INTEGRATED DESIGN AND OPERATION OF PLUG AND ABANDONMENT OF GEOTHERMAL WELLS

B. T. H. Marbun [1], A. R. Novrianto[2], M. I. Firdaus[2], D. Setiawan[2], Y. A. S. Pradana[2],

J. W. A. Nugroho[2] and D. R. Duha[2]

[1]Geothermal Engineering, Institute of Technology Bandung, Indonesia

[2]Petroleum Engineering, Institute of Technology Bandung, Indonesia

bonar.marbun@tm.itb.ac.id

Keywords: *Well abandonment, designing, workflow*

ABSTRACT

The well abandonment operation is part of a well life cycle. It is needed to terminate efforts to produce reservoir fluid from a drilled well and to plug the well without adversely affecting the environment. Failure of the design of the well abandonment may result in harm to the surrounding vegetation near the abandoned well. Plug and abandonment in geothermal wells has many challenges and complexities that increase the cost and the probability of failure, especially in the well abandonment operation. Furthermore, standards for the well abandonment design and procedure for geothermal wells are still not yet available.

On the other hand, in the petroleum industry, there are several guidelines and standards that are usually used for plugging and abandoning the well, i.e. American Petroleum Institute (API) Recommended Practice (RP) 96, API Bulletin E3, and *Norsk Sokkels Konkuranseposisjon* (NORSOK) Standard D-010. Those standards should be modified, so they can be applied for plugging and abandoning geothermal wells. Each requirement of the well abandonment operation based on those standards should then adapted for the design methodology.

In this study, a workflow is proposed for designing a well abandonment operation for a geothermal well based on the modified plug and abandonment procedures that are used in the petroleum industry. The proposed workflow of the plug and abandonment operation is then verified using Field X data. The result of the study shows that the proposed workflow can be used for plugging and abandoning Well Y in Field X. Thus, the plug and abandonment of geothermal wells in Field X can be designed and optimized accurately.

1. INTRODUCTION

The life cycle of wells, either in the oil and gas industry or in the geothermal industry, and for exploration, production or injection wells, is started with the drilling phase, and ends with the abandonment phase. The abandonment process, also called the “plug and abandon” process, has to be carried out after the production phase, when the well is uneconomical for production. Also, this phase may be implemented after the drilling phase, when we cannot continue the drilling process through the loss zone, or when the reservoir is not economical for production.

Plug and abandonment in oil and gas industry has several standards that are usually used, such as American Petroleum Institute (API) RP 96, API Bulletin E3, and *Norsk Sokkels Konkuranseposisjon* (NORSOK) Standard D-010. These standards regulate the process and give some procedures that can be used so that plug and abandonment of a well can be done effectively. However, in the geothermal industry, there is no standard that give instructions how to carry out a plug and abandonment operation in an effective way. Consequently, more attention should be given to geothermal systems, which have some different characteristics to oil and gas systems. Geothermal systems have a high temperature, ranging from 160ºC to 300ºC, very hard formations, with compressive strength up to 240 MPa, highly fractured formations, abrasive formations, consisting of up to 50% quartz, and under-pressured formations. In addition, geothermal systems contain water and its impurities, and non-condensable gas, such as: CO_2, H_2S, CH_4 H_2, Hg, and NH_3 (G. Bidini, et al 1999). Thus it is certainly a challenge to do the plug and abandon process for geothermal wells, and to ensure that the designs used meet the objectives.

As a result, in order to develop an effective well plug and abandonment operation, this study uses the oil and gas plug and abandonment standards as a basis, but introduces modifications so that they can be applied for plugging and abandoning geothermal wells, overcoming the constraints of the geothermal operations.

2. METHODOLOGY

In this paper, a geothermal plug and abandonment workflow has been developed. The geothermal well abandonment methodology must comply with local regulation and guidelines. This workflow was developed based on American Petroleum Insitute (API) Recommended Practice (RP) 96, API Bulletin E3, and *Norsk Sokkels Konkuranseposisjon* (NORSOK) Standard D-010. From the oil and gas standard, modifications are made to adapt to the environmental conditions of geothermal. This modification was conducted by using New Zealand Standard (NZS) 2403: 1991 as an additional reference.

The approach of geothermal well abandonment design will consider several factor such as well data, geological data, material and equipment design, and plugging methods. This methodology of study is presented as flowchart in Figure 1: **Methodology**

3. BASIC THEORY

3.1 Comparison of Oil & Gas and Geothermal Wells

A comparation of oil & gas and geothermal wells is summarized in Table 1.

3.2 Plug & Abandon Theory and Elements

3.2.1 Plug & Abandonment in Geothermal

Based on the New Zealand Standard, NZS 2403:1991, Abandonment refers to the sealing of a well in a safe and permanent manner which precludes subsequent flow from the well. The reasons a well may be abandoned (NZS 2403:1991) include:

- Resource management including reduction of draw-off and flow between different sections of a reservoir.
- The well has reached the end of its useful life.
- Well components have failed or deteriorated.
- The well is not to be used for a long period.

In a geothermal well, the plug and abandon operation needs to be adapted to the specific conditions of the geothermal environment. In this study, the specific conditions to be considered are focused on:

- Higher Temperature System
  Higher temperature can affect the cement hydration process and the strength of the cement.
- Highly Saline formation water and water containing toxic heavy metals. Saline brines and other destructive materials can cause degradation of the cement.
- H_2S and CO_2 content. The content of H_2S and CO_2 can reduce the strength of the cement over time, as a result of a deterioration phenomenon.
- Loss of circulation. Loss of circulation problems can complicate the process of plug and abandon operation.

3.2.2 Well Barrier

The well barrier is one of the principal points in designing a well plug and abandon program. As pointed out in the Oil and Gas standard, NORSOK D-010 (revision in 2004), the function of the well barrier is to prevent the flow from a source.

By adapting and modifying the Oil & Gas standard, the well barriers which are used in geothermal well can be listed as follows:

- Liner Top or Lap Seal
- Cement Plug (Except surface)
- Bridge Plug or Cement Retainer
- Casing
- Surface Cement Plug
- Cement Behind Casing
- Casing Hanger Seal Assembly

3.2.3 Plug Material & Method

Plug Material

Cement is the material that is usually used as the barrier and plug in wells. The cement may vary in complexity, but that usually used is based on Portland cement, which is known as hydraulic cement. When hydraulic cement reacts chemically with water, it will gradually set and harden.

In a geothermal well, the material used in plug and abandonment operations need to be modified for the geothermal environment, so that the purpose of the operation can be achieved.

1. High Temperatures will cause cement to loose its strength, above a particular temperature of approximately 110^0C. Normally cement in a geothermal well will need 6.9 MPa / 1000 psi compressive strength and water permeability of less than 10^{-4} m^2 / 0.1 mD (API Task Group on Cement for Geothermal Wells 1985). Portland class G & J cements are used for high temperature applications, together with silica flour and the omission of extenders. However, if the cement is required to work at 400^0C, high alumina cement provides more stability, as Portland Cement shows declining bond strength in the first 70 cycles (Berard et al., 2009).

2. Carbon dioxide (CO_2) is one of typical components in downhole fluids. As CO_2 comes into contact with the Portland cement that is used to cement well casings, carbonation happen, which is a deterioration phenomenon in the cement. This phenomenon can cause serious damage to downhole casings and destroy zonal isolation integrity over time, which leads to costly remedial services or even abandonment of a well.
   From field analysis, the amount of cement carbonation relies on the fraction of CO_2 in the fluid, cement agents and temperature. To avoid reduction of the strength, the cement system must be designed with low bulk lime to silica (C/S) ratio, of less than or equal to 1.0 (Nelson and Gouedard 2006) and low permeability as well, but it does not apply in environments which have high levels of CO2 (Hedenquest and Stewart 1985). Tubermorite and Xonotlite are the cement phases which respond least well to carbonation, and their deterioration is accelerated when bentonite is present in the cement (Eilers, Nelson and Moran 1980). Reducing the silica flour concentration from 35% to 20%, by weight of cement (BWOC), improves the cement resistance to CO_2 (Milestone et al. 1986). For high levels of CO_2, it is necessary to use calcium alumino-silicate or calcium phosphate to prevent a weight loss. In order to increase the ability of Portland cement to withstand corrosion, fly ash or latex can be used (Berard *et al*., 2009).

3. Cement resistance to sulfate is a critical criteria for cement used in geothermal wells. This is important to prevent deterioration of downhole cement caused by sulfate attack from formation waters. The selection of high sulfate resistance will improve its durability in the geothermal environment, and reduce the risk of deterioration.

There are other considerations in designing cement which will be used to plug a well. The cement slurry must have free water values as low as possible, even down to 0%. This is done to avoid trapped water boiling or flashing, due to the high geothermal temperature (Diaz, 2015).

3.3 Plug & Abandon Standard

Table 3 shows a comparison between three standards related to plug and abandonment operations. First of all is NZS 2403-1991. The second standard used is NORSOK, which discusses the plug & abandon process in Chapter 9. The third standard that is compared to the other standards is API Bull E3.

3.4 Plug Procedures & Design

- *Analysis of the well proposed to be plugged and abandoned.*

The existing condition of the well components needs to be assessed, as it may affect either the abandonment operation or the long term effectiveness of the abandonment. In particular, the following conditions need to be adequately understood before the well is abandoned (NZS 2403:1991):

i) The nature, size and depth of any obstruction in the casing.
ii) The nature and depth of any penetration (e.g. by parting, corrosion or perforating) of the casing allowing fluids to pass through the casing wall.
iii) Static downhole temperatures
iv) Static water levels and pressures
v) Section of uncemented or poorly cemented lengths of casing
vi) Any annulus between the casing which is not sealed
vii) Any change in heat flow at, or adjacent to the well site, which may be associated with deterioration of well components below ground level.

By analyzing the well, we can determine which parts of the well can be used as the well barrier and the depth of the plug placement.

The casing integrity needs to be considered, as it can be a major reason as to whether or not the casing can be used as a barrier. So does the state of the cement behind the casing. If it is poorly cemented or not good enough to become a barrier, then remedial cementing by squeeze cementing should be done.

This is because at the time of cement placement in a geothermal well, the temperature of the casing tends to be lower due to the influence of the cement slurry temperature which is lower than the formation temperature. After some time, the temperature increases and the cement will exposed to great thermal stress (Steingrimsson. 2011). Additionally, poor cementing will cause the casing to expand and damage the cement.

Evaluation of the cement behind the casing (annular cement) can be done by using a Cement Bond Log/Variable Density Log (CBL/VDL). However, the temperature of the tool should be monitored as it normally operates in oil and gas environment, which has a maximum temperature of 175ºC. So for a geothermal well, different equipment with a higher temperature rating is required.

- *Conduct a geological analysis*

Geological analysis will provide us with geological status and information such as lithology, risks, and hazards regarding the plug and abandonment operation.

- *Determine intervals of isolation*

After studying the well and analysing the formation lithology, we can determine the interval of isolation. For geothermal wells, there are a number of zones that can potentially flow and need to be isolated:

i) Top of reservoir (initial plug)
ii) Injection/disposal intervals
iii) Loss of circulation zones
iv) Overpressured zones
v) Casing stubs
vi) Casing shoe for open hole completed wells
vii) Liner tops
viii) Unrecovered casing string
ix) Casing shoe with or without cement behind pipe
x) Surface

- *Plugging material selection.*

Material selection is crucial, as geothermal specific characteristics are required. Modification to cement properties need to be made to ensure that the materials can isolate the well properly.

- *Plug design.*

Cement plug design is important for determining the height/volume of cement slurry that will be required to plug each interval. Considering intervals of isolation above, the implementation of abandonment will require setting a cement plug along the production casing. The cement is set above a competent plug, such as the bridge plug or packer, close to the casing shoe of the production casing (NZS 2403:1991).

With a greater possibility of buckling or collapse in geothermal wells, the plugging method need adjustment to the casing condition, as there will is likely to be an obstacle when the tool is run into the well (Diaz, 2015). To overcome this problem, running a calliper survey can be used to detect obstacles in the casing.

- *Design plug and abandon well schematic.*

A well schematic can be used to summarize the whole process and to design the plug and abandonment operation, so it can be easily understood and evaluated in the future.

4. CASE STUDY

Well Y is an exploration well which is located in Indonesia. Well Y reaches 2,142.51 mMD. The purpose of drilling well Y was to get subsurface data and to prove geothermal potential of the reservoir.

4.1 Well Y Geological Information

Megascopic analysis that is obtained from the drill cutting of Well Y, from depth interval 36 mMD – 2413 mMD, shows interbedded layers of breccia andesite, tuff metamorphic breccia, metamorphic breccia andesite, metamorphic andesite, and metamorphic andesite basaltic.

Another consideration in planning the plug and abandon process in well Y was the analysis of pressure temperature (PT) data. The PT survey results are shown in Table 3, and plotted as graphs in Figure 2.

Table 3: PT Survey of Well Y

Elevation (m)	BPD (deg.C)	Pressure (bar)	Elevation (m)	BPD (deg.C)	Pressure (bar)
804.670	107.049	1.297	-121.290	292.328	76.973
699.908	156.303	5.622	-199.017	298.889	84.541
608.664	181.960	10.486	-273.364	304.162	91.027
557.972	197.694	14.811	-337.573	309.154	97.514
487.005	215.585	21.297	-415.300	314.280	104.541
426.175	228.572	27.243	-489.647	318.045	109.946
351.828	241.354	34.270	-567.373	322.728	116.973
274.101	251.471	40.757	-641.720	326.522	122.918

Elevation (m)	BPD (deg.C)	Pressure (bar)	Elevation (m)	BPD (deg.C)	Pressure (bar)
203.134	261.125	47.784	-695.791	329.848	128.324
132.166	268.478	53.730	-756.621	332.748	133.189
54.439	277.562	61.838	-817.450	336.180	139.136
-9.770	283.661	67.784	-868.141	338.603	143.459
-70.599	288.354	72.649	-905.315	340.087	146.162

4.2 Drilling Problems

When Well Y was drilled, it had some drilling problems. They were:

a. Partial Loss
20 bbls was lost to the formation when well Y reached 692 – 695 mMD. It also happened when well Y was drilled from 765 mMD until 930 mMD. At this interval depth, it took 0.5 – 2 BPM.
b. Tight Hole
Tight hole conditions were observed at 1812 mMD to 1875 mMD, with tripping out of the logging tool.
c. High Torque
High torque was observed between 147 mMD and 2143 mMD.
d. There was a fish in the bottom hole. The fish was a two cone 6"bit as there was damage in the 6" bit, although the bit is in a good condition.

4.3 Well Abandonment Procedure

4.3.1 Plugging Material and Equipment

In order to plug well Y, cement can be used as the plugging material as based on the information from the well Y data, the geological information, and the requirements that are provided. Furthermore, cement has high compressibility and the fluid loss results are low. Generally, there are eight types of cement, but, cement class "G" was used as it can be used in all depths interval, especially when combined with a retarder as high temperatures which are found in the geothermal well can accelerate the thickening time.

Based on API, mechanical plugs were used along with cement plugs. Consequently, a cement retainer is required to provide additional protection for isolating well Y. The selected cement plug and the cement retainer will influence the plugging design.

4.3.2 Plugging Design

Designing the plugging method started with selecting the zones that were going to be isolated in well Y. Based on the geological information and well data, there were eleven critical zones that had to be isolated with the cement plugs, namely:

1. Loss of circulation zone at 692 – 695 mMD (first loss zone)
2. Loss of circulation zone at 765 – 930 mMD (second loss zone)
3. 30" casing shoe at 36 mMD
4. 20" casing shoe at 143 mMD
5. 13-3/8" casing shoe at 427 mMD
6. 9-5/8" casing shoe at 928 mMD
7. Top liner 7" at 878.89 mMD
8. Shoe liner 7" at 1895 mMD
9. Top liner 4 ½" at 1,863.51 mMD
10. Shoe liner 4 ½" at 2,142.51 mMD
11. Surface

The eleven critical zones to be isolated with the cement plugs and the volume of the cement plugs required, had to be determined by the methodology provided. A standard plugging operation would require eleven cement plugs to be set in Well Y. However the interval of critical zones number 6 and 7 can be coupled with the critical zone number 2. Therefore, there were only nine major points for cement plugs required in order to plug Well Y. The cementing process was done by setting the cement plug along the production casing.

4.3.3 Well Abandonment Schematic

The last step in designing a well abandonment operation is making a well abandonment schematic. It is important as it records the complete schematic of the well when plug and abandonment operation is completed.

5. CONCLUSION

The geothermal industry does not have a detailed standards and procedures for implementing the Plug & Abandon operation. As the basic reference, oil and gas standards are used (API and NORSOK). In addition, NZS also used as guide for geothermal operations. Modifications were made by comparing the standards and used to develop a Plug & Abandon procedure for Geothermal.

As validation for the established new Plug & Abandon procedure in Geothermal, a case study of Well Y was executed using the new Plug & Abandon procedure.

The results of the study show that the proposed workflow could be used for plugging and abandoning Well Y in Field X. Therefore, the plug and abandonment of geothermal wells in Field X can be designed and optimized accurately.

REFERENCES

Marbun, B.T.H., 2016. Internal Report.

American Petroleum Institute. 1993. *API Bulletin E3 – Well Abandonment and Inactive Well Practices for US Exploratory and Production Operations*, first edition. Washington, D.C.: API Publishing Services.

Standards Association of New Zealand. 1991. *Code Practice for Deep Geothermal Wells*, Wellington.

Standards Norway. 2004. *NORSOK Standard D-010: Well Integrity in Drilling and Well Operations*, Revision 3, Strandveien.

Bourgoyne, A.T., Millheim, K.K., Chenevert, M.E. et al. 1986. *Applied Drilling Engineering*, first edition. SPE Text Book Series.

Halliburton. 2016. *Cementing Solutions for Geothermal Wells*, http://www.halliburton.com/en-US/ps/solutions/clean-energy/geothermal-energy/cementing-solutions-for-geothermal-wells.page (accessed 11 Aug 2016).

Salim, P. and Amani, M. 2013. *Principal Points in Cementing Geothermal Wells*. CSCanada - Advances in Petroleum Exploration and Development.

http://dx.doi.org/10.3968/j.aped.1925543820130501.1145.

Arianto, S., Souvanir, T., and Fuad , A. 2016. *Plug and Abandonment of Geothermal Obeservation Wells Using Coiled Tubing and in Compliance with Global Standard*. Presented at the Indonesia International Geothermal Convention &Exhibition, Jakarta.

Steingrimsson, B. 2011. *Geothermal Well Logging: Cement Bond and Caliper Logs*. Presented at Short Course on Geothermal Drilling, Resource Development and Power Plants – United Nations University Geothermal Trining Programme, Santa Tecla, El Savador 2011.

APPENDIX

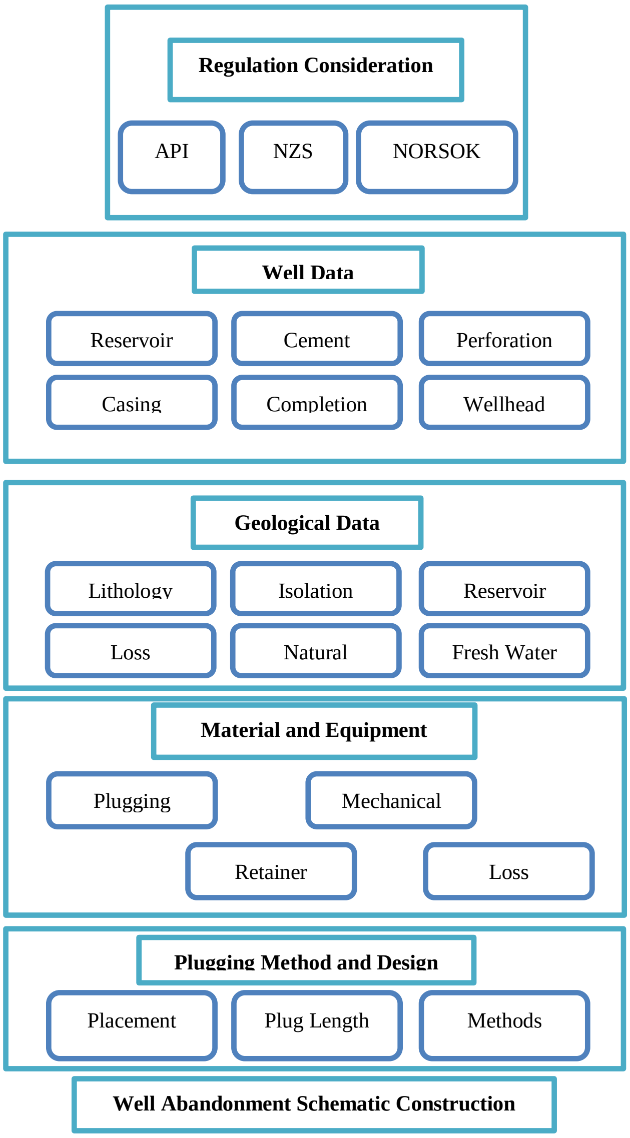

Figure 1: Methodology

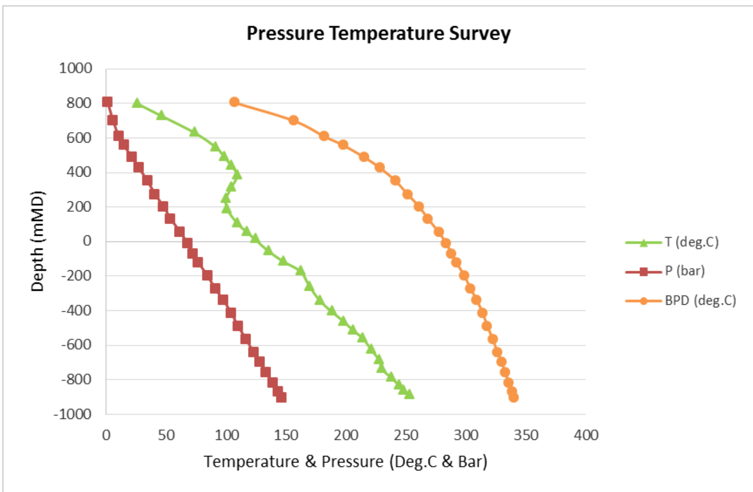

Figure 2: Pressure Temperature Survey

Table 1: Oil & Gas and Geothermal Characteristics Comparison

No	Category	Characteristics	
		Oil and Gas	Geothermal
1	Temperature	Average earth temperature, typically 25°C/km. In some cases, especially in deep well, the temperature could be higher.	Geothermal area has higher than average subsurface temperatures. The production temperature intervals from 160°C to above 300°C.
2	Rock Types	Clastic and Biogenic Sedimentary formations.	Granite, granodiorite, quartzite, greywacke, basalt, rhyolite and volcanic tuff.
3	Rock Compressive Strength	Generally has a lower compressive strength range of 50-150 MPa.	Typically hard, above 240 MPa compressive strength.
5	Permeability	Has a lower permeability values, thus generally use milidarcy unit.	High fracture permeability dominated the geothermal resource productivity.
6	Porosity	Generally has single porosity, but in some reservoirs such as carbonate and limestone, has double porosity.	All commercial hydrothermal resources exist as dual porosity systems which have both matrix and fracture porosity.
7	Impurities	In some field, it is common to encounter some problems related with corrosive fluid, high solid content, and dissolved or free CO_2.	1. Often contain corrosive fluids, and some formation have a very high solid content. 2. Dissolved or free CO_2 and H_2S gases are usually found in most of geothermal systems.
8	Production Fluid	Oil and/or Gas	Hot water and/or steam
9	Production Rate	-	Geothermal wells produce fluid —hot water or steam— with higher flow rates (often >100,000 kg/hr) than for oil and gas wells.
10	Production Tubular	In most oil wells, it produce from the reservoir through production tubing inside casing.	Produce directly from the reservoir into the casing
11	Well Configuration	The most common well configuration used is conductor, surface casing, intermediate casing and production casing.	Larger casing diameter is needed in geothermal well, compared to oil and gas wells of comparable depth.

Table 2: Comparison of Plug & Abandon Standards

No	Categories	Standard		
		NZS 2430:1991	**NORSOK D-010**	**API BULL E3**
1	General	1. Temporary Abandonment 2. Permanent Abandonment	1. Suspension of well activities and operations 2. Temporary abandonment of wells 3. Permanent abandonment of wells 4. Permanent abandonment of a section in a well	1. Guidance on procedures for permanently plugging and abandoning a well used in onshore E&P operations 2. The procedures involve setting cement plugs at critical intervals to prevent the wellbore from becoming a conduit for fluid migration 3. The primary objectives of a well abandonment operation are protecting fresh water aquifers and confining hydrocarbon resources
2	Abandonment Criteria	1. Resource management including reduction of draw-off and flow between different sections of a reservoir 2. The well has reached the end of its useful life 3. Well components have failed or deteriorated in a manner which renders the well potentially unsafe or not economically repairable 4. The well is not to be used for a long period	N/A	N/A
	Well Assessment	1. The nature, size and depth of any obstruction in the casing 2. The nature and depth of any penetration (e.g. by parting, corrosion or perforating) of the casing allowing fluids to pass throgh the casing wall 3. Static downhole temperatures 4. Static water levels and pressures 5. Sections of uncemented or poorly cemented lengths of casing 6. Any annulus between casings which is not sealed 7. Any changes in heat flow on or adjacent to the well site, which may be associated with deterioration of well components below ground level.	1. Well configuration including depths and specification of formations which are source of inflow, casing strings 2. Stratigraphic sequence of each wellbore showing reservoir and information about their current and future production potential 3. Logs, data and information from cementing operations 4. Formations with suitable well barrier element properties 5. Specific well conditions such as scale build up, casing wear, collapsed casing, hydrate, CO_2,H_2S, benzene or similar issues	N/A

No	Categories	Standard		
		NZS 2430:1991	**NORSOK D-010**	**API BULL E3**
3	Abandonment Operations/ Method	1. Drilling wellhead including BOPs shall be used for the abandonment of the well 2. The well should be quenched 3. The well should be backfilled from total depth to the production casing shoe with granular heat resistant materials 4. Permanent abandonment shall include filling the production casing with cement plugs which are continous over the length of the casing 5. If the annulus cannot be squeeze cemented, then removal of the upper joints of casing prior to filling the well with cement may be considered 6. Cement placement shall be programmed to minimize dilution of the cement slurry with fluid present in the well 7. Cement material shall be selected to provide minimum deterioration of the set cement with time 8. The well left in a condition which would allow reuse by drilling out the cement, then a cement plug shall be placed to provide not less than 100 m of continous sound cement in casing 9. The cement plug shall be placed on a bridge plug or packer not more than 50 m above the production casing shoe and not less than 10 m above the top of any liner 10. The cement plug shall be placed in a manner which minimizes dilution of the cement slurry by fluids in the well 11. The cement materials should be selected to withstacn ambient fluids and temperatures and also to develop a limited compressive strength to avoid casing damage when the cement is subsequently drilled out 12. The casing above the sound cement shall be filled to the surface with a weak bentonite and cement type of filler 13. The casing head flange and near-surface casing shall be protected against corrosion or damage	N/A	1. Displacement Method 2. CIBP Method. Perforated intervals may be iso-lated by setting a CIBP (or other permanent casing tools, including a permanent production packer with a plug installed) 50-100 ft from the top set of perfo¬rations 3. Cement Squeeze Method. Set a cement retainer or squeeze packer in the next larger casing at least 50 ft above the casing stub, and squeeze cement below the tool
4	Maintenance of Temporarily Abandoned Wells	1. If there is any indication that geothermal fluids are leaking from the well, then the well shall be uncovered and appropriate remedial action undertaken	N/A	An inactive well should be classified as TA when the completion interval is isolated. The completion interval may be isolated using the bridge plug method, the cement squeeze method, or the balanced cement plug method. As an alternative to the bridge plug method, isolation of the completion interval may also be achieved by installing a plug in an existing packer which does not have tubing.
5	Design and placement of well barrier elements	N/A	1. Downhole placement techniques; 2. Minimum volumes required to mix a homogenous slurry; 3. Surface volume control; 4. Pump efficiency/ -parameters; 5. Contamination of fluids; 6. Shrinkage of cement or plugging material; 7. Casing centralization; 8. Support for heavy slurry; and 9. WBE degradation over time.	1. Critical plugs are those which isolate hydrocarbon pro-ducing zones, injection zones, the lowermost fresh water aquifer, and the surface 2. Critical plug placement should be verified during plugging operations to ensure any fluid migration pathways have been sealed 3. Plug verification is important to ensure that the plug is where it is supposed to be and that the cement has hardened

No	Categories	Standard		
		NZS 2430:1991	NORSOK D-010	API BULL E3
6	Well barrier acceptance criteria	N/A	Permanently abandoned wells shall be plugged with an eternal perspective taking into account the effects of any foreseeable chemical and geological processes. The eternal perspective with regards to re-charge of formation pressure shall be verified and documented.	N/A
7	Risk assessment	N/A	1. Pressure and formation integrity uncertainties 2.Time effects 3. Long term development of reservoir pressure 4. Deterioration of materials used 5. Sagging of weight materials in well fluids. 6. Scale in production tubing; 7. H_2S or CO_2; 8. Release of trapped pressure; 9. Unknown status of equipment or materials; 10.Environmental issues.	1. The key risk factor for inactive wells is the presence of pressured formations which are potential sources of contaminants for fresh water aquifers

WELL Y PROFILE

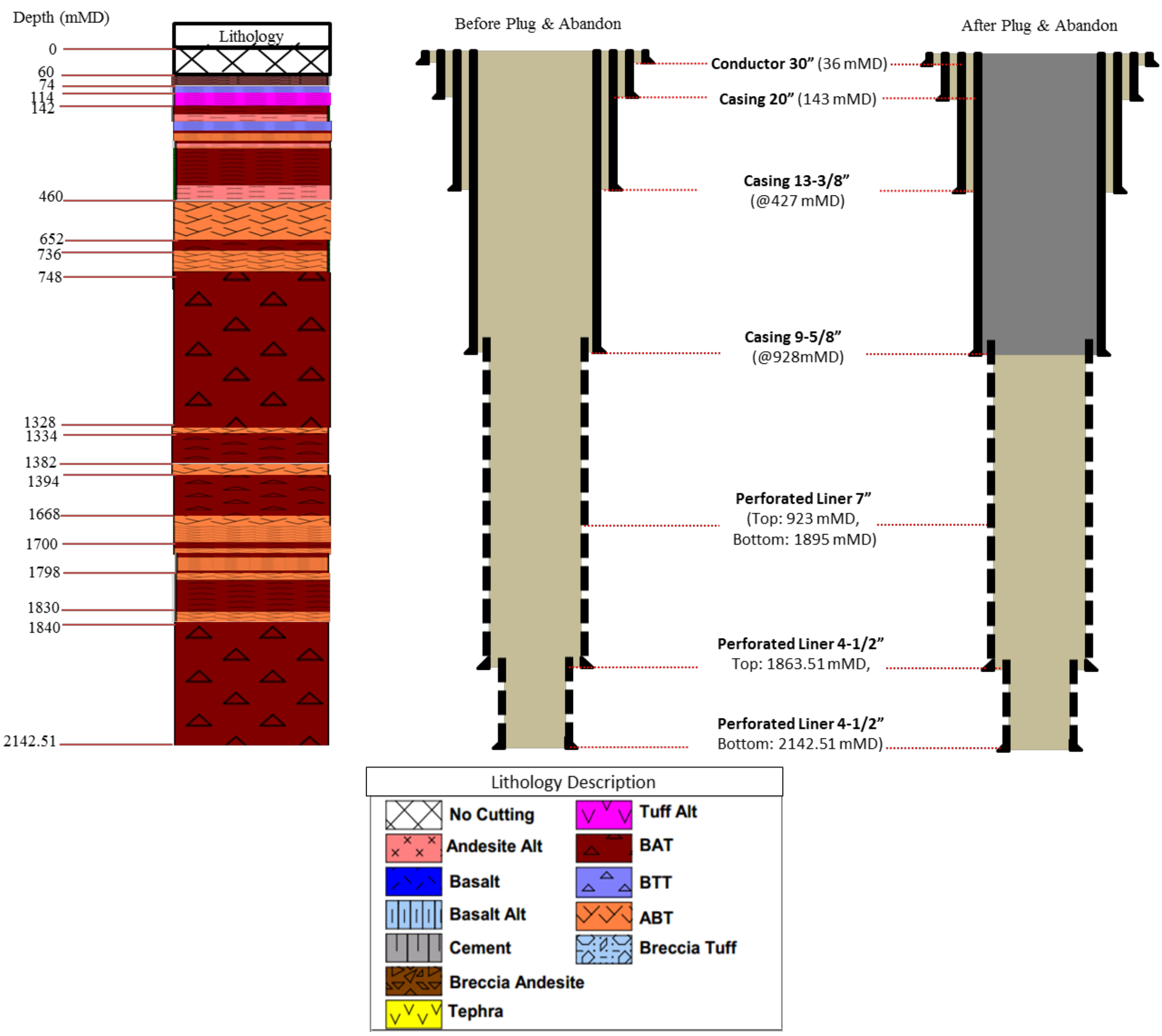

Figure 3: Well Y Profile and Lithology