Pipe materials for borehole heat exchangers

Dimitrios Mendrinos[1], Spyridon Katsantonis[1], Constantine Karytsas[1]

[1] Centre for Renewable Energy Sources and Saving, 19th km Marathonos ave., 19009 Pikermi Attikis, Greece

dmendrin@cres.gr

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ABSTRACT

This paper investigates and evaluates alternative options of higher thermal conductivity as borehole heat exchanger (BHE) piping materials, such as mild steel, galvanized steel, various coating options, stainless steel, copper and its alloys, aluminum, titanium, as well as reinforced polymers and other plastic materials including thermally enhanced polyethylene.

1. INTRODUCTION

High density polyethylene (HDPE) is the most commonly used material in borehole heat exchanger (BHE) applications due to its wide availability, low cost, zero maintenance needs, low weight, user friendly installation, long life in the ground (75 years expected) and reliability. It is also characterized by the highest thermal conductivity among thermoplastic materials, but its thermal conductivity is still much lower than the one of metals and those of most geologic formations surrounding the BHE.

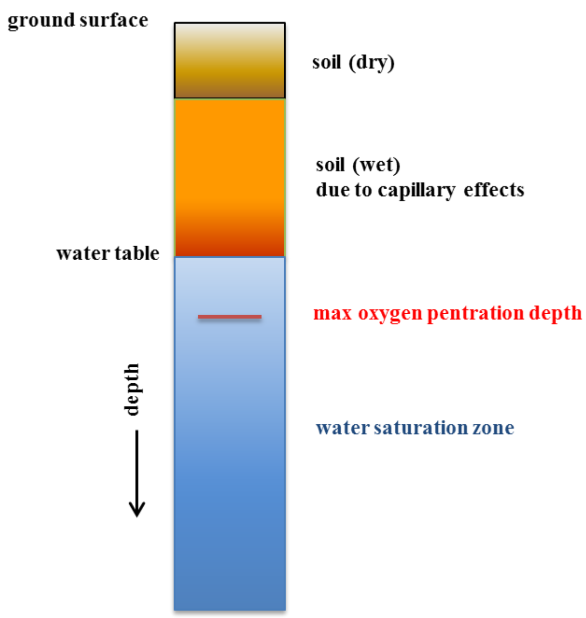

Figure 1: Typical underground environment to depth.

The underground environment around a BHE usually follows the pattern described in Figure 1.

During BHE construction natural underground conditions are disturbed, so that atmospheric oxygen penetrates to depth, and underground water rises around the BHE up to the water table.

2. METALS

2.1 Mild steel

It corresponds to low yield steel of low carbon content (0,05-0,15%) for structural applications, such as the ASTM A366/1008 type. It is characterized by low cost, wide availability and ease of fabrication.

When placed underground it corrodes with uniform or pitting corrosion types, depending on soil pH and resistivity, with rates 40% less than ordinary carbon steel. This occurs because its low yield strength provides resistance to stress corrosion cracking. Resistance to stress corrosion cracking is very important in BHE applications, due to the thermal stresses resulting from continuously occurring temperature changes of the heat transfer fluid during heat pump on-off cycles.

In most underground conditions, where pH is more than 6 and chloride concentration in underground water is less than 2%, its corrosion rate is in the range 0,02-0,25 mm/year. This implies that adding 5 mm to pipe walls thickness improves pipe service life by 20-250 years. Resulting pipe cost increase is by 100%.

Localized corrosion attack is initiated by chloride ion dissolved in underground water, with highest corrosion rates occurring in the presence of oxygen. This makes the capillary zone and the upper part of the water saturation zone (see Fig. 1) as the most critical underground zones for corrosion. Corrosion severity increases in the rare case of hydrogen sulfide presence (Conover et al. 1980). Connection of pipes is also important in order to minimize localized corrosion, making threaded connections preferable, as welding may deteriorate metal properties.

In case of corrosive underground environments, e.g. when pH is less than 6, a protection method must be employed, in order to ensure the desired service life of the BHE. External corrosion protection can be achieved by an excellent grouting job with water impermeable grout. If this practice is not followed, then cathodic protection must be employed.

Cathodic protection is achieved by inducing an electric current from a buried anode electrode, through the ground and to the BHE pipe. The electric current can be either self-induced by a sacrificial anode usually made of Magnesium, or Zinc or Aluminum (see Fig. 2), which is consumed during the process, or can be imposed to the ground by a permanent anode supplied by an electrical power source located at the surface (see Fig. 3). Typical electric current properties are 0,1-0,3 mA/m^2 density and less than 15 mW intensity. Cathodic protection must be installed by a professional, who should take care to avoid damage of existing metallic structures buried between the anode and the BHE.

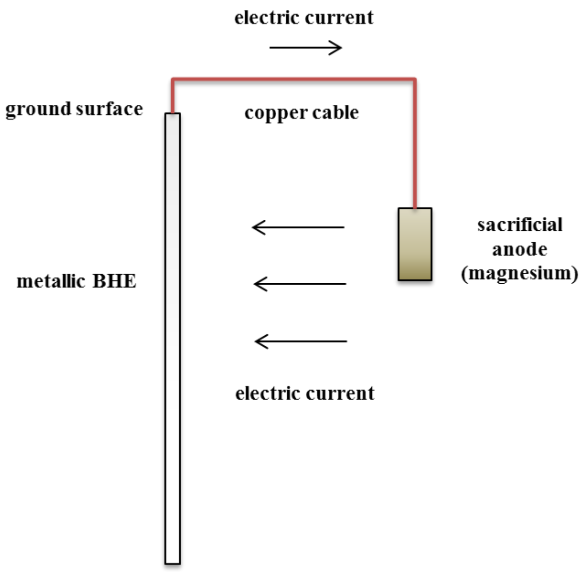

Figure 2: BHE cathodic protection layout by a sacrificial anode.

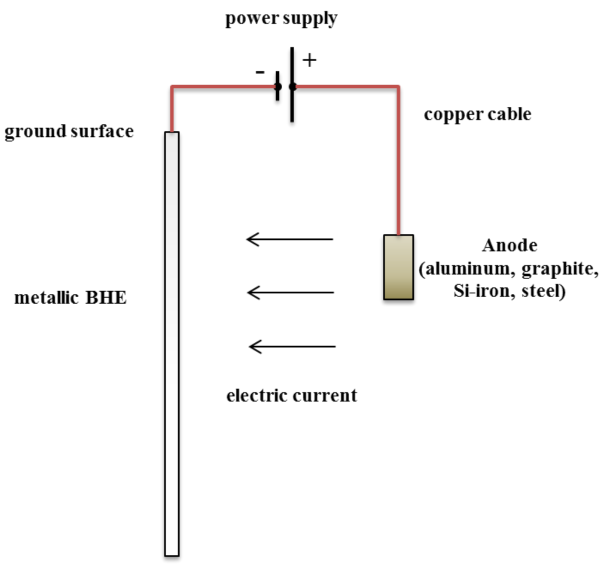

Figure 3: BHE cathodic protection layout by externally imposed current.

2.2 Galvanized steel

Hot dip galvanizing in Zinc provides an external sacrificial anode attached to the pipe, which is consumed first before corrosion starts in the steel section of the pipe. It provides excellent corrosion protection for temperatures up to 60 °C. During installation however, care should be taken to avoid damaging of the external Zinc coating.

Depending on prevailing underground properties, a BHE service life increase by 30-80 years is anticipated for 0,1 mm of zinc layer thickness. The corresponding cost increase of the BHE pipe is in the range 50-60%.

2.3 Steel externally coated

Other options for providing corrosion protection to steel pipes are external coatings. Commercially available options ate bituminous coating, polyethylene coating and glass flake epoxy coating. In all cases BHE installation should take care to avoid damages to the coatings, which will leave the inner pipe exposed to potentially corrosive environment.

Bituminous coatings are the oldest used application to buried piping and the current trend is to be replaced by polyethylene coatings. Both are widely available. Due to the much different thermal expansion coefficients between steel, and asphalt (which forms the bituminous coating) or polyethylene, we anticipate that the coating may fail during BHE operation, when continuous temperature differences of 3-6 °C are common, caused by heat pump on-off cycling.

A new, but not widely available type of coating is the glass flake epoxy. It has the advantage of thermal expansion coefficient similar to low carbon steel, while it is characterized by good surface tolerance, good chemical resistance and good water resistance. Expected BHE service life increase is by 20 years and corresponding cost increase by 60%.

2.4 Stainless steel

Stainless steel is the steel with Chromium content 12% or higher. 12% Chromium content is sufficient to react with oxygen and form a protective Chromium oxide layer covering all metal surface and stopping corrosion. If this protective layer is removed, e.g. by abrasion, chromium reacts with oxygen and replaces the chromium oxide layer, making the metal stainless. Therefore, stainless steel is stainless only in presence of oxygen. The level of corrosion resistance of stainless steel depends on its chromium and molybdenum concentration (Pessall and Nurminen 1974).

Like other metals, stainless steel also benefits from high thermal conductivity, in the range 13-24 W/mK (see Table 1), much higher than typical geologic formations surrounding a BHE, which usually is in the order of 2-3 W/mK.

Table 1: Thermal conductivity λ of selected metals and alloys (Heat atlas 2010).

Metal/Alloy	λ, W/(mK)	λ, W/(mK)
	T=0°C	T=20°C
Aluminum	236,00	
Copper	401,00	
Iron	84,00	
Low yield carbon steel		43,00
Stainless steel		
X20 Cr11 MoV 1 (SS 410)		24,00
X2 Cr18 Ni10 C0,03 max (SS 304L)		17,00
X6 Cr18 Ni10 C0,08 max (SS 304)		15,00
X15 Cr20 Ni12 Si1,5 max (SS 310)		13,00
X6 Cr17 Ni12 Mo2 Ti (SS 316)		13,00
Nickel	94,00	
Ni 99.2 (Nickel 201)	72,20	
Ni - Cu30 – Fe2 (Monel)	21,40	
Ni - Cr15 Fe (Nichrome)	14,50	
Ni - Cr 21 Mo9 (Inconel 825)	11,40	
Ni - Mo16 Cr15 W3 (Hastelloy C22)	9,60	
Ni - Cr22 Mo9 Nb (Hastelloy)	9,30	
Tantalum	57,00	
Titanium	22,50	
Ti - Al6V4		6,50

In BHE applications, stainless steel is protected from internal heat transfer fluid, as it always contains dissolved oxygen. Concerning the external part of the pipe which is in contact with groundwater, stainless steel will remain stainless down to the upper part of the water saturation level. This is also the zone with the highest corrosion rate of carbon steel. Oxygen penetration depth varies from place to place and can be as shallow as few millimeters, or as deep as 100 meters. At depths below the maximum oxygen penetration level, stainless steel is expected to corrode with rates similar to normal carbon steel depending on ground pH and resistivity.

In coastal environments, where seawater penetrates the water table, the high chloride concentration causes severe pitting corrosion to stainless steel. Resulting pitting penetration rates are 1,0-2,0 mm/y for 400 series, 0,25-2,0 mm/y for 304 and 0,05-2,0 mm/y for 316. L-grades are expected to have 40% reduced rates, due to their low yield strength.

Furthermore, 200 and 300 stainless steels series (austenitic) are subject to stress corrosion cracking in costal environments. 400 series stainless steels (martensitic and ferritic) are susceptible to stress corrosion cracking in the rare presence of sulfides in the groundwater. While additions of molybdenum and silicon improve resistance to stress corrosion cracking (Lizlovs 1977; Dundas 1975; Loginow et al. 1972), complete immunity can be achieved in cases of nickel content less than 1% or greater than 45% (Latanision and Stähle 1967; Watkins and Green 1976).

Indicative costs of stainless steel are 50% higher than carbon steel ones for 304 and 100% than carbon steel ones higher for 316.

2.5 Nickel and its alloys

Nickel is characterized by high corrosion resistance proportional to its nickel content, especially in alkaline environments. Nickel-chrome-molybdenum alloys such as Inconel and Hastelloy are mainly used in high temperature geothermal applications (Conover et al. 1980). The Inconel group alloys show excellent corrosion resistance in neutral or slightly acidic environments, but not in intensely oxidizing environments such as nitric acid, ammonia and others.

In the rare occasion where sulfides are present in the groundwater, nickel alloys become brittle. Also, in high temperature environments with high chlorides concentration, nickel alloys are susceptible to localized corrosion, such as pitting and crevice (Miller 1980).

2.6 Aluminum and its alloys

In high temperature geothermal environments aluminum alloys suffer from very high corrosion rates, especially in the forms of pitting and crevice corrosion that have been encountered after geothermal tests. In addition, corrosion attack caused by galvanic coupling can be particularly severe (Miller 1980; Conover et al. 1980).

Aluminum and its alloys are common material in low temperature applications such as exterior siding, construction and seawater desalination, as they exhibit high corrosion resistance. In BHE applications, aluminum can be freely used in the majority of underground conditions, provided that pH is in the range 5,5-8,5 and resistivity is higher than 15 Ohm.m.

2.7 Copper and its alloys

In high temperature geothermal applications, where hydrogen sulfide is present in the geothermal water copper and its alloys are subject to hydrogen sulfide attack and de-alloying (Miller 1977), even in trace H_2S concentration (Conover 1980). If ammonia is present in the water even in very low concentrations of the order of a few mg/l, copper alloys suffer from stress corrosion cracking (Miller 1980).

In BHE applications, copper and its alloys show outstanding corrosion resistance in the majority of underground conditions. Expected life spans can reach several thousands of years under favorable conditions.

Copper corrosion resistance is attributed to the protective layer of cuprous oxide Cu_2O, which forms with the reaction of copper with oxygen; as a result copper needs oxygen presence to maintain its corrosion resistance. In aggressive geologic environments containing groundwater of high concentration in chlorides, sulfates, ammonia and/or sulfides, characterized by low resistivity below 5 Ohm.m, copper and its alloys are subject to general or localized corrosion (Myers and Cohen, 1984). In that case cathodic protection, or an excellent grouting job with water impermeable grout, is necessary.

2.8 Titanium and its alloys

Titanium and its alloys are among the most corrosion resistant materials known today. For this reason they are widely used in many applications. The corrosion resistance of titanium is attributed to the formation of a stable, substantially inert oxide film consisting mainly of TiO_2 at the surface with presence of Ti_2O_3 and TiO at metal interface. This oxide film provides the material with outstanding resistance to corrosion. In contrast to stainless steel, aluminum and copper, TiO_2 is formed by the reaction of titanium with traces of either oxygen or water, which is available in almost every geologic environment. In BHE applications titanium life spans exceeding 1000 years are expected.

Titanium immunity to crevice corrosion is for temperatures up to 300 °C, by far higher than any other metal and alloy mentioned in this paper, making it also suitable for high temperature geothermal applications. The uniform corrosion rate of titanium and its alloys tested in high temperature geothermal fluids is less than 0,008 mm per year, and under even the most aggressive conditions it does not exceeded 0,13 mm per year (George et al. 1975). In chloride concentrations less than 10%, which are encountered in almost every geologic environment, no significant pitting and crevice corrosion occurs (Conover 1980).

As titanium is cathodic to most other metals in saline environments, galvanic coupling with other metals should be avoided, as the other metal may corrode severely. Furthermore, as cathode in such galvanic coupling, titanium may absorb the hydrogen formed on its surface and become susceptible to hydrogen embrittlement (Covington 1997).

Corrosion resistance can be further improved by adding very small quantities of corrosion resistant metals to titanium (Conover et al. 1980). Such alloys are the "Ti 0,2Pd", a nearly pure titanium with 0,2% palladium, and the "Ti Code 12", a very near pure titanium alloy with some molybdenum and nickel additions.

Fabrication process of titanium and its alloys is very important, in order to avoid the formation of any cracks, which facilitate stress corrosion cracking (Boyd 1967). For the same reason, system design should avoid excessive vibration of the titanium parts.

2.9 Other alloys

Cobalt-base alloys are noted for their hardness and for their good sulfide stress cracking resistance and can be used in high temperature geothermal environments. Zirconium and tantalum has very good corrosion resistance in a number of environments, but the cost of these materials is such that no applications to geothermal environments are projected (Miller 1980; Conover et al. 1980).

3. PLASTICS

Plastics are generally resistant to conditions that may adversely affect metal and alloys, while having installation costs lower than those for metals. Thermoplastic materials are characterized by low temperature and low pressure service limits, which in most cases are suitable for BHE applications. Their thermal conductivity is in the range 0,14-0,46 W/mK (Table 2), values much lower than the effective thermal conductivity of most underground formations, which is in the range of 1,5-3,0, resulting in a substantial temperature gradient through the pipe wall and increased borehole thermal resistance.

Table 2: Thermal conductivity λ of thermoplastic piping materials. (*)

Thermoplastic material	λ [W/(mK)]
Acrylonitrile butadiene styrene (ABS)	0,16
Cellulose acetate butyrate (CAB)	0,17-0,33
Polyoxymethylene (POM)	0,30
HDPE	0,46
LDPE	0,32
PEX	0,41
Thermally enhanced HDPE (**)	1,2-2,2
Polypropylene (PP)	0,23
Reinforced PP	0,15
Polyvinyl chloride (PVC)	0,16
Chlorinated polyinyl chloride (CPVC)	0,14
Polynivylidene fluoride (PVDF)	0,22
Polyamide-6 (Nylon-6)	0,22
Polybutylene (PB)	0,22
Polyphenylene oxide (PPO)	0,20
TPE	0,17

(*) Boudenne et al. 2004, Heat atlas 2010, Wypych 2016, Zhao and Ye 2011
(**) new material, http://www.rtpcompany.com/

3.1 ABS

Acrylonitrile butadiene styrene (ABS) is a strong and rigid material commonly used in drainage, waste and air exhaust pipes. Its 3 monomers provide the following advantages (Huang et al. 2010):

- Acrylonitrile improves ABS's chemical, weathering and heat resistance, and increases tensile strength.
- Butadiene improves the low temperature toughness.
- Styrene provides rigidity, good electrical properties, easy processing ability and surface gloss.

ABS recommended service temperature is in the range of -34 to 82 °C. In comparison to HDPE, ABS costs are 40% higher at approximately 1850 €/ton.

3.2 CAB

Cellulose acetate butyrate (CAB) is commonly used as a piping material, due to its toughness, dimensional stability and resistance to extreme weather. The recommended long term service temperature for CAB is in the range of -18 to 60 °C.

3.3 Chlorinated polyether

The recommended temperature service for chlorinated polyether is in the range of -18 to 99 °C.

3.4 POM, Polyacetal

Polyoxymethylene (POM) is selected as a piping material, when high resistance to repeated impacts, fatigue endurance, dimensional stability and electrical insulating capabilities are required. The long term recommended service temperature for POM is in the range of -18 to 77 °C.

3.5 Polyethylene (PE)

As already mentioned, polyethylene, and particularly high density polyethylene (HDPE) has the highest thermal conductivity among thermoplastics (Table 2). Due to its wide availability, low maintenance needs, low weight, continuity, flexibility, versatility, excellent biocompatibility, ease of installation, long lifespan in the ground and reliability in service, HDPE has become the standard piping material for BHE. In addition, because of its bimodal nature, it shows a good high temperature and high pressure performance, resistance to rapid crack propagation, slow crack growth and toughness (Wypych 2016). The recommended long term service temperature for HDPE is in the range of -34 to 60 °C.

Low density polyethylene (LDPE) has similar costs (~1400 €/ton), to HDPE (~1300 €/ton). Its long term service temperature is up to 70 °C. A recently new polymer that is gaining market share is the linear low density polyethylene (LLDPE), which has the same thermal conductivity as LDPE, costs ~1300 €/ton and service temperature up to 50 °C.

3.6 Crosslinked polyethylene (PEX)

Crosslinked polyethylene (PEX) is a stronger version of polyethylene with upper operating temperature limit at 99 °C. It is commonly used in underground thermal energy storage systems supplied by solar energy, where temperatures exceeding 60 °C are common. In addition, PEX finds many applications in geothermal and district heating systems due to its high service temperature, chemical resistance, abrasion resistance, memory effect, thermal and aging stability (Wu 2007). Its costs are approximately double than the ones of HDPE.

3.7 Polypropylene (PP)

Polypropylene (PP) is a widely available thermoplastic material with similar costs to HDPE (~1300 €/ton). Its recommended service temperature is in the range of -1 to 99 °C. Special types of polypropylene, such as Beta PP-H and multilayer reinforced PP have extended operating temperature range down to -10 °C. PP is suitable for BHE use, provided that system design results in minimum pipe wall temperatures not less than 0 °C.

3.8 Thermally enhanced polyethylene

As the thermal conductivity of PE (0,46 W/mK) is lower than the one of most grouts (0,8-2,0 W/mK) and than the one of common geologic formations (1,5-3,0 W/mK), using polyethylene with enhanced thermal conductivity will effectively reduce BHE thermal resistance and its required length for a given thermal output.

Typical production method is by introducing a secondary material of high thermal conductivity in the polymer matrix, in order to enhance thermal conductivity up to 10 times, which is sufficient enough for BHE applications. Adding graphite is one good option, due to its availability and low cost. Recent technological advances allow the addition of carbon nanoparticles as another efficient method. The challenge is to balance the addition of both coarse and fine particles with the goal of maximizing conductivity, while minimizing the subsequent effects to viscosity and mechanical strength.

There are one or two manufacturers of thermally enhanced polyethylene today located in USA. RTP is one of them, which supplies two types of thermally enhanced PE, with through plane thermal conductivities of 1,2 and 2,2 W/mK respectively. In USA, research is under way towards further improving this material to reach thermal conductivities of 20-30 W/mK.

3.9 Polyvinyl chloride (PVC)

Polyvinyl chloride (PVC) pipes are strong and rigid, used mainly in water, gas and drainage systems. Its recommended temperature service is in the range of -18 to 60 °C. PVC costs are approximately 40% lower than the ones of HDPE at 800 €/ton.

3.10 Chlorinated polyvinyl chloride (CPVC)

Chlorinated polyvinyl chloride (CPVC) is a similar material to PVC, but with higher long term service temperature range from -18 to 80 °C. CPVC is selected as a piping material, when good frame and thermal resistance are required (Wypych 2016).

3.11 Polyvinylidene chloride (PVDC)

The recommended temperature service of polyvinylidene chloride (PVDC) is in the range of 4 to 71 °C.

3.12 Polyvinylidene fluoride (PVDF)

Polyvinylidene fluoride (PVDF) pipes show a remarkably good strength and durability. The recommended long term service temperature of PVDF is in the range of -18 to 135 °C.

3.13 Polyamide (Nylon)

There are several types of polyamide-6 (nylon 6), which show completely different material properties from one another. Polyamide-6,66 (PA-6,66 or nylon-6,66) pipes show a remarkably good wear resistance and low friction between the pipe's walls and the circulating medium. Nylon-6 is used when good temperature resistance and chemical resistance to greases and oils is required. Recommended temperature service of nylon is in the range of -34 to 80 °C.

3.14 Polybutylene (PB)

Polybutylene (PB) pipes are mainly used for pressurized water systems with compression and banded joints due to their creep resistance and semi-crystalline structure and temperature service between -18 and 99 °C. In United States, PB pipes used for both residential and commercial water distribution during the 1980s and 1990s, exhibited an unusually high rate of failure under normal operating conditions, attributed to the presence of chlorine additives in the water.

3.15 Polyphenylene oxide (PPO)

The recommended service temperature of PPO pipes is in the range of -1 to 99 °C.

3.16 Thermoplastic rubber (TPE)

Thermoplastic rubber includes six different types of thermoplastic materials: (1) thermoplastic olefins (TPE-o), (2) styrene block polymers (TPE-s), (3) elastomeric alloys (TPE-v or TPV), (4) thermoplastic polyurethanes (TPU), (5) thermoplastic co-polyester and (6) thermoplastic polyamides.

The operating temperature range of thermoplastic rubber (TPE) pipes is in the range of -10 to 100 °C. TPE materials show excellent resistance to dynamic fatigue, good tear and abrasion resistance, low deformation under compression and traction, as well as good resistance to aqueous fluids, oils and hydrocarbons. They have low density, below 1 kg/m³ and high cost ~5100 €/ton.

4. EVALUATION

Alternative materials for BHE applications were evaluated in terms of unit cost of delivered geothermal power. Only pipe materials that are widely commercially available were considered.

4.1 Required BHE length

A model coaxial BHE was considered comprising two pipes, an external one of 60-63 mm diameter made of the material under evaluation and an internal one made of HDPE of 32 mm in diameter (Fig. 4).

Using EED simulation code we estimated the required length of the above model BHE needed to supply a heat pump delivering 5 kW peak heating power.

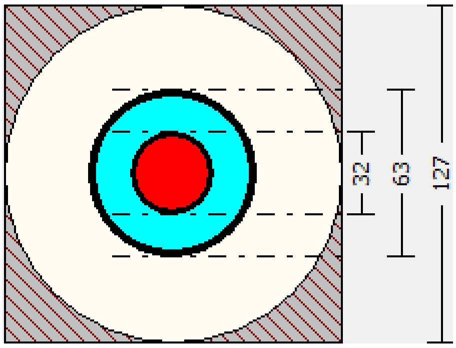

Figure 4: Model coaxial BHE φ63 placed in a 5" borehole used for the evaluation; figure generated by EED code; dimensions are in mm.

A heat pump SPF of 4,0 was considered, resulting in the geothermal output of the model BHE to be 3,75 kW. Base load corresponded to annual heat provision of 17,5 MWh of heating with typical base load distribution throughout the heating season for Central European climate (Fig. 5).

Ground temperatures of 10 °C were assumed. Ground thermal conductivity used was 2,8 W/mK and grout thermal conductivity was 1,5 W/mK, value typical for boreholes filled with water or thermally enhanced grout. Ethanol was considered as heat transfer fluid with minimum mean temperature of -3,0 °C after 20 years of operation.

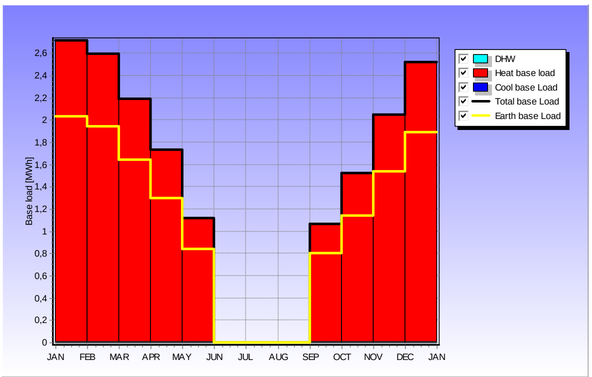

Figure 5: Geothermal energy delivered by the model BHE and heat supplied to the building by the heat pump used for the evaluation; figure generated by EED code.

4.2 BHE cost estimation

For each case of commercially available pipe material, we obtained a quote from local suppliers, which are presented in Table 3. In addition to that, local drilling and grouting costs were used, which were 30 €/m for drilling and 6 €/m for grouting.

BHE costs were estimated by adding the costs per meter of internal pipe, external pipe, drilling and grouting and multiplying by the BHE length calculated by EED in previous paragraph. Unit BHE costs were estimated by diving total BHE costs with geothermal energy delivered. The results are shown in Figure 6.

Table 3: Pipe costs for commercially available materials.

Pipe material	External diameter mm	Wall thickness mm	Cost, €/m
HDPE Φ32 (internal)	32	3	1,38
HDPE Φ63	63	3,8	3,44
PEXa Φ63	63	3,8	6,88
PVC Φ63	63	3	3,08
PB	63	10,5	19,94
PP random	63	10,5	10,90
PP reinforced	63	5,8	8,04
seamless steel black	60,3	5,54	38,96
seamless steel galvanized	60,3	3,6	37,18
welded steel galvanized	60,3	2,5	28,01
seamless steel with external PE coating	60,3	2,9	23,83
seamless steel with external bitumen coating	60,3	2,9	23,67
stainless steel 304	60,3	1,5	22,00
stainless steel 316	60,3	1,5	37,41
stainless steel 304L Cheap-GSHPs quote	60	2	6,37
aluminum	63	2,5	9,76
copper	64	2	37,08
titanium, seamless	73,02	3,05	134,75

4.3 BHE life span

For the above materials considered, an indicative expected life span for BHE use was evaluated, using the information provided in this paper, as well as experience gained from underground pipes in USA (White 2011). The results are presented in Figure 6.

Titanium is expected to have almost infinite life of the order of 1000 years, but for presentation purposes it is listed as 100 years in the graph.

For plastics used commonly in underground piping, such as different types of Polyethylene, PVC and reinforced Polypropylene, we used the widely expected service life for such applications, which is 75 years.

For thick walled low carbon steel, galvanized steel and copper, we used a service life of 50 years, as the standard design life for such pipes. For thin walled aluminum and lightweight stainless steel pipes, even though their corrosion rates depend on subsurface prevailing geological and hydrological conditions, we considered 50 years' service life, as we assumed that grouting provides external sufficient corrosion protection by prohibiting direct contact of the metal with the underground formations and groundwater.

For Polybutylene we used 45 years of expected service life, as this is the time when deterioration is reported for such piping. For coated steel pipes we used the service life of carbon steel of the same wall thickness, as we expect that coating will be damaged during BHE placement in the ground or from thermal expansion and contraction during BHE operation. Last, for random polypropylene we used a service life of 25 years, as random PP becomes fragile in temperatures below 0 °C, condition often encountered in BHEs in heating mode during wintertime.

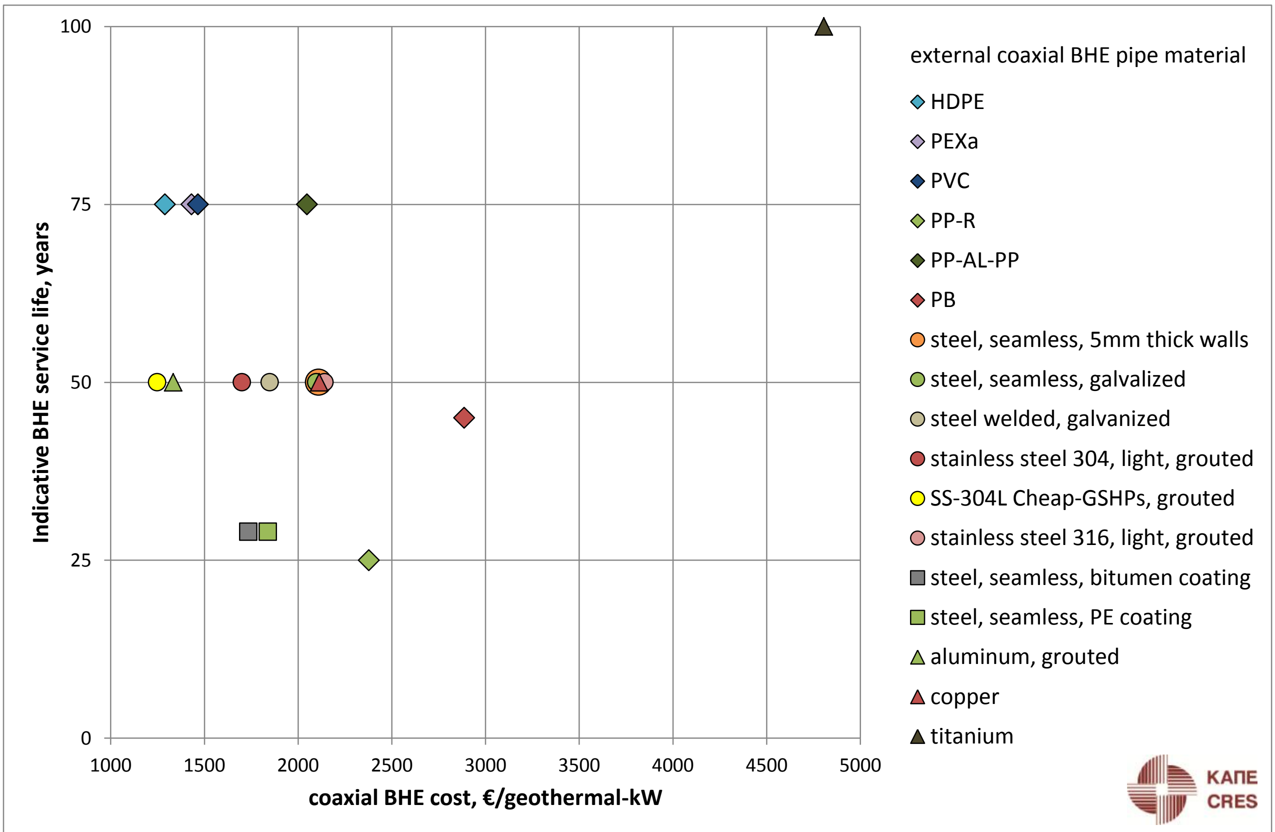

Figure 6: Expected service life (indicative) versus delivered geothermal energy costs by a coaxial BHE using external pipe made of different market available materials.

4.4 Results

The evaluation results for different BHE materials are summarized in a graph comparing expected BHE service life with delivered geothermal energy costs, which is presented in Figure 6.

5. CONCLUSIONS

There is a wide range of alternative materials to HDPE for BHE use, including thermoplastics such as PVC, PEX and reinforced PP, as well as metals such as thick walled mild steel, galvanized steel, L-grade stainless steel, aluminum, copper and titanium. With the exception of titanium and perhaps copper, local ground conditions must be considered when using metallic materials. Thermally enhanced HDPE is a new material which may be promising for BHE use in the future, when such pipes become commercially available.

In each case, material selection should consider the corresponding BHE costs. In the evaluation done in this paper, HDPE despite its low thermal conductivity remains a very competitive option for use in every geologic environment. With proper commercial agreements for pipes procurement, metallic solutions can also become competitive, as in case of 304L stainless steel and aluminum using the special quotes offered for the Cheap-GSHPs option.

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