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COMMON GEOTHERMAL WELL DESIGN AND A CASE STUDY OF THE LOW-TEMPERATURE GEOTHERMAL RESERVOIR IN OTOPENI, ROMANIA

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ABSTRACT

The report describes a design of a well for the low-temperature geothermal, Therme Balotesti reservoir in Otopeni in the Romanian Plain. The well was designed by specialists with great experience in the field using the main features from the offset wells as references. The report includes assumed design calculation regarding the drill string design and casing design characteristics based on the information gathered from various published papers and drilling handbooks. More information for the project could not be accessed due to confidentiality with regard to technical information.

Romania has the third largest potential geothermal capacity in Europe after Greece and Italy. The development of direct utilization of geothermal resources in Romania is however not far advanced due to high investments costs and the very low price of hydrocarbons. Exploration drilling for geothermal resources in Romania started in the 1960s. Over 200 drilled wells for hydrocarbons explorations have been drilled to depths between 800 and 3000 m, encountering geothermal resources of low and medium enthalpy (40-120°C). Thermal springs are the only visible manifestations of geothermal resources across the country. The main direct uses of geothermal heat are district heating and individual space heating and health and recreational bathing. Geothermal energy is also used for greenhouse heating, fish farming, industrial processes and drying. Currently further geothermal development is facing unfavourable conditions as the international market prices for fossil fuels and domestic oil and gas production have dropped dramatically.

1. INTRODUCTION

Geothermal energy is thermal energy generated and stored in the Earth. Geothermal energy extracted from the Earth's crust has a relatively stable temperature and is utilized to generate electricity and to provide heating. Geothermal fluids may be steam or hot water and can serve for electrical power generation or for different projects as space heating, aquaculture, snow melting, food processing and hot tubs and spas. Geothermal energy is a clean and renewable energy resource which can be found in

many places in the world and especially in tectonically active areas. The heat from geothermal sources has been used by mankind from the earliest days for cooking and bathing. Major development has taken place during the past 30-40 years, when significant advances have been made in deep drilling practices. The equipment and techniques used in the drilling of geothermal wells have many similarities with those used in the oil and gas industry.

Drilling operations are performed in order to open up geothermal reservoirs for energy exploitation. The drilling phase of the geothermal power plant requires heavy equipment, such as drill rigs, fuel and materials. Geothermal wells have been used for several decades for the existing heating and cooling systems. The geothermal reservoirs can be high-temperature and steam-dominated or low-temperature water-dominated reservoirs.

Geothermal wells can be expressed like other types of wells with different purposes created by drilling into the Earth's surface, cased and cemented.

There are different geothermal well types which can be utilized in various ways, ranging from wells that connect to sources of steam used to power turbines, to wells utilized for thermal energy with geothermal heat pumps. With the help of a recirculating water system a stable indoor temperature will be maintained for district heating. A geothermal production well can be considered successful when it has sufficient capacity to be connected and utilized in the respective power plant or utilization scheme.

Nowadays price for drilling geothermal wells may be approximately ~2,000 USD/m and take 35-70 days to drill (Thórhallsson, 2016). Several factors influence the costs such as the type of the drilling rig used, cost of materials, total depth of the well and additional services. The hook load capacity dictates the depth that can be reached using a specific rig, a common lifting capacity of 400 tons is quite normal in oil industry, while in geothermal industry for many different reasons to reduce the costs of drilling, smaller rigs may be adequate to reach the target depth safely.

Time spent on drilling (rotating the drill bit) is about 50% of the total, the rest is spent on installing casings, cementing, logging, mobilising the rig and other activities (Thórhallsson, 2016).

2. COMMON WELL DESIGN

The main aspects of the well design process focus on the objectives and the purpose of the well. The well design considers the casing programme selection, casing setting depths and drilling procedures to achieve satisfactory well completion and integrity of the well.

The well construction process can be split into five sequential phases of work, as follows:

1. Preliminary well design;
2. Detailed well design;
3. Preparation of drilling programme;
4. Execution of well programme;
5. Analysis and improvement of performance.

Preliminary and detailed well design are important factors for the preparation of the drilling programme. Once the geological and geophysical studies have identified a potential well location, the subsurface team will work up a basis of design. The preliminary well design will generally involve the following:

- Well name and number;
- Well objectives;

- Total depth;
- Surface location;
- Water depth;
- Target;
- Target size and tolerance;
- Target constraints;
- Geological prognosis;
- Seismic section;
- Expected hydrocarbons;
- Anticipated pore pressures;
- Anticipated temperature profile;
- Offset wells.

A review of all the available offset data and regional data is also needed and includes:

- Pore and fracture pressure plots;
- Time depth curves;
- Daily drilling reports;
- Daily mud reports;
- Mud logging records;
- Bit records;
- Casing and cementing reports;
- Survey records.

This will give an understanding of how previous wells were drilled, what problems were encountered and how they were solved, what casing programme, mud type and density was used, any directional problems experienced, how long the well took to drill, etc.

Detailed well design entails taking the preliminary well design and developing it further to the point that a drilling programme can be prepared. Detailed well design includes, but is not limited, to a detailed engineering study and design of the following areas:

- Pore and fracture pressure profiles;
- Temperature profiles (HPHT wells);
- Casing design;
- Casing running and jewellery (hardware);
- Drilling fluids;
- Hydraulics and hole cleaning;
- Cementing design;
- Trajectory and surveying;
- Torque and drag;
- Drill string design;
- Well abandonment;
- Completion design;
- Well cost and duration;
- Contingency planning.

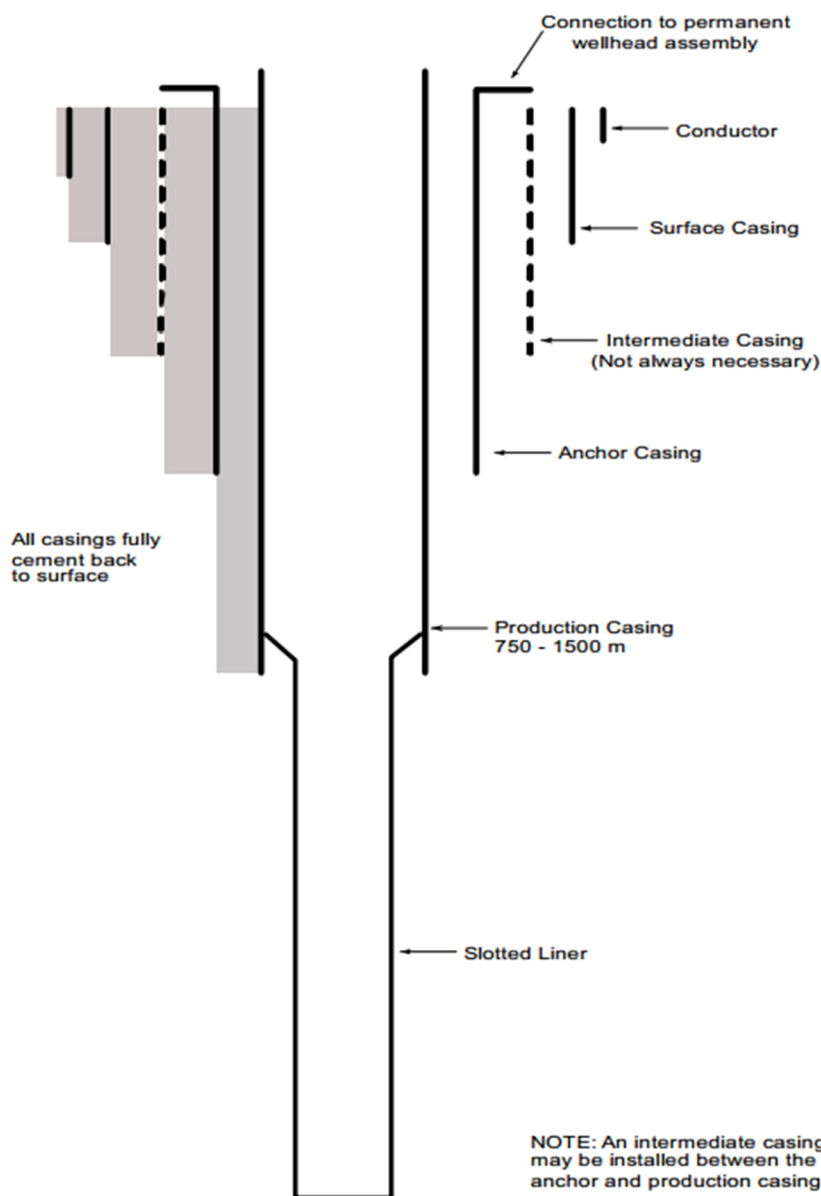
Obviously, the amount of time spent on each area is a function of the complexity of the well being planned.

The initial estimate of determining casing setting depths is best determined graphically, plotting pressure and fracture gradient, expressed in equivalent density, against depth.

Factors that may affect casing depth selection in addition to pore pressure and fracture pressure are:

- Shallow gas zones;
- Fresh water sands;
- Lost circulations zones;
- Directional well profile;
- Hole cleaning;
- High pressure zones;
- Lithology, casing shoes should, where practicable, be set in competent impermeable formations.

The initial casing setting depths need to be adjusted accordingly considering all of the above factors. The design stage involves determining the loads each casing string will be exposed to during the life of the well and the selections of tubular with suitable mechanical and physical properties that can withstand the predicted loads.



As many of these issues are inter-related it is essential that a system of change control be used to ensure that the effect of changing a parameter is carried throughout the complete design. Figure 1 illustrates a typical geothermal well design.

According to Thórhallsson (2016) in low enthalpy reservoirs in Iceland the design of well is based on installing 2-3 casing strings with casing diameters of: 18⁵/₈" , 13³/₈" and 9⁵/₈". The diameter of the open hole is 12¹/₄" or 8¹/₂" as there is no liner. For low-temperature wells under 1,500 m depth, casing sizes of 13³/₈" and 10³/₄" are used and an open hole of 9⁷/₈". All casings for low-temperature well have welded connections.

Prior to the well drilling, both office and rig site personnel from the operator, drilling contractor and additional service providers have a meeting to perform an exercise drilling of the well on paper, aimed to identify any problems ahead of time, obtain information from the rig site personnel as to performance improvements

FIGURE 1: Casing strings and liner for typical geothermal well (Hole, 2008)

that could be made. Regular meetings are a vital tool to maintain the team spirit and provide a vehicle for two ways communication. To reduce the drilling cost there is a need to schedule the next operations and be ahead of all activities, anticipate problems and avoid non-productive time.

2.1 Drill string

The principal components of the drill string consist of the assembled components of drill pipe, heavy weight drill pipe (HWDP), drill collars and special subs and drill bit.

The drill string is used to:

- Lower the bit into the hole and withdraw it;
- To penetrate the formations more effectively, placing weight on the bit;
- Transmit the rotation action to the bit, including axial and torsional loads;
- Transport the drilling fluid and cuttings under pressure from the bit to the surface.

The *Top Drive System (TDS)* or *kelly*, is not exactly part of the drill string but transmits and absorbs torque to or from the drill string while carrying all the tensile load of the drill string.

Drillpipes (DP) are the major component of the drill string and transmit power by rotating motion from the rig to the bit and allow mud circulation.

American Petroleum Institute (API) drill pipes and other tubular products are gauged by the nominal outside diameter (OD) of the tube. The OD of a given pipe must be a specific measurement in order for threaded fittings and pipe-handling tools, such as elevators and slips, to fit properly. Although the OD of API drill pipes is the same for each size, the inside diameter (ID) varies with the nominal weight per unit length. API seamless drill pipes are offered in five grades of steel, varying in strength from D (the weakest) through E, X, G to S (the strongest). High strength drill pipes require heavier and longer upsets than those used on grades D and E. Appendix I shows the different API Specifications Standards.

The most common used grades of steel to meet different hole requirements for drill pipes are G105 and S135. G105 is most commonly used in shallow or H₂S environments. S135 is a high strength drill pipe with heavier and longer upsets than those used on grades D and E (API RP 5A5).

U150 is relatively new grade that is being used for deep water operations.

Heavy weight drill pipes (HWDP) make the transition between drill pipe and drill collars, thus avoiding an abrupt change in cross-sectional area used with drill collars. HWDP can provide weight on the bit. This tubing product is an intermediate sized drill pipe, having the same nominal outside diameter (OD) as a drill pipe but having a smaller interior diameter (ID), thus giving it more strength.

HWDP reduce the stiffness of the Bottom Hole Assembly (BHA). They are easier and faster to handle than drill collars (DC) and one of the important factors is that they reduce the possibility of differential sticking.

Differential sticking occurs when drilling a well with a greater well bore pressure than formation pressure. As a result, the pipe becomes stuck to the wall, and requires additional force to release the stuck pipe string.

Drill collars (DC) are similar to drill pipes, but have larger outside diameters (up to 11 inches) and have small inside diameters. The drill collars provide the desired weight on the bit, keeping the drill pipe section in tension during drilling, and drilling a nearly vertical hole providing the pendulum effect

and the rigidity. The weight on bit (WOB) should not exceed 85% of the buoyed weight of the total drill collar weight to ensure the neutral point remains within the collars.

One important aspect is that the drill pipe should never be subjected to compression, as it would bend and twist-off (break) very easily. That is also the main reason for adding heavy-weight drill pipes to the drill string when deciding how many collars to run, because total drill collar weight must exceed the WOB during drilling.

Other downhole tools include: Stabilizers, crossover, jars, under reamer, measurement while drilling tool (MWD), mud motor, etc.

The word “sub” includes any short length of pipe, collar, casing; all of these drill string components in a certain arrangement below the drill pipe will form the BHA. Crossover subs have different threaded ends to change between different sizes and types of drill pipe or collars.

Stabilizers are short subs with blades which are full borehole size or a fixed amount below gauge. Configuration of blades may be straight or spiral and made from aluminium, rubber or steel with tungsten carbide inserts on the edges. In order to maintain a straight hole, centralized stabilizers are located between the collars, also to maintain a full gauge hole by a scraping action, reduce bit wobble and help prevent wall sticking.

Drilling jars are included in the drill collar string, usually having 3-5 DC above, in order to deliver a sharp blow in order to free the drill string should it become stuck. Hydraulic jars are activated by a straight pull to give an upward blow, mechanical jars may be pre-set at surface and fired downwards by a given compression load.

All the above listed components of the drill string represent an important part of the drilling equipment cost, but the consequence of a downhole failure can be even greater.

Good care must be taken while handling these tubulars, especially for the tool joint which is generally the weakest point.

2.2 Casing design

In the pre-planning stage, important decisions have to be made in selecting casing depths for each casing string to achieve the total depth of the well safely.

In order to allow the drilling and completion of a well, it is necessary to select the drilled open hole diameter with respect to the steel pipe / casing. Once in place, this pipe is cemented, supporting the casing and sealing the annulus in order to:

- Strengthen the hole;
- Isolate unstable/underbalanced / overbalanced formations;
- Prevent the contamination of freshwater reservoirs;
- Provide a pressure control system;
- Confine and contain drilling / completion / produced fluids and solids;
- Support wellhead and additional casing strings;
- Support the blow out preventer (BOP) and Christmas tree (or Xmas tree – named for its crude resemblance to a decorated tree, is an assembly of valves, spools, and fittings used in oil industry);
- Act as a conduit for associated operations (drilling, wireline, completion and further casing / tubing string) with known dimension (Serban, 2014).

Primarily six types of casings are installed in onshore/offshore wells:

- Stove pipe, marine conductor, foundation pile;
- Conductor string;
- Surface casing;
- Intermediate casing / anchor casing;
- Production casing;
- Liner, slotted or perforated with holes.

Casing properties: Casing is usually specified by the following properties:

- Outside diameter;
- Weight per unit length;
- Grade of steel;
- Type of connection;
- Length of joint.

The outside diameter refers to the pipe body and not to the coupling. Diameter of the coupling is important as it determines the minimum hole size that the casing can be run into and the wall thickness determines the inside diameter of the pipe and hence the maximum bit size that can be run through the pipe.

In API Spec 5CT the permitted tolerance on outside diameter and wall thickness is given as a general rule:

Casing outside diameter $\geq 4\frac{1}{2}$ "	Tolerance + 1.00%, - 0.50%
Casing outside diameter $< 4\frac{1}{2}$ "	Tolerance $\pm 0.031\%$
Wall thickness	Tolerance - 12.5%

The mechanical and physical properties of casings are dependent upon the chemical composition of the steel and the heat treatment it receives during manufacture.

API defines nine grades of steel for casing:

H40 J55 K55 C75 L80 N80 C95 P110 Q125

The grade has a letter, which indicates the grade, and a number which indicates the minimum yield strength in thousands of psi, e.g. K55=55,000 psi (API SPEC 5CT). In Table 1 are listed API casing grades and properties:

TABLE 1: API casing standards

API Grade	H-40	J-55	K-55	C-75	L-80	N-80	C-90	C95	P-110	Q-125
Minimum yield strength (1,000 psi)	40	55	55	75	80	80	90	95	110	125
Minimum ultimate tensile strength (1,000 psi)	60	75	95	95	100	100	105	105	125	135

Casing setting depth determination

The initial selection of casing setting is based on the anticipated pore pressure and fracture gradients. The drilling engineer is responsible for ensuring that, as far as possible, all the relevant offset data has been considered in the estimation of pore pressure and fracture gradients, and that, for directional wells, the effect of the hole angle on offset fracture gradient data has been considered.

Surface and conductor setting depth design

The minimum setting depth for surface and conductor casings is the depth at which the bottom hole pressure created by the circulating drilling fluid (ECD - equivalent circulating density) is exceeded by the fracture value of the formation. Formation fracture pressure or formation breakdown pressure is the pressure required to rupture a formation, so that the whole mud can flow into it. The ECD can be significantly affected in large diameter holes by a high rate of penetration (ROP) and poor hole cleaning.

The total depth of the well, and hence the setting depth of the production casing or liner, is driven by logging, testing, and completion requirements. The shoe must be set deep enough to give an adequate sump for logging, perforating, and test on production activities. The following information used to describe the setting depths has been extracted from IWCF Well Control (Serban, 2014).

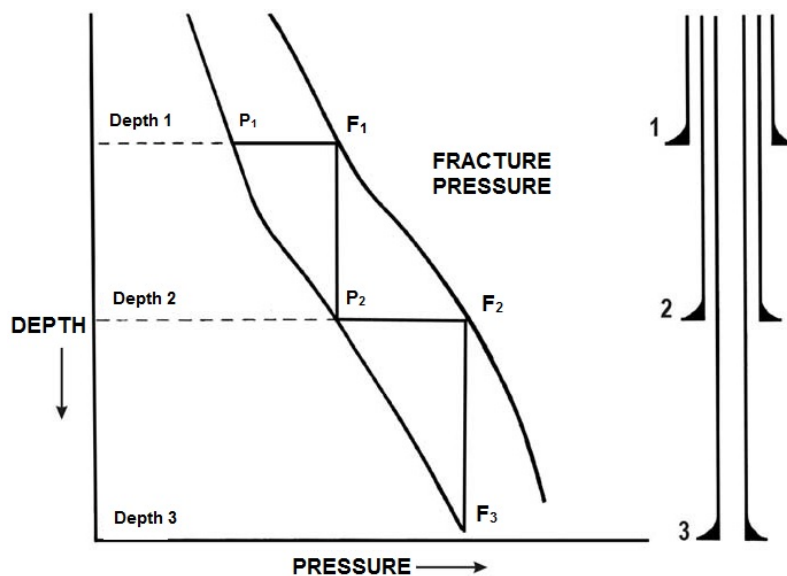


FIGURE 2: Casing Seat Selection (Serban, 2014)

The key to satisfactory casing seat selection is the assessment of pore pressure (formation fluid pressures) and fracture pressures throughout the well. Evidently, as the pore pressure in a formation being drilled approaches the fracture pressure at the last casing seat then a further string of casing is necessary. Figure 2 illustrates, an idealised casing depth selection:

Casing is set at Depth 1, where pore pressure is P_1 and the fracture pressure is F_1 . Drilling continues to Depth 2, where the pore pressure P_2 has arisen to almost equal the fracture pressure (F_1) at the first casing

seat. Another casing string is therefore set at this depth, with fracture pressure (F_2). Drilling can thus continue to Depth 3, where pore pressure (P_3) is almost equal to the fracture pressure F_2 at the previous casing seat (Serban N., 2014).

In practice, there is a need to include safety margins so take into account that this is an example.

For all casing strings a collapse load occurs when the external pressure is greater than the internal pressure. Collapse design focuses on the internal and external pressure profiles. Normally the collapse load will be highest at the casing shoe during cementing and other load cases, such as axial tension / compression, and burst load cases when the maximum load is expected.

2.3 Cementing programme

Planning a cementing job consists of evaluating a number of factors, including:

- Assessment of hole conditions (loss zones, hole cleaning, size, washouts, temperatures);
- Mud properties;
- Slurry design;
- Slurry placement;
- Additional equipment (float equipment, centralizers).

In Primary cementing the key solutions consist of:

- Isolation of casing shoe;
- Isolation of production zones – prevent cross flow between intervals at different pressure;
- Protection of water zones – prevent drilling fluid contamination of aquifers;
- Isolation of problem interval – extreme losses, well control, side-tracking;
- Protection of casing – from corrosive formation fluids e.g. H₂S, CO₂;
- Casing support – e.g. support for conductor (load bearing – bending moments derived from supporting BOP/tree/riser and potential snag loads from fishing activities), prevent thermal buckling.

For Secondary or remedial cementing, additional cementing can be done at a later stage e.g. sealing off perforations, top up job on conductor, repair casing leaks, squeeze casing shoe, setting plugs, etc. Common problems that affect all cement jobs include:

- Poor hole condition (doglegs, borehole stability, washouts, hole fill, cuttings beds, etc.);
- Poor mud condition (high gel strengths and yield point, high fluid loss, thick filter cake, high solids content, lost circulation material, mud / cement incompatibility);
- Poor centralization (cement not placed uniformly around the casing, leaving mud in place);
- Lost circulation;
- Abnormal pressure;
- Subnormal pressure;
- High temperature.

Cement types

API defines nine different classes of cement (A to H) depending on the ratio of the four fundamental chemical components (C₃S, C₂S, C₃A, C₄AF where C = calcium, S = silicate, A = aluminite and F = fluoride). Table 2 indicates API classes of cement.

TABLE 2: API cements classes.

API Class	Mix water (gal / sx)	Slurry wt. (ppg)	Depth (m)	BHST* (°C)
A (Portland)	5.2	15.6	0-1828.8	26.6-76.6
B (Portland)	5.2	15.6	0-1828.8	26.6-76.6
C (High early)	6.3	14.8	0-1828.8	26.6-76.6
D (Retarded)	4.3	16.4	1828.8-3048	76.6-110
E (Retarded)	4.3	16.4	1828.8-3048	76.6-143.3
F (Retarded)	4.3	16.4	3048-4876.8	110-160
G (Basic California)	5.0	15.8	0-2438.4	26.6-93.3
H (Basic Gulf Coast)	4.3	16.4	0-2438.4	26.6-93.3

* Bottom hole static temperature

Notes:

Class A and B – Shallow depth use. Composition 50% C₃S, 25% C₂S, 10% C₃A, 10% C₄AF.

Class C – Produces high early strength due to high C₃S content.

Class D, E and F – Retarded cements due to coarse grind or inclusion of organic retarders (lignosulphonates).

Class G and H – General purpose, compatible with most additives and able to be used over a wide range of temperature and pressure. H coarser than G – better retarding in deeper wells.

Class G is the most common type of cement used.

Other common cement variants out with API specification include:

Pozmix cement – 50% Portland, 50% pozzolan (ground volcanic ash) and 2% bentonite.

Gypsum cement – mixture of Portland cement and gypsum. Used for remedial work.

Diesel oil cement – “Gunk squeeze”. Mixture of basic cement with base oil used to seal off loss zones. Will set if water present.

Silica flour – At temperatures above 110°C cement will initially strengthen and then later weaken due to the subsequent formation of calcium silicate hydrate (C₂SH). By adding 30-40% silica flour to the cement, CSH forms in preference to C₂SH thus extending the temperature range of the mix.

2.4 Drilling problems

Additional equipment is required to be adapted for geothermal drilling in order to face conditions in geothermal reservoirs: Rotating head, blow out preventer (BOP), cooling tower for mud, air compressors and separator for aerated drilling.

During drilling, the pore pressure has to be considered in order to determine the optimum mud weight needed to face any gas or steam pressures encountered, while maximising rates of penetration and minimising loss of circulation, differential sticking and hole stability problems.

There are different aspects of the problems while drilling geothermal wells:

- Hard fractured rocks will create drill string vibrations which will affect the rig equipment;
- Drill string getting stuck in the hole;
- Loss of circulation requiring cementing;
- Breaking of the drill string requiring fishing;
- No returns while cementing the casing;
- Well problems: kicks and blow-outs;
- High concentration of H₂S;
- Slow ROP in hard rocks;
- Selecting inadequate drill bits may cause slow ROP;
- Drilling incidents as equipment failures, personal accidents.

3. GEOTHERMAL RESOURCES IN ROMANIA

The presence of the main geothermal resources in Romania is confirmed in porous and permeable sandstones and siltstones, or in fractured carbonate formations. The first shallow geothermal applications were implemented in the late 1990s.

Hydrological research for geothermal water began in 1981, when it was established that geothermal water temperature of 70-85°C could be found at depths between 3,000 and 3,300 m. Geothermal waters are a source of renewable energy regulated by the order number: 87/2008 of National Agency for Mineral Resources (NAMR). The agency was established in 1993 as the regulatory authority which administers the mineral resources of Romania and is under government subordination.

The first geothermal well was drilled in Felix in 1885. The well was 51 m deep, with a flow rate of 195 l/s, and a temperature of 49°C. It is still operating for health and recreational bathing and heating. For 14 geothermal wells drilled in Romania from 1995 to 2000 to depths of 1,500-3,000 m, the rate of success was 85%; only 2 geothermal wells were recorded unproductive (Codruta et al., 2015).

Two main companies in Romania are currently exploiting geothermal resources. They are Transgex S.A. and Foradex S.A. and have the long term concessions for practically all known geothermal reservoirs.

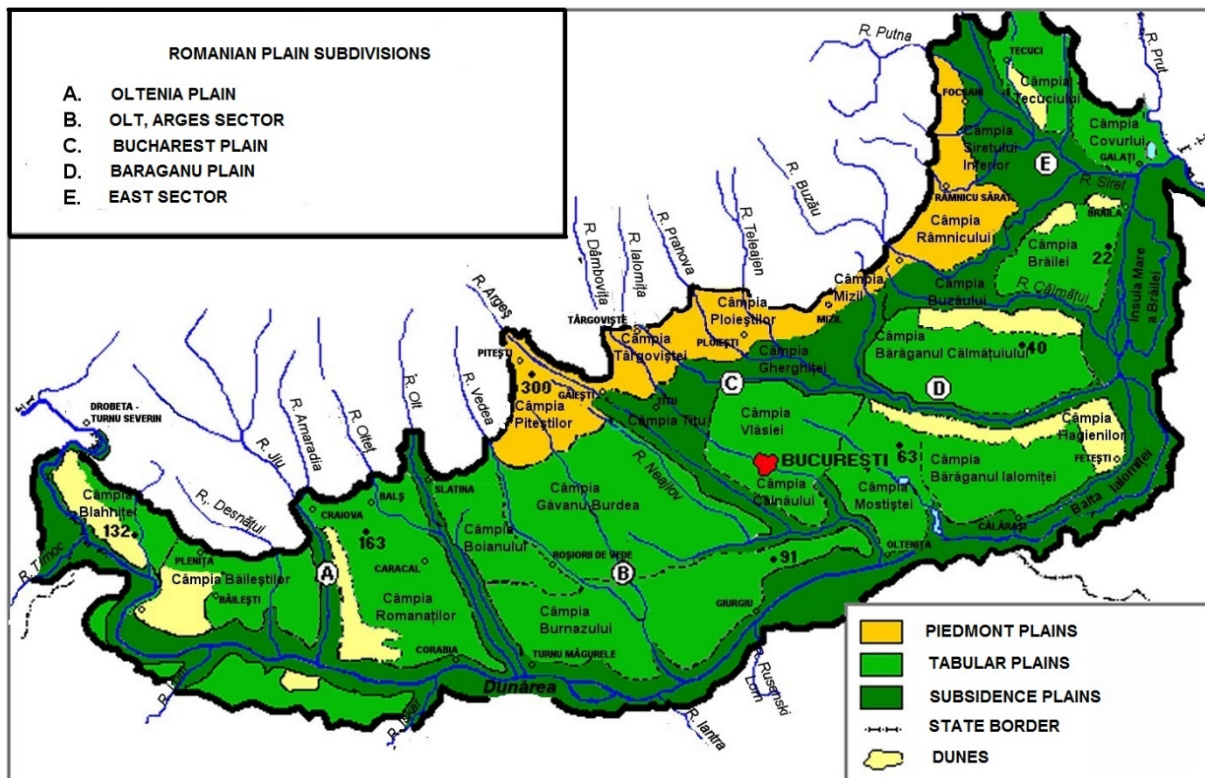


FIGURE 3: Map of Romanian Plain subdivisions (Wikipedia, 2016)

The Romanian Plain is represented by a foundation pleated, consists of green schist formations over submitted Palaeozoic aged sedimentary formations, Mesozoic and Neozoic (Figure 3). Situated in southeast of Europe, approximate 80% of the plain is within the southern Romania’s territory. It is well known as Wallachian Plain and sometimes referred to as the Danubian Plain. Geomorphologically the area belongs to the great geological unit of the Moesian Platform that was overlapped by the geomorphological unit of the Romanian Plain.

The most important geothermal reserves are found in the western part of Romania:

- Panonian aquifer;
- Oradea reservoir;
- Bors confined reservoir;
- Beius reservoir;
- Ciumeghiu reservoir.

Other geothermal reserves can be found in south and central Romania:

- Cozia – Calimanesti reservoir;
- Otopeni reservoir (North Bucharest).

The well drillings effort executed in Otopeni reservoir during 1991-1999 have resulted in proving the existence of geothermal water. The main features are presented in Table 3 below (RAH, 2016).

TABLE 3: Wells and main output characteristics

Location	Drilling (NO.)	Year	Temperature (°C)	Flow (l/s)
Balotesti	2669	1991	73	28
Balotesti	2684	1998	83	12
Balotesti	2685	1999	73	11

The geothermal resources in Romania are suitable for direct heat utilisation, low enthalpy indicating temperatures of 50-120°C, and being used for other different purposes: space heating, greenhouse heating, aquaculture, health and recreational bathing resorts, swimming pools. Figure 4 shows the main uses of geothermal energy in Romania.

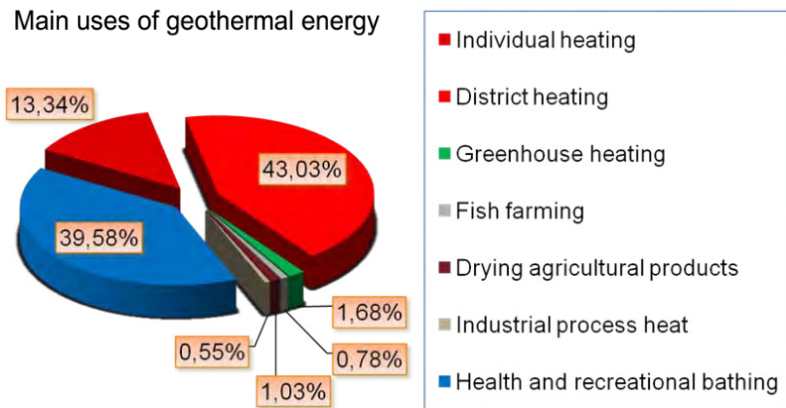


FIGURE 4: Geothermal energy distribution (Marcel, 2011)

3.1 Case history of the Therme Balotesti well in the Otopeni reservoir

The Otopeni geothermal reservoir is located north of Bucharest. Based on the offset data from wells drilled previously, both wells for oil and gas and for geothermal energy, the presence of a huge aquifer (300 km²), located in fissured limestone and dolomites has been confirmed. The existence of a geothermal field has been established evaluating hydrodynamics characteristics of carbonate collector from Jurassic Superior and Cretaceous inferior formations. The geothermal water temperature is 58-84°C. In the Otopeni geothermal reservoir 23 wells have been drilled (of which only 17 are potential producers or injectors). They confirm the aquifer being located in fissured limestone and dolomites, situated at depth of 2,000-3,200 m, belonging to the Moesian Platform. The depth to the static water level in the wells is about ~80 m, or even greater, down hole pumps being required. The geothermal water has wellhead temperatures of 58-84°C and a rather high Total Dissolved Solids (TDS) (1.5-2.2 g/l), with a high H₂S content (up to 30 ppm), for environmental protection reinjection is compulsory (Codruta et al., 2015).

The analysed well, named Therme Balotesti, was drilled in the Otopeni reservoir on the basis of an exploration license obtained from the National Agency for Mineral Resources (NAMR). The area is located in the middle of Romania Plain, the altitude is between 90 and 98 m below sea level (bsl) and the average annual temperature of the soil is 12°C, January average is -30°C and July average 23°C. The aim of the well was to explore the thermal field, evaluate hydrodynamic characteristics and hydro as well as the possibilities of exploiting geothermal waters.

In order to find the hydro geothermal potential of the area, information from previous exploration drillings were used:

- To identify the lithological sequence in this area to get an assessment of the flow capacity of the geothermal reservoir.
- Formation research to establish hydrodynamics and geochemical conditions.
- Detailed evaluation of geothermal field characteristics for evaluating the possibility for reinjection of used geothermal water.

3.1.1 The well design

A Romanian group of geologists and drilling engineers with great experience in the field have dealt with the design and the construction project supervising drilling. The respective engineers were Marin Gheorghe, Romanian Association of Hydrogeologists member (RAH) and National Agency for Mineral Resources expert (NARM), Cornel Popescu and Mircea Lungu.

The drilling Company S.C. DAFORA S.A. has successfully drilled the well Therme Balotesti with the Bentec Euro Rig 350. Below are presented the main features (Bentec Ltd., 2016).

EURO RIG™ general features:

- Climate: Temperate -20 to 40°C.
- Draw works capacities: 1,000 –2,000 hp.
- Hook Load capacities: 440,000-1,000,000 lbs/200-450 t.
- Drilling depth capacities: Up to 19,700 ft/or just over 6,000 m.

The width sections and their depths
Construction drilling activity was carried out with very few interruptions. Small inclination of the well led to successful casing of long sections of the well demonstrating professionalism of those who designed and / or supervised the construction.

Crossing areas with unconsolidated sediments, the presence of gas-bearing formations, drilling mud loss, and difficulty in cementing long sections, represented important features that needed to be considered in modifying the drilling programme.

The stratigraphic depths in the drilling project encountered some difference limits of maximum 10 m. Figure 5 illustrates the Therme Balotesti well design.

Casing design

Some of the technical features of the design and execution drilling of Therme Balotesti were presented by Marin Gheorghie in a paper published in the Romanian Association of Hydrogeologists website (RAH, 2016).

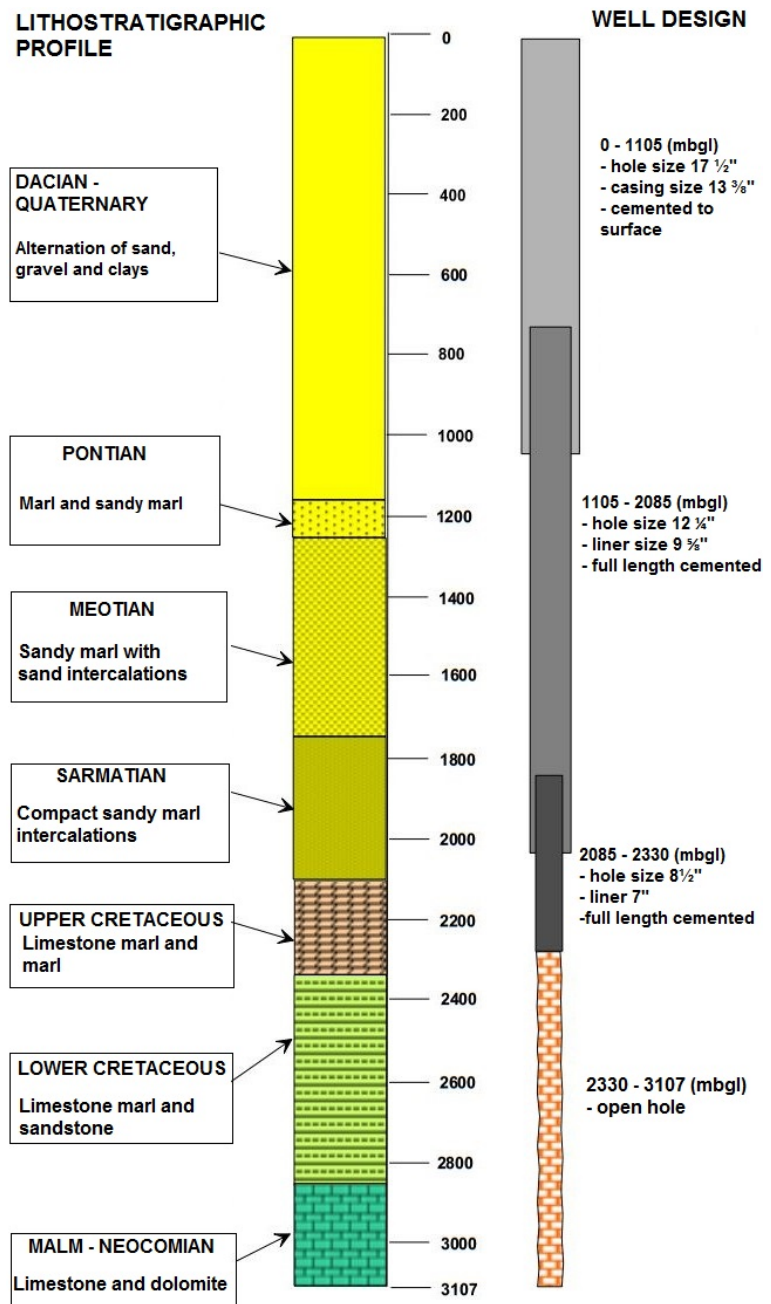


FIGURE 5: Therme Balotesti well construction and lithostratigraphic profile (RAH, 2016)

Cementing the Anchor Casing to the surface and the liners was carried out by a specialized company using two aggregates and cement silos, the cement density used was 1.75 kg/dm³. Due to lack of available data about the casing design and cementing techniques, according to Figure 5, I assumed the anchor casing was fully cemented back to surface and the liners were cemented by their entire length.

Water and bentonite with a specific weight of 1.14-1.25 kg/dm³ was used for the first 1,100 m (casing depth of the anchor casing). Mud with inhibitors for preventing potential issues up to 2,330 m and for the free hole section water was used with loss of circulation without affecting productive potential range. Table 4 shows the length and widths of the sections and the casings in the well.

API CASING AND BIT PROGRAMS - COMBINATIONS

The figure shows possible combinations of API casing and bit sizes that can make up a casing program. The **red** line shows the most common selection for geothermal wells. **Blue** line is for slimholes. The figure shows possible combinations of API casing and bit sizes that can make up a casing program. The legend shows the liner size for different programs.

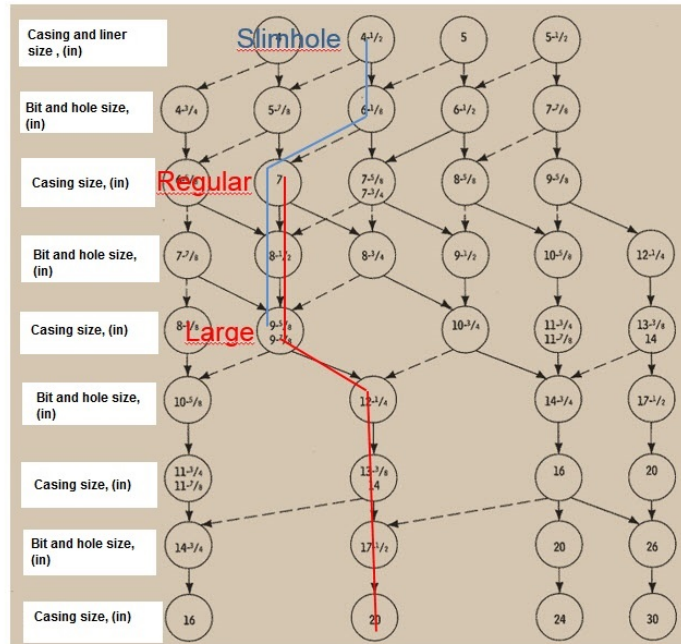


FIGURE 6: Possible combination of casing and bit sizes (Thórhallsson 2016)

TABLE 4: Length and widths of the sections and the casings in the well

Sections of the well		Casing/liner	
Depth	Width	Length	Size
(m)	(")	(m)	(")
0 – 1,105	17½	1,105	13¾
1,105 – 2,085	12¼	2,085	9⅝
2,085 – 2,330	8½	2,330	7
2,330 – 3,107	5¾	None	

The casing string selection is specific for geothermal wells according to API where it is recommended practice for combination of casing sizes and drill bit diameter (Figure 6). The presence of H₂S requires using K55 as grade for all the casing strings. It conforms to ANSI/NACE MR 0175/ISO 15156 (NBS 2403:2015) and has resistance to H₂S environments.

3.2 Drilling history of the well

Technical details of the project required the involvement of specialized teams in all stages of construction and completion of drilling. Choosing the right rig, equipment and the regime drilling parameters demonstrated record time in drilling the Therme Balotesti well. The total depth of the well was 3,107 m and it was completed in 60 days. Construction drilling activity was carried out in shifts, (2x12 hours). During all activities very few interruptions were caused by technical problems. Well logging was performed by *Weatherford Atlas Gip* for each drilled interval before running the casing. Cementing the Anchor Casing and the two liners was carried out by specialized teams of *Rompetrol*, a Romanian Well Services Company. Completion of each stage construction according to technical project without incidents, ensures long-term operation of the well in safe conditions (RAH, 2016).

3.2.1 Drilling parameters

Figure 7 is presenting an example of a composited log with key drilling parameters recorded while drilling, the compiled log. The Log Plot program is used to display well drilling design and programme for geothermal wells and plot key drilling parameters as: rate of penetration (ROP), weight on bit (WOB), rotation per minute (RPM), drilling fluid specific gravity (SG) expressed in kg/dm^3 .



Well	AB	Field	Romanian Plain
Section	0-3100	Drilling fluid	Water based / Proterm Dispersated
Rig	350	Geology	Sedimentary

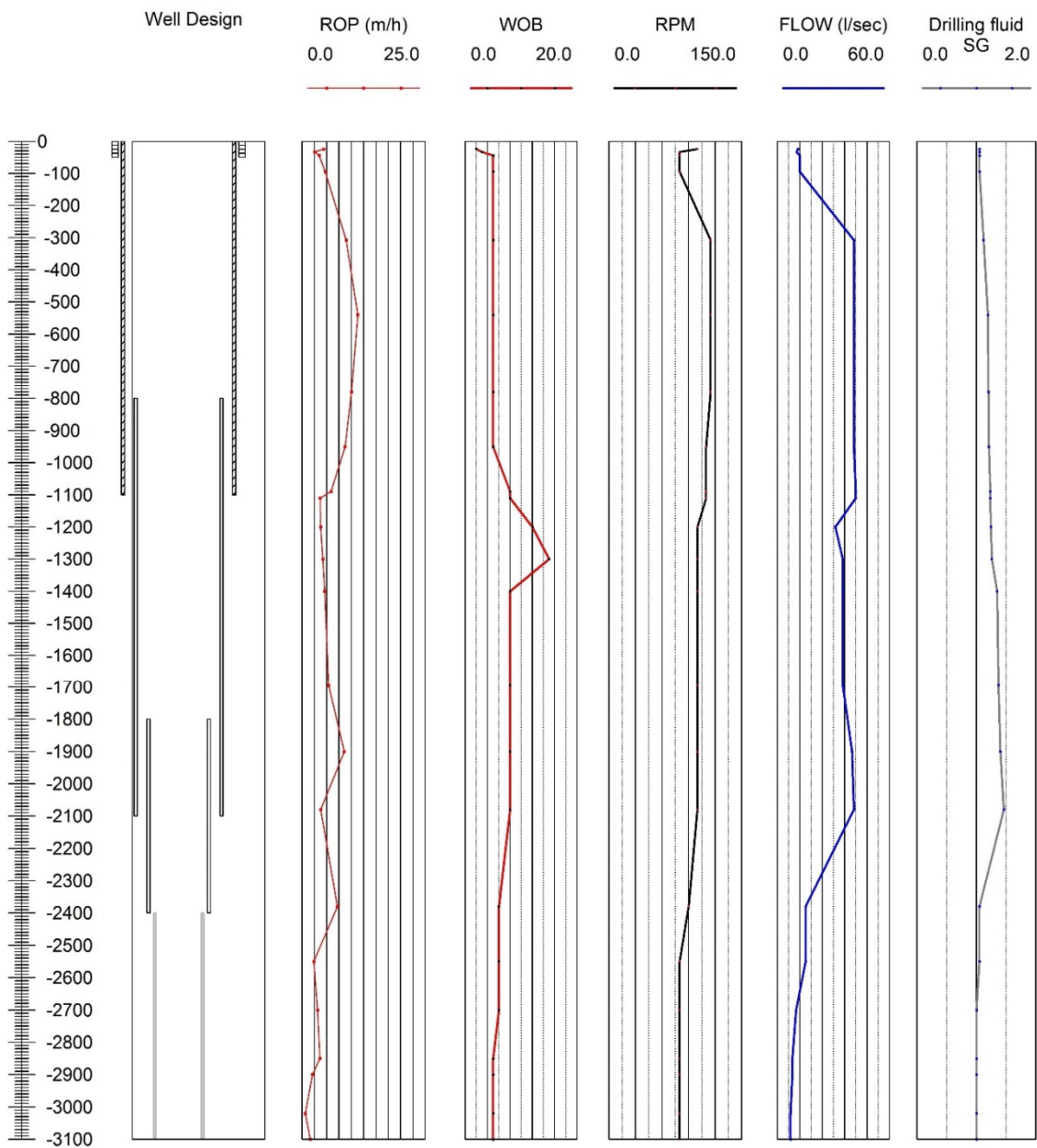


FIGURE 7: Design and drilling parameters for the Therme Balotesti well

3.2.2 Drilling evolution

As the well was being drilled, the progress was monitored with the rig instrumentation system and analysis of cuttings and reported daily, often against a time depth curve. One thing to note is any changes that may indicate the transition from one pressure regime to another, thus formations properties have to be closely monitored. The well target objective was to intercept the Jurassic Superior – Cretaceous Inferior collector which has a relatively high temperature and productivity for low-temperature geothermal fields.

Due to the different structure of the formation sections of the well, the drilling fluid characteristics had to be adapted for each interval:

- For the first interval from 0 to 1,100 m: water and bentonite at a density of 1.14-1.25 kg/dm³;
- Down to 2,330 m mud was used with inhibitors to prevent problems caused by the interaction of contractile clays with mud;
- Below 2,330 m water was used, with loss of circulation, so as not to influence the productive potential.

3.2.3 Problems encountered

Offset information from previous studies in Otopeni geothermal reservoir confirmed the presence of H₂S and other gases. During drilling through the formations due attention should be given to eruptive manifestations that may occur and adjust the drilling parameters and mud properties. In order to avoid getting stuck in the open hole section due to fractured zones, the stabilizers were excluded from the BHA.

A very important aspect that could affect completion of drilling is the perfect cementing operation of liners, especially in crossing areas of unconsolidated sediments; the water quality was not affected by the aquifers from some intervals. The Cement Bond Log (CBL) evaluating the integrity of cement work was performed by a specialised company that checked the cement integrity after each section of the well has been cased and cemented.

3.3 Success of drilling and outcome

The safety factors used for drill string assembly made the total depth of the well successfully achieved. The Air-lift pump system was used to clean the well, finally getting a flow rate of 25 l/s and a temperature of ~81°C. Chemically speaking, the water is chlorinated bicarbonate, calcium-magnesium. The reservoir conditions were known in Otopeni. The casing selection path was respected according to common selection for geothermal wells. The water properties analyses revealing the absence of any bacteriological groups considered pathogenic was confirmed by different accredited institutions, Table 5 shows the result of water analysis.

TABLE 5: Water analysis results (RAH, 2016)

Parameter	Unit	Value
Temperature	(°C)	81-82
Electrical conductivity, EC	(µS/cm)	3,900
Chloride, Cl	(mg/l)	1,090
Bicarbonate, HCO ₃	(mg/l)	268
Calcium, Ca	(mg/l)	134.88
Ammonium, NH ₄	(mg/l)	2.6
Hydrogen sulphide, H ₂ S	(mg/l)	30

Each step of well design has been successfully completed without any incidents, which guarantees safe operation and long life of the well utilization.

4. DISCUSSION

Geothermal utilization has evolved through time in different parts of the world; modern day technology has made it possible in better conditions. Drilling of geothermal wells is not such a big market, meaning that there are not so many drilling companies specialised in drilling for geothermal resources. In each country the wells are drilled with their own contractors, and the drilling rigs are the same commonly used in the oil and gas industry, including some additional equipment such as cooling towers for the mud and a rotating head preventer to provide added protection for the crew in case of a kick and also when doing aerated drilling (Thórhallsson, 2016).

Based on data from the well project, the drilling company needs to decide about important details in order to successfully complete the well, such as: rig capacities, drill string characteristics, required equipment etc. The next subchapters will present some calculations on the drill string and the casings and safety factors. Regarding drilling costs, there is a lack of open data due to confidentiality, each drilling rig having its own trend, drilling contractors and the drilling material costs are influenced by the oil and gas industry.

4.1 Calculations of the drill string

The Therme Balotesti well design was based on the design of previous wells and the anticipated geology and lithology; these are important factors to decide the setting of the casing shoe depths and to obtain a better image about the drill string design.

The next calculations are obtained with the help of formulas and drill string characteristics from Drilling Data Handbook, 7th edition (DDH) (Gabolde and Nguyen, 2006), for example of drill string used to drill a ~3,100 m deep vertical geothermal well.

Design parameters

Hole diameter: Final section from 2,330 to 3,107 m drilled with 5¾" diameter bit.

Assumed mud weight: 1.2 (kg/m³); buoyancy factor = 0.847 (DDH, A-28).

Table 6 describes the drill pipe sizes and the tensile strengths used when drilling the final section of the well.

TABLE 6: Drill pipes features

Composition of the drillstring	Outer diameter (OD)	Total length with tool joints, (L _{xxx})	Weight per m with tool joint in air (W _{xxx})	Grade	Tool joint (NC)	Tensile strength
	(")	(m)	(kg/m)			(daN*10 ³)
Drill pipes 1 (DP ₁)	5	1,781	32.55	G105	50	193.8
Drill pipes 2 (DP ₂)	3½	980	25.37	G105	38	132.0
18 Heavy weight drill pipes (HWDP)	3½	165.5	37.70	-	38	153.0
18 Drill collars (DC)	4¾	169.6	73.84	-	38	

To reduce the fatigue failure above the BHA, HWDP are used to provide a flexible transition between the drill collars and the drill pipes.

Checking for a maximum WOB in tons, rearranging formula from DDH, B-56:

$$WOB_{\max} = \frac{L_{DC} \cdot \cos(i) \cdot F_{PN} \cdot P_{DC} \cdot k}{10^5} = \frac{169.6 \cdot 1 \cdot 85 \cdot 73.84 \cdot 0.847}{10^5} = 9 \text{ tons which is very much for } 5\frac{3}{4}'' \text{ bit.}$$

For a $5\frac{3}{4}''$ bit $F_{PN} = 50$ would give 5.3 tons which is recommended. As a rule of thumb there should be used 1 ton weight on per inch of the bit diameter.

Here L_{DC} = Length of the drill collars (m);
 WOB = Maximum weight on bit (tons);
 i = Hole angle from vertical (0°);
 F_{PN} = Neutral point position as percentage of total drill collar string length (85 for 85%);
 k = Buoyancy factor (DDH);
 P_{DC} = Weight per m of drill collars (kg/m).

Checking for tensional loading, T (DDH):

Checking tensional loading for the $3\frac{1}{2}''$ drill pipes, DP_2 :

$$T_{DP2} = g \cdot (L_{DP2} \cdot W_{DP2} + L_{HWDP} \cdot W_{HWDP} + L_{DC} \cdot W_{DC}) \cdot k$$

where T_{DP2} = Submerged load hanging below the upper end of this section of drill pipe (10^3 daN);
 L_{DC} = Length of the drill collars (m);
 W_{DC} = Weight of collars per m (kg/m);
 L_{HWDP} = Length of the heavy wall drill pipes (m);
 W_{HWDP} = Weight of those pipes per m (kg/m);
 L_{DP2} = Length of the $3\frac{1}{2}''$ drill pipes (m);
 W_{DP2} = Weight of those pipes per m (kg/m);
 k = Buoyancy factor for the mud.

Hence:

$$T_{DP2} = 0.981 \cdot (980 \cdot 25.37 + 165.5 \cdot 37.7 + 169.6 \cdot 73.84) \cdot 0.847 = 36.25 \cdot 10^3 \text{ daN}$$

This is much less than the tensile strength, T_{e2} , of the pipes, $132 \cdot 10^3$ daN – tensional loading OK.

Checking tensional loading for the $5''$ drill pipes, DP_1 :

$$T_{DP1} = 0.981 \cdot (L_{DP1} \cdot W_{DP1} + L_{DP2} \cdot W_{DP2} + L_{HWDP} \cdot W_{HWDP} + L_{DC} \cdot W_{DC}) \cdot k$$

$$T_{DP1} = 0.981 \cdot (1781 \cdot 32.55 + 980 \cdot 25.37 + 165.5 \cdot 37.7 + 169.6 \cdot 73.84) \cdot 0.847 = 84.42 \cdot 10^3 \text{ daN}$$

which is much less than the tensile strength, T_{e1} , of the pipes, $193.8 \cdot 10^3$ daN – tensional loading OK.

Consideration of the weakest link in the stem, i.e. the $3\frac{1}{2}''$ drill pipes DP_1 :

Allowable load - factor of safety = 10% or 1.1. Margin of over pull (MOP) using formulas from DDH:

$$\text{Allowable load in tension (daN), } T_a = 0.9 \cdot T_{e2} = 0.9 \cdot 132 \cdot 10^3 \text{ daN} = 118.8 \cdot 10^3 \text{ daN}$$

$$\text{Calculate } R_T = \text{Margin of over pull (MOP)} = T_a - T_{DP2} = 118.8 \cdot 10^3 \text{ daN} - 36.25 \cdot 10^3 \text{ daN} = 82.55 \cdot 10^3 \text{ daN.}$$

$$\text{Calculate safety factor in tension, } F_s = \frac{T_a}{T_{DP2}} = \frac{82.55 \cdot 10^3}{36.25 \cdot 10^3} = 2.28 - \text{which is OK.}$$

Consideration of the 5" drill pipes DP₁:

Allowable load - factor of safety and margin of over pull (MOP) using formulas from DDH:

Allowable load in tension (daN), $T_a = 0.9 * T_{e1} = 0.9 * 193.8 * 10^3 \text{ daN} = 163.8 * 10^3 \text{ daN}$

Calculate $R_T = \text{Margin of over pull (MOP)} = T_a - T_{DP1} = 163.8 * 10^3 - 84.42 * 10^3 \text{ daN} = 79.32 * 10^3 \text{ daN}$.

Calculate safety factor in tension, $F_S = \frac{T_a}{T_{DP1}} = \frac{163.8 * 10^3}{84.42 * 10^3} = 1.94$, which is OK.

Estimate of maximum drilling depth with this drill stem if the MOP is lowered to $30 * 10^3 \text{ daN}$, using formula from DDH:

$R_T = T_a - T_{DP1}^*$; $T_{DP1}^* = T_a - R_T = 163.8 * 10^3 \text{ daN} - 30 * 10^3 \text{ daN} = 133.8 * 10^3 \text{ daN}$

$T_{DP1}^* = 0.981 * (L_{DP1} * W_{DP1} + L_{DP2} * W_{DP2} + L_{HWDP} * W_{HWDP} + L_{DC} * W_{DC}) * k = 133.8 * 10^3 \text{ daN}$

$L_{DP1} * 32.55 * 10^3 = 117,404 \text{ kg}$

$L_{DP1} = \frac{117,404}{32.55} = 3,606.9 \text{ m}$

The maximum drilling depth is $= L_{DP1} + L_{DP2} + L_{HWDP} + L_{DC} = 3,606.9 + 980 + 165.5 + 169.6 = 4,922 \text{ m}$.

Checking for collapse due to annular hydrostatic pressure for the 3½" drill pipes, DP₂ according to maximum depth, using formulas from DDH.

For drill pipe DP₂ the limit collapse pressure is $P_{ct2} = 139.7 \text{ MPa}$.

If there is no fluid in the drill pipe the pressure from outside the pipe is:

$$P_C = 9.81 * d * z$$

where P_C = Collapse pressure (kPa);
 z = Vertical depth of the drill pipes (m), $L_{DP1} + L_{DP2} = 3,606.9 + 980 = 4,586.9 \text{ m}$;
 d = Mud weight (kg/m^3).

1. Mud weight $d = 1,200 \text{ kg/m}^3$.

The units are: $\text{m/s}^2 * \text{kg/m}^3 * \text{m} = (\text{kg} * \text{m/s}^2) / \text{m}^2 = \text{N/m}^2 = \text{Pa} = 10^{-6} \text{ MPa}$

$P_C = 9.81 (\text{m/s}^2) * 1.2 * 10^3 (\text{kg/m}^3) * 4,586.9 (\text{m}) = 54 \text{ MPa}$ which is OK.

2. Mud weight $d = 1,000 \text{ kg/m}^3$.

$P_C = 9.81 (\text{m/s}^2) * 1 * 10^3 (\text{kg/m}^3) * 4,586.9 (\text{m}) = 45 \text{ MPa}$ which is OK.

Checking for safety against hydrostatic collapse for drill pipe 2.

1. Mud weight $d = 1,200 \text{ kg/m}^3$.

Drilled depth about 3,100 m.

Allowed safety factor 10% or 1.1.

$L_{DP2} = 3,100 - 165.5 \text{ m} - 169.6 \text{ m} = 2,764.9 \text{ m}$

$$2,764.9 = P_{ct1} / (9.81 * 10^3 * d * F)$$

$F = 40 * 10^6 / (9.81 * 1.2 * 10^3 * 2,764.9) = 1.23$, which is OK

where F = Safety against collapse.

2. Mud weight $d = 1,000 \text{ kg/m}^3$.

Drilled depth about 3,100 m.

$$L_{DP2} = 3,100 - 165.5 \text{ m} - 169.6 \text{ m} = 2,764.9 \text{ m}$$

$$2,764.9 = P_{ct1} / (9.81 * 10^3 * d * F)$$

$$F = 40 * 10^6 / (9.81 * 1 * 10^3 * 2,764.9) = 1.48, \text{ which is OK}$$

4.2 Casing calculations

With the information gathered from the paper presented in AHR and the casing features from New Zealand Standards and Drilling Data Handbook (Gabolde and Nguyen, 2014), the following was calculated for each casing:

- Axial tensile forces on casing during running and cementing;
- Axial force due to temperature rise;
- Maximum differential burst pressure of casing near shoe or stage cementing ports;
- Hoop collapse pressure during cementing.

Table 7 represents the results of axial tensile forces on casing during running and cementing:

TABLE 7: Axial tensile forces

CSG Grade K55 width (")	Length (m)	$F_{\text{csg air wt}}$ (kN)	$F_{\text{csg contents}}$ (kN)	$F_{\text{displaced fluids}}$ (kN)	F_{hookload}, F_p (kN)	Minimum tensile strength (kN)	Calculat. DF	Minimum DF
13 $\frac{3}{8}$	1,105	879	863	970	772	6,556	8.5	1.8
9 $\frac{5}{8}$	1,285	882	475	584	773	5,735	7.4	1.8
7	480	161	95	115	141	2,813	19.9	1.8

Here $F_{\text{csg air wt}}$ = Air weight of casing (kN);
 $F_{\text{csg contents}}$ = Weight of internal contents of casing (kN);
 $F_{\text{displaced fluids}}$ = Weight of fluids displaced by casing (kN);
 F_{hookload} = Surface force suspending casing that is subjected to gravitational and static hydraulic loads (kN);
 DF = Design factor.

Checking for the design factor for each casing string according to New Zealand Standards (New Zealand Standard, 2015) the minimum tensile design factor is 1.8. The results on calculated design factor as shown in Table 7 are:

- For 13 $\frac{3}{8}$ " = 8.5 which is OK;
- For 9 $\frac{5}{8}$ " = 7.4 which is OK;
- For 7" = 19.9 which is OK.

Table 8 represents the results of axial force due to temperature rise.

TABLE 8: Axial force using NZS 2403:2015

Outer diameter (")	E (GPa)	α ($^{\circ}\text{C}^{-1}$)	T ₁ ($^{\circ}\text{C}$)	T ₂ ($^{\circ}\text{C}$)	A _p (m ²)	F _c (kN)	F _r (kN)	Minimum compressive strength (kN)	Calculated DF	Minimum DF
13 ^{3/8}	210	0.000013	30	85	0.010009	-1,503	-731	3,793	5.19	1.20
9 ^{5/8}	210	0.000013	40	85	0.008756	-1,076	-303	3,319	10.95	1.20
7	210	0.000013	45	85	0.004294	-469	-327	1,627	4.97	1.20

Here E = Modulus of elasticity (GPa);
 α = Coefficient of linear thermal expansion;
T₁ = Neutral temperature (temperature of cement set ($^{\circ}\text{C}$));
T₂ = Maximum expected temperature ($^{\circ}\text{C}$);
A_p = Cross-sectional area of pipe (m²);
F_c = Compressive force due to heating (kN);
F_r = Resultant force (kN).

Minimum design factor is 1.20 (New Zealand Standard, 2015). Results on calculated design factor are:

- For 13^{3/8}" = 5.19 which is OK;
- For 9^{5/8}" = 10.95 which is OK;
- For 7" = 4.97 which is OK.

Table 9 represents maximum differential burst pressure of casing near shoe or stage cementing ports.

TABLE 9: Burst pressure using NZS 2403:2015

CSG Grade K55 width (")	L _z (m)	ρ_c (kg/l)	L _f (m)	ρ_f (kg/l)	g (m/s ²)	Differential burst pressure (MPa)	Internal yield pressure (MPa)	Calculated DF	Minimum DF
13 ^{3/8} Shoe	1105	1.75	1105	1.25	9.81	5.42	18.90	3.5	1.5

where L = Length of casing (m);
 ρ_c = Slurry density (kg/l);
L_f = Total vertical length of fluid column in an annulus (m);
 ρ_f = Density of water (kg/l);
g = Gravitational acceleration (9.81 m/s²).

Minimum design factor is 1.5 (New Zealand Standard, 2015). The results calculated on maximum differential burst pressure of 13^{3/8}" casing near the shoe = 3.5, which is OK.

Table 10 represents Hoop collapse pressure during cementing.

TABLE 10: Hoop collapse NZS using NZS 2403:2015

CSG Grade K55	L _z (m)	ρ_c (kg/l)	ρ_f (kg/l)	g (m/s ²)	Δ_{pe} (MPa)	Internal collapse pressure (MPa)	Calculated DF	Minimum DF
13 ^{3/8} " Shoe	1,105	1.75	0.988	9.81	8.26	7.80	0.944	1.2
9 ^{5/8} " Shoe	2,085	1.75	0.988	9.81	15.59	26.80	1.720	1.2
7" Shoe	2,330	1.75	0.988	9.81	17.42	26.80	1.539	1.2

where L_z = Total vertical length of liner (m);
 Δ_{pe} = Differential pressure on casing during cementing (MPa).

Minimum design factor is 1.20 (New Zealand Standard, 2015). The results on hoop collapse pressure during cementing are:

- For 13 $\frac{3}{8}$ " at shoe = 0.944 – assumed that water was used to calculate, it is recommended to use mud *which is not OK*.
- For 13 $\frac{3}{8}$ " at shoe = 1.439 – with mud density of 1.25 (maximum density for 13 $\frac{3}{8}$ " section), *which is OK*.
- For 9 $\frac{5}{8}$ " at shoe = 1.720 *which is OK*.
- For 7" at shoe = 1.539 *which is OK*.

5. CONCLUSIONS

Therme Balotesti is the name of a successful geothermal well drilled in Otopeni geothermal reservoir for the supply of water for a spa complex. Therme Bucharest is the name of a private project which was the development of a modern spa concept near the capital Bucharest. Therme Bucharest, a 30,000 m² wellness, relaxation and entertainment centre based on thermal waters was completed and inaugurated in January 2016 becoming the largest thermal wellness centre in Europe. The success of the well was highlighted in the final stage by getting a flow rate of 25 l/s and temperature of 81°C. Water quality was tested at recognized institutions nationally and internationally, the analyses revealing the absence of any bacteriological groups considered pathogenic.

On the surface, the well is equipped with a pump head fitted with valves and gauges. For exploiting the geothermal aquifer a submersible pump was installed with variable flow located at a depth of 150 m, operable to temperatures of 90°C.

Checking for a maximum weight on bit in tons with a neutral point of 85% in the collars with this drill string gave 9 tons which is very much for 5 $\frac{3}{4}$ " bit. As a thumb of rule it is said 1 ton's weight is needed on each diameter inch of the drill bit. For a 5 $\frac{3}{4}$ " bit $F_{PN} = 50$ would give 5.3 tons which is close to the recommended value.

Tensional loading for the 3 $\frac{1}{2}$ " drill pipes was $36.25 \cdot 10^3$ daN which is much less than the tensile strength of the pipes, $132 \cdot 10^3$ daN. Therefore, the tensional loading is OK.

Tensional loading for the 5" drill pipes was $84.42 \cdot 10^3$ daN which is much less than the tensile strength of the pipes, $193.8 \cdot 10^3$ daN. Therefore, the tensional loading is OK.

Consideration of the weakest link in the stem, i.e. the safety factor of 10% or 1.1. For the 3 $\frac{1}{2}$ " drill pipes the safety factor in tension was 2.28 which is OK. Consideration of the 5" drill pipes the safety factor in tension was 1.94 which is also OK.

The maximum length of the 5" drill pipes if the Margin of Over pull, (MOP) is lowered to $30 \cdot 10^3$ daN with the same components of the drill string is 3,609.9 and maximum drilling depth with this drill string is 4,922 m.

Checking for collapse due to annular hydrostatic pressure if there is no fluid in the drill pipe and mud weight $d = 1,200$ kg/m³ for the 3 $\frac{1}{2}$ " drill pipes, according to maximum depth of the pipes to 4,586.9 m gave 54 MPa which is much lower than the collapse limit pressure, 139.7 MPa. For a mud weight $d = 1,000$ kg/m³ the hydrostatic pressure was 45 MPa which is also much lower.

Checking for safety factor against hydrostatic collapse for the 5" drill pipes, mud weight $d = 1,200$ kg/m³ and drilled depth about 3,100 m gave safety factor 1.23. For mud weight $d = 1,000$ kg/m³ the safety factor was 1.48. The drill string composition design was successful, drilling the well safely.

The casing design programme, the mechanical and physical properties of casing was conducted by S.C. Therme Nord Bucuresti S.R.L. Each service company uses safety factors from different handbooks. The minimum acceptable casing design factors (NZS 2403:2015) are:

- Internal yield (burst) design factors 1.5 -1.8;
- Collapse design factors 1.2;
- Tensile design factor 1.8;
- Compressive factor 1.2.

Checking for the design factor for each casing string according to New Zealand Standard (New Zealand Standard, 2015) the minimum tensile design factor is 1.8.

For 13 $\frac{3}{8}$ " this means 8.5 which is OK, for 9 $\frac{5}{8}$ " 7.4 which is OK, and for 7" 19.9 which is OK.

Checking for axial force due to temperature rise, minimum design factor is 1.20 (NZS 2403:2015). The result on calculated design factors: for 13 $\frac{3}{8}$ " it was 5.19 which is OK, for 9 $\frac{5}{8}$ " it was 10.95 which is OK and for 7" it was 4.97 which is OK.

Checking for maximum differential burst pressure of casing near shoe, the minimum design factor is 1.5 (New Zealand Standard, 2015). The results calculated for 13 $\frac{3}{8}$ " at shoe was 3.5 which is OK. This load case occurs due to cement density, with the casing full of cement and the annulus full of water, creating a pressure difference that can lead to burst of casing in case of inadequate choices regarding casing features.

Checking for hoop collapse pressure during cementing the minimum design factors is 1.20 (New Zealand Standard, 2015), where: for 13 $\frac{3}{8}$ " at shoe it was 0.944, assuming that water was used for calculation. However, it is recommended to use mud, hence for 13 $\frac{3}{8}$ " at shoe it was 1.439 – with mud density of 1.25 (maximum density for 13 $\frac{3}{8}$ " section), which is OK, for 9 $\frac{5}{8}$ " at shoe it was 1.720 which is OK and for 7" at shoe it was 1.539 which is OK.

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REFERENCES

- Bentec Ltd., 2016: *Stationary standard euro rigs*. Bentec Ltd., website: www.bentec.com/rigs/euro-rigs/stationary-standard-euro-rigs/
- Codruta, B., Cornel, A., and Marcel, R., 2015: Geothermal energy in Romania: Country update 2010-2014. *Proceedings of the World Geothermal Congress 2015, Melbourne, Australia*, 9 pp.
- Gabolde, G., and Nguyen, J.P., 2006: *Drilling data handbook* (7th ed.). Editions Technip, Paris, 576 pp.
- Gabolde, G., and Nguyen, J.P., 2014: *Drilling data handbook* (9th ed.). Editions Technip, Paris, 576 pp.
- Hole, H., 2008: Geothermal well completion tests. *Paper presented at "Petroleum Engineering Summer School", Dubrovnik, Croatia, Workshop*, 26 pp, website: <https://www.geothermal-energy.org/pdf/IGAstandard/ISS/2008Croatia/Hole02.pdf>
- Marcel, R., 2011: Geothermal resources of Romania. *Paper presented at GEOELEC Workshop, Athens*, 16 pp.
- New Zealand Standard, 2015: *Code of practice for deep geothermal wells*. Standards Association of New Zealand, Wellington, NZ, 102 pp.
- RAH, 2016: *Forajul hot springs, Bucarest*. Romanian Association of Hydrogeologists (in Romanian), website: www.ahgr.ro/media/85718/forajgeoterm_balotesti.pdf.
- Serban, N., 2014: *UPG – Ploiesti, Romania, well control training program*. International Well Control Forum (IWCF), unpublished lecture notes.
- Thórhallsson, S., 2016: *Well designs and geothermal drilling technology*. UNU-GTP, Iceland, unpublished lecture notes, 379 pp.
- Wikipedia, 2016: *Romanian plain*. Wikipedia, website: ro.wikipedia.org/wiki/C%C3%A2mpia_Rom%C3%A2n%C4%83

APPENDIX I: API SPECIFICATIONS STANDARDS

- API SPEC 5CT:** Specification for casing and tubing.
- API BULL 5C2:** Bulletin on performance properties of casing and tubing.
- API BULL 5C3:** Bulletin on formulas and calculations for casing, tubing, drill pipe and line pipe properties”
- API RP 5 A5:** Specifies requirements and gives recommendation for filed inspection of new casing, tubing and plain-end drill pipe.
- API SPEC 10A:** Specification for cements and materials for well cementing, 23rd edition. 2002 Washington, DC, API.