# GEOTHERMAL WELL DESIGN – CASING AND WELLHEAD

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## ABSTRACT

The Geothermal well design process includes consideration of the objectives and purpose of the well, the subsurface conditions likely to be encountered during the drilling process, and the identification of required equipment, materials, and drilling procedures needed to ensure a satisfactory well completion and an acceptable well life.

The design steps which are necessary to drill and complete a deep geothermal well safely are:

- Subsurface rock and fluid conditions.
- Depths of casings and well completion.
- Casing specification and cementing materials and programmes
- Wellhead specification
- Drilling fluids, drill string assemblies
- The necessary drilling tools and equipment.

Perhaps the most critical aspects of these design steps is the selection of casings, casing specification, casing shoe depths, and how the well is completed. This paper reviews the casing and wellhead specification process.

*Keywords: geothermal, well design, casing design and specification.*

## INTRODUCTION

The choice casing depths and specification of the materials weights and connections is vital to the success and safety of the well drilling process and to the integrity and life of the well.

The casing design and specification process includes reviewing the required services of the casings, determination of the setting depths and checking possible failure modes.

## CASING SERVICES

What is the purpose of the casing?

The reasons for including casing strings and liners include:-

- Prevention of loose formation material from collapsing into and blocking the hole.
- Provision of anchorage or support for drilling and the final wellhead.
- Containment of well fluids and pressures.
- Prevention of ingress or loss of fluid into or from the well, and “communication” or leakage of fluids between different aquifers.
- To counter losses of drilling fluid circulation during drilling.
- Protection of the well and formation against erosion, corrosion, fracturing and breakdown.

In general, the shallower and outer casing strings are necessary for the drilling operations, while the inner strings are required for production purposes. The drilling process follows a sequence of drilling to a certain depth, running and cementing a casing string, establishing a wellhead (drilling or final), which allows the drilling of the next smaller diameter section to proceed. As a minimum two, but usually more, completely cemented, concentrically located, steel casing strings are obligatory both from a technical and legal sense for a geothermal well.

Casing strings and liner for a typical geothermal is illustrated below in Figure 1.

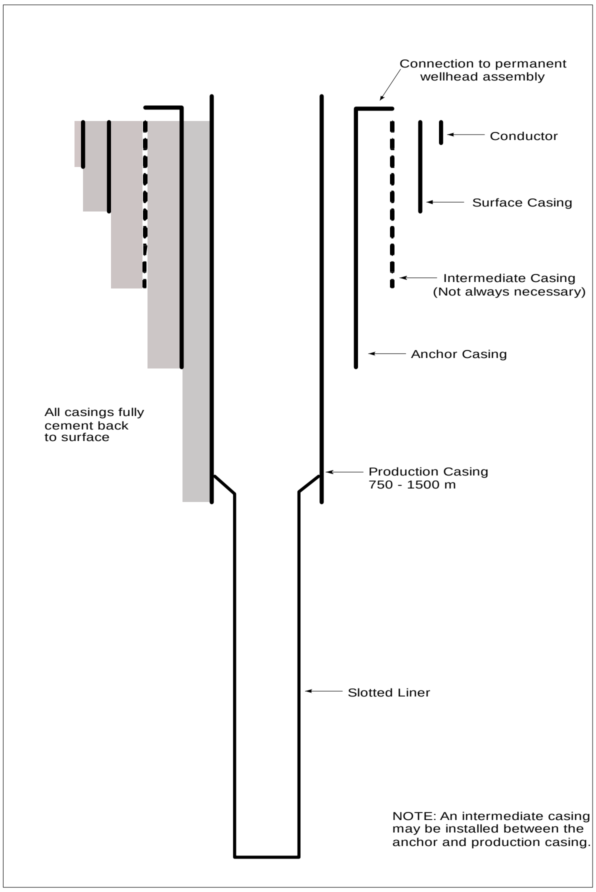


Figure 1. Casing strings and Liner for Typical Geothermal Well.

## CASING SETTING DEPTHS

The casing setting depths for a typical geothermal well will be chosen from the following information and expectation related to the following aspects:

- Surface or Conductor Casings Strings –
  These are the largest casings which are set at a shallow depth and are employed to prevent loose near-surface material collapsing into the hole. They are also utilised to support the initial drilling wellhead, and to contain the circulating drilling fluid. The setting depth of the casing shoe will estimated from geological deduction, but may be altered to reflect conditions found during the course of drilling, and may have to contain hot fluid under pressure if there is a thermal zone close to the surface.

- Anchor or Intermediate Casing Strings –
  These casings are intermediate in diameter and in setting depth which are set to support successive wellheads (usually including the permanent wellhead) and to contain drilling and formation fluids of relatively high temperature and pressure. Setting depths will be chosen from expected formation rock and fluid conditions to provide adequate permanent anchorage and additional security against drilling problems including blowouts.

- Production Casing –
  This casing is smaller in diameter and set at greater depth than previous casings, and is used primarily to convey steam and water to the surface, but it is also important in facilitating drilling to total depth and to prevent unwanted leakage of fluids into or out of different aquifers. The depth of this string should be chosen first, on the basis of the expected depths and temperatures of fluids to be included and excluded from production.

In the situation of appraisal or production drilling, the experience of earlier drilling and well testing in the area is the most useful guide in selecting casing depths. However, when drilling a first well in a new area, reasonable assumptions must be made as to the possible rock and fluid conditions to be expected down to the total drilled depth. These will be deduced from consideration of surface scientific surveys possibly supplemented by the results of drilling a shallow investigation hole at the site. In the absence of a clear understanding from the scientific data, it is frequently assumed that the reservoir fluid can be approximated to a column of water at boiling temperature throughout its depth – 'Boiling Point for depth (BPD). If the ground water level is known, the depth should be taken from below that datum.

In a hot water or two phase field with boiling conditions as assumed above, it is possible (although unlikely) at any stage of the drilling for the well to be filled with a column of steam at a temperature and saturation pressure corresponding closely to formation conditions at hole bottom, or at the level of greatest permeability. As this pressure is more than that of the formation fluid, there is a tendency for steam to escape into upper permeable formations, and in weak geological conditions blow out at the surface. Upper casing depths should beset to seal off possible leakage paths to the surface and to limit the well fluid pressure at the shoe to that imposed by the overburden pressure, or by the fracture gradient of the materials if this is known.

The competence of the rock and the incidence of drilling circulation fluid losses are likely to govern casings depths, and thus the number of casing strings needed to allow the target depth to be reached most economically.

This 'competence of the rock' can only be derived from experience as suggested above, but usually falls somewhere between a theoretically derived fracture gradient and a theoretical overburden pressure.

Figure 2 below illustrates a theoretically based casing shoe depth selection procedure.

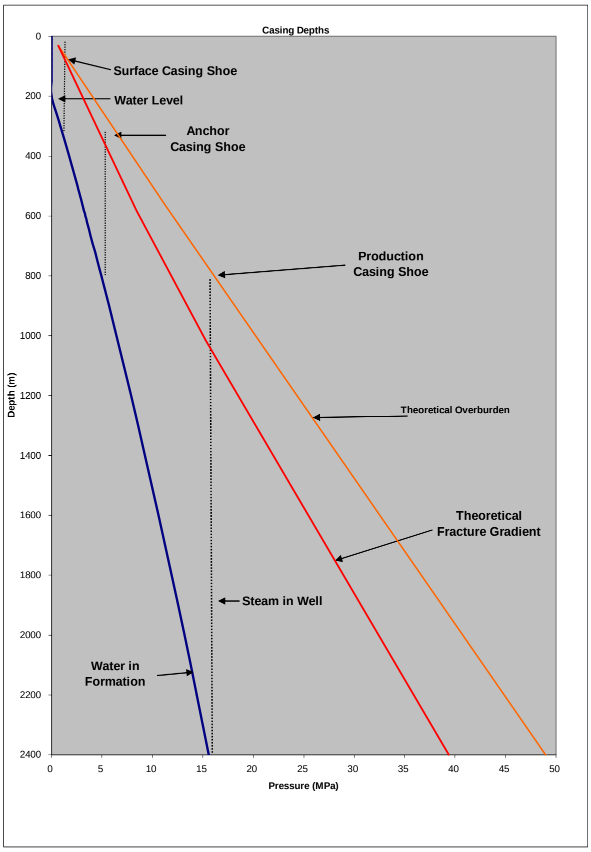


Figure 2. Example of Theoretical Casing Depth Selection.

This theoretical situation would require the production casing shoe being set at a depth of 800 m depth; the anchor casing shoe being set at 300 m depth; and the surface casing shoe being set at around 60 m depth.

## CASING DIAMETERS

The diameters of the various strings of casing in any well are chosen after consideration of the following aspects:-

- Sufficient cross-sectional area to convey the expected / desired flow of fluid;
- Sufficient annular clearances to run and cement concentric casing strings;
- The use of casing sizes which are standard manufactured products which are readily available and match the handling tools usually held by drilling contractors.

Due to the manner in which different pipe thicknesses are manufactured, tubular sizes are identified by their outside diameters and in accordance with the API specifications.

## SERVICE CONDITIONS AND FAILURE MODES

Whereas deep petroleum drilling considers the most important parameters in casing design to be fluid pressure, casing weight, and tensile loading, in geothermal service generally the most severe service occurs as a result of high temperature loadings. The problem is compounded by facts that the service temperatures can seldom be predicted at all accurately; and that the various types of casing steel grades and casing connections are manufactured specifically for petroleum service rather than geothermal service.

The effects of elevated geothermal temperatures on well components include:-

- Change in length of unrestrained pipe – for example, 1.8 m expansion over a length of 1000 m with a temperature change of 150°C.
- Alternatively a compressive stress due to restrained (cemented) pipe – for the same temperature rise of 150°C the compressive stress will be 360 MPa (52,000 psi).
- Reduction in steel strength – 5% or more in casing tensile strength tests at 300°C, and 17% in wellhead equipment pressure ratings at 300°C under ANSI Standards.
- Destruction of material competence – particularly flexible seals.

While loading in a longitudinal direction induces secondary stressing in the circumference of a pipe, it is convenient to separate the primary modes of failure into axial and radial.

## AXIAL STRESS CONDITIONS

Axial stressing occurs due to:-

- Casing self weight
- Temperature effects – expansion and contraction
- Restraint from the surrounding cement and/or and connection at the wellhead or downhole (such as a hanger).

The design checks for axial stress can be separated into two sets of conditions – before and after the casing is cemented.

### *Axial Loading before and during cementing*

Until the annular cement sets around the casing the tensile force at any depth includes the weight of the casing in air less the buoyant effect of any fluid in the well.

T–
Thus: $F_p = [\, L_z W_p - (L_z\text{-}L_w)A_p/n]g$

Where:
- $F_p$ = the tensile force at the surface from casing weight
- $L_z$ = depth of casing
- $W_p$ = unit weight of casing
- $L_w$ = depth of water level in well
- $A_p$ = cross sectional area of pipe
- $n$ = mean specific volume of hot fluid
- g = acceleration due to gravity

The design tensile force shall allow for the dynamic loads imposed during the running of the casing, which will include the drag force of the casing against the side of the well, particularly in a deviated well. This dynamic loading must be limited by specifying the maximum hook load which may be applied.

In a deviated hole the maximum bending stress induced is:-

$$F_b = EqD$$

*Where:*
- $F_b$ = maximum stress due to bending
- $E$ = modulus of elasticity
- $q$ = curvature of deviated hole (° per 30 m)
- $D$ = pipe outside diameter

This stress is additional to that caused by casing weight, temperature change etc.

Where axial loadings before cementing can occur simultaneously they shall be added together and the resultant maximum axial load checked against the minimum tensile strength of the casing.
The design factor applied to this is 1.8.

### *Axial Loading After Cementing*

The thermal stress built up can be calculated by imagining that the pipe expands (using the coefficient of thermal expansion and the estimated temperature difference), and is then forced back to its original length by axial compression (using the modulus of elasticity).

For the compressive stress quoted above:-

Unit extension = strain = coefficient x temp. change
$= (12 \times 10^{-6}) \times 150$

$= 1.8 \times 10^{-3}$

Stress = modulus x strain = $(200 \times 10^3) \times 1.8 \times 10^{-3}$

$= 360$ MPa

The total axial stress in a cemented string varies continuously with depth and also with the difference in temperature at any time between the neutral value (when the casing was fixed in position) and that at any time subsequently. It should also be noted that if the formation into which casing has been cemented moves differentially by faulting or subsidence, then this too induces further stresses. An additional complication is that when steel is loaded at high temperatures over a long period of time, stress relaxation will occur.

The compressive force due to temperature rise when the casing is constrained both longitudinally and laterally by cement is:-

$$F_c = C_t (T_2 - T_1) A_p$$

$$Ct = Ea = 200 \times 12 \times 10\text{-}6 = 2.4 \text{ MPa/°C}$$

Where:

$F_c$ = compressive force due to heating
$C_t$ = thermal stress constant for casing steel
$T_1$ = neutral temperature (temp. at time cement set)
$T_2$ = maximum expected temperature
$A_p$ = cross sectional area of pipe.
$E$ = modulus of elasticity
$a$ = coefficient of linear thermal expansion

The tensile loading as calculated for the pre-cementing axial loading remains in the casing after cement setup (ignoring stress relaxation with time), therefore the resultant axial force ($F_r$) on the casing after cement setup and heating will be:-

$$F_r = F_c - F_p$$

The design factor to be utilised will be

$$\frac{\text{minimum compressive strength}}{\text{resultant compressive force}}$$

where the minimum strength refers to the lesser of the pipe body or the connection. The design factor shall not be less than 1.2.

Many of the casing failures that occur are the result of rapid cooling of the well. After the well has been completed and has heated and perhaps has been in production for some time and if the well is re-entered for subsequent drilling activities; undergoes a series of pumping tests; or is used for reinjection, the temperature reduction when cool fluid is pumped from the surface into the well causes contraction of the steel with a resultant tensile force. This tensile force can exceed the original resultant axial force.
Casing failures can occur if the well is not cooled in accordance with a strict well quenching and cooling programme. A slow and gradual cooling process allows the stress to be uniformly distributed over the full length of casing is essential.

Tensile axial loading of the top section of casing, which anchors the wellhead against the lifting force applied by the fluid in the well is:-

$$F_w = (\pi/4) P_w d^2$$

where

$F_w$ = lifting force due to wellhead pressure
$P_w$ – maximum wellhead pressure
$d$ = pipe inside diameter

The design factor for all axial tensile and compressive loading shall not be less than 1.2

### *Axial Loading with Buckling and Bending*

The setting of un-cemented liners through the production section of a well presents a number of design problems. Liners are either hung in tension using a liner hanger from just above the production casing shoe, or more preferably sat on the bottom of the hole with the top of the liner sitting free inside the production casing shoe – in this case the liner is in compression.
The perforated liner in the production section of the well is not cemented and is therefore not radially supported or constrained. Liners in this situation is subject to axial self weight compression and helical buckling and therefore must be analysed for extreme fibre compressive stress.

$$f_c = L_z W_p g [(1/A_p) + (D e/2l_p)]$$

where:

$f_c$ = total extreme fibre compressive stress due to axial and bending forces.
$L_z$ = length of liner
$W_p$= nominal unit weight of casing
$g$ = acceleration due to gravity
$A_p$ = cross sectional area of pipe
$D$ = pipe outside diameter
$e$ = eccentricity (actual hole diameter minus $D$)
$L_p$ = net moment of inertia of the pipe section, allowing for slotting or perforating.

While the hole is drilled with a drill bit of known diameter, the actual hole diameter is usually some greater – due reaming caused by stabiliser, hole erosion and in some formations washouts. An uncemented liner string supported at the hole bottom and subject to compressive self weight stressing, will bend helically, within the limits set by the hole wall. The ratio of the hole diameter to the pipe diameter (eccentricity), will determine the amount of bending and therefore the bending stresses.
The buckling analysis is sensitive to the eccentricity term. It is therefore necessary to analyses for a range of actual hole diameters from the bit diameter up to

around 1.5 times the bit diameter, depending formation integrity.

The design factor is –

$$\frac{\text{minimum yield stress x } R_j}{\text{total compressive stress}}$$

where ($R_j$) – the connection joint efficiency does not exceed 1.0.

where ($R_j$) – the connection joint efficiency does exceed 1.0., the design factor is –

$$\frac{\text{minimum yield stress}}{\text{total compressive stress}}$$

and shall be not less than 1.2.

The ability of the casing string to resist the above loadings is governed by the steel grade (which prescribes its strength), the type of connections, and the loading condition at the neutral temperature state. As high strength steels are susceptible to stress corrosion cracking in a geothermal ($H_2S$) environment, API Grade K-55 and L-80 grade steels are typically utilised. The "round" (Vee) threaded couplings typically used in oil and gas wells, tend to jump threads under high compressive loads. Geothermal service requires a square thread form and/or shouldered connections to transfer the full axial loading of the pipe body. API buttress threads and various proprietary square threaded connections have been found to be suitable.

## RADIAL STRESS CONDITIONS

Radial (Hoop or circumferential) loadings are applied primarily by internal and/or external fluid pressures. The ability of tubulars to resist the resultant differential pressures are listed in the API Standards.
In particular consideration must be given to;-

- The differential pressures that occur before and during cementing operations
- Well fluid pressures in the static condition or when producing or reinjecting.

### *Internal Yield – Bursting*

The casing design must ensure that adequate safety margins exist against internal yield or 'burst, resulting from high internal fluid pressure due to a range of situations that occur during and after the cementing of the casing.
The maximum differential burst pressures usually occur near the casing shoe or stage cementing collar ports and will apply when-

- The casing is filled with high density cement slurry
- The annulus is either completely filled with water back to the surface or partially filled with water as controlled by formation pressure.
- A restriction within the casing, such as a blocked float valve or a cementing plug which will hold the differential pressure.

This scenario is not a likely situation, but it is possible, and therefore must be taken as a worst case scenario.
The differential burst pressure in this case is:-

The hydrostatic pressure inside the casing at the casing shoe caused by the cement slurry plus any applied pumping pressure – minus the hydrostatic pressure in the annulus at the casing shoe caused by the head of water in the annulus.

$$P_i = [(L_f\ G_f + P_p) - (L_z\ G_z)]g$$

Where:
$P_i$ = maximum differential internal pressure
$L_f$ = height above casing shoe of cement column inside casing
$G_f$ = cement slurry density (eg 1.87 kg/l)
$P_p$ = applied pumping pressure
$L_z$ = height above casing shoe of water column in annulus
$G_z$ = mean density of water in annulus

The design factor is:-

$$\frac{\text{casing internal yield pressure}}{\text{differential burst pressure}}$$

and the design factor shall be not less than 1.5.

Once the cement has been successfully displaced to the annulus and the well completed, the maximum differential burst pressure will occur at the wellhead and will be as a result of the wellhead pressure.
The design factor will be:-

$$\frac{\text{casing internal yield pressure}}{\text{maximum wellhead pressure}}$$

and the design factor shall be not less than 1.8.

Typically the maximum wellhead pressure occurs when the well is left shut in and a cold gas cap develops within the casing depressing that static water level to the casing shoe.
In this case the casing internal yield pressure must be limited by the sulphide stress corrosion limit.

If the casing being considered is the Anchor casing, to which the wellhead is connected, biaxial stressing will apply – the combination of the radial burst stresses and the tensile stress caused by the lifting force of the wellhead pressure against the wellhead.
The combined effects of axial and rradial tension is calculated by the expression:-

$$f_t = \sqrt{3}/2\ (P_w\ d)/(D\text{-}d)$$

Where:

- $F$ = maximum tensile stress
- $Pw$ = maximum wellhead pressure
- $D$ = casing outside diameter
- $d$ = casing inside diameter

The top section of the anchor casing – from surface to around 25 m depth, also requires design compliance with the ASME Boiler and Pressure Vessel Code

### *Collapse*

The casing design shall ensure an adequate margin of safety against pipe collapse due to external pressure from entrapped liquid expansion, applied pressure during pumping, and/or static pressure from a dense liquid column such as cement slurry.

Typically, the maximum differential external pressure occurs at the completion of displacement of high density cement slurry from inside the casing to the annulus. At this time the annulus is totally filled with high density cement slurry, and the inside is filled with water.

The hydrostatic pressure outside the casing at the casing shoe caused by the cement slurry plus any applied pumping pressure (such as a cement squeeze pressure) – minus the hydrostatic pressure inside the casing at the casing shoe caused by the head of water in the casing.

$$p_z = [\,(L_z\, G_z + P_p) - (L_f\ \ G_f\,)\,]g$$

Where:

- $P_z$ = maximum differential external pressure
- $L_f$ = height above casing shoe of water column inside casing
- $G_f$ = mean density of water column inside casing.
- $L_z$ = height above casing shoe of cement slurry column in annulus
- $G_z$ = density of cement slurry in annulus (eg 1.87 kg/l)
- $P_p$ = applied pumping pressure

The design factor is:-

$$\frac{\text{casing external collapse pressure}}{\text{net external pressure}}$$

and the design factor shall be not less than 1.2.

It is to be noted that the large diameter, relatively thin walled surface and intermediate casings are particularly susceptible to this mode of failure.

For example:- the standard $18^5/_8$” diameter 87.5 lb/ft, Grade K-55 casing has a collapse pressure rating of only 4.3 MPa. If the design factor of 1.2 is applied, the maximum allowable differential collapse pressure is 3.58 MPa.
This implies that the deepest this casing can be set and cemented with a standard SG 1.87 cement slurry totally displaced to the annulus is 420 m depth.

### *Thermal Expansion of Trapped Fluid*

As the bulk modulus of thermal expansion of water is not constant, particularly at low temperatures and pressures, the effect of heating water in a wholly confined space is best calculated by reference to the steam table, using a constant specific volume. However, at temperatures above 100°C, the resultant pressure rise due to change in temperature approximates to 1.6 MPa/°C.

The rated collapse pressure of $9^5/_8$” 47 lb/ft Grade L-80 casing is 32.8 MPa. In the event that a volume of water was trapped between an outer casing and this $9^5/_8$” casing, the collapse pressure of the $9^5/_8$” casing would be reached with a temperature rise of less than 20.5°C, although a large volume of trapped water would be required to deform the pipe to failure.
As indicated previously, a temperature rise from a nominal neutral temperature of say 80°C to a formation temperature of 240°C is typical, and therefore the maximum pressure possible from the thermal expansion of a trapped volume of liquid between casings far exceeds the strengths of normal casings strings in either burst or collapse. Because it is important to retain the integrity of the production casing string, it is desirable that any failure should be designed to occur in the outer string. Therefore, for the final pair of cemented casings, the collapse resistance of the inner string should exceed the burst resistance of the outer string with a design factor of not less than 1.2, being the ratio of:-

$$\frac{\text{production casing collapse strength}}{\text{outer casing burst strength}}$$

The added resistance to ‘burst’ provided by the cement sheath is to a degree countered by the secondary stressing effects of the thermal axial compression, which tends to reduce the resistance to burst and increase the resistance to collapse.
For the purposes of design calculations and in the interests of conservative design, this support provided by the cement sheath is ignored.

## WELLHEADS

The permanent wellhead components include:

- Casing Head Flange (CHF) usually, and preferably, attached to the top of the Anchor casing – but in some instances is attached directly to the top of the production casing. The casing head flange may incorporate side outlets to which side valve are attached.

- Double flanged Expansion / Adaptor spool. Side outlets may be incorporated in the expansion spool (as an alternative to those on the CHF).
- Master Valve

A typical wellhead assembly for a ‘Standard’ well completed with an 8½” diameter production hole section, $9^5/_8$” production casing and $13^3/_8$” anchor casing is illustrated schematically in Figure 3 below.

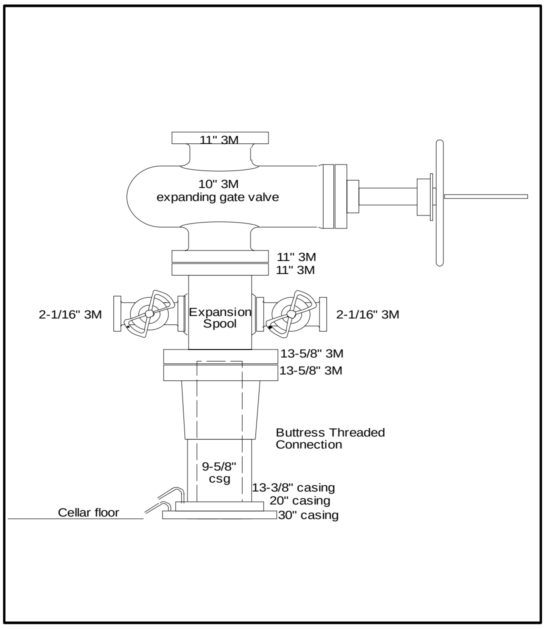


Figure 3. Typical Completion Wellhead.

In spite of the best efforts made in cementing the casing strings, there is usually some residual relative axial thermal expansion between casings at the surface. If the wellhead is mounted on the anchor casing (which is typical), the production casing movements relative to the anchor casing is accommodated below the master valve, within a double flanged spool such that interference with the base of the master valve is prevented.
The wellhead should be designed to comply with codes of practice for pressure vessels or boilers, and in accordance with API Spec. 6A – and most importantly, rated for the maximum pressure / temperature exposure possible at the surface under static or flowing conditions. The fluid at the wellhead may be water, saturated steam, superheated steam, cold gas, or mixtures of some of these fluids. Due to the column of fluid in the well, surface conditions cannot equate to downhole values, but in some circumstances can approach downhole conditions closely.

The pressure ratings are derated as temperature increases in accordance with ANSI B16.5 and API 6A. The derated pressures are plotted against temperature in Figure 3.

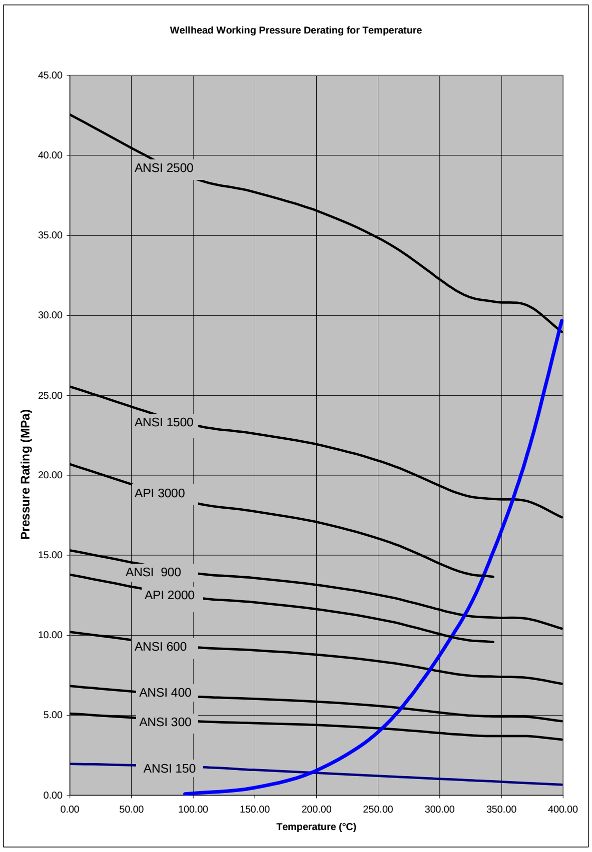


Figure 4. Wellhead Working Pressure Derated for Temperature.

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