

Although the safe depth calculation suggests an over-design, it is important to remember that strength considerations were not the driver in selecting the pipe base screen design. This design was selected because of advantages it offered in OD and ID dimensional tolerance as well as joint strength, straightness and ease of makeup in the field.

The vertical strength of the pipe base screens used for the R-well project was computed from Equations (11) and (12) to be 83,900 pounds for the original design and 71,300 pounds for the updated design. Based on a pipe weight of 12.5 pounds per foot and the required 2:1 safety factor, the maximum casing length that could be suspended from a particular screen section is 3360 feet for the original design and 2850 feet for the new design. Pipe weighing 13.8 pounds per foot would reduce the allowable suspended casing length to 3040 feet and 2580 feet for the old and new designs, respectively.

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The foregoing calculations show that the materials specified for the R-wells will readily withstand the rigors of installation for these wells, which are generally expected not to exceed about 2000 feet.

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