TNO PUBLIC

Molengraaffsingel 8
2629 JD Delft
The Netherlands

www.tno.nl

T +31 15 820 09 20
F +31 15 820 09 20

TNO 2023 R10385

Feasibility of complete composite geothermal well systems

Date	11th May 2023
Author(s)	Michiel Hagenbeek, Sander Dragt, Loris Pergod
Copy no	-
No. of copies	-
Number of pages	55 (incl. appendices)
Number of appendices	-
Sponsor	TKI Urban Energy
Project name	Com2Geo
Project number	060.50546

1 Project Information

Project title: COM2GEO

Project number: 1921405

Project coordinator:

Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek (TNO)

Project partners:

Huisman Geo BV
Well Engineering Partners (WEP) BV
TechnipFMC
ECW Energy BV
HP Well Screen BV
VDL Fibertech Industries BV
Eco-Well BV

Project period: 01-08-2021 to 01-02-2023

This report can also be found in the TNO repository: https://repository.tno.nl/

“Het project is uitgevoerd met PPS-programmatoeslag subsidie van het Ministerie van Economische Zaken en Klimaat voor TKI Urban Energy, Topsector Energie. www.tki-urbanenergy.nl.”

Contents

2 Technical report

2.1 Summary

Background
Geothermal energy has great potential as a baseload heat source for district heat systems for built environment. To improve the economics for large scale implementation, technology and methods are explored to lower the Total Costs of Ownership (TOC). Geothermal systems are currently mainly made out of steel and therefore subjected to corrosion and deposits. This will result in high maintenance costs for corrosion prevention (inhibitors), inspections and repairs which will reduce uptime of the system. Not always recognized, but it will also raise the cost of energy for circulation due to increased flow resistance. A non-corrosive material such as Glass Reinforced Epoxy (GRE) material can reduce the cost of operation and the risk of production shutdown for unscheduled maintenance and additional production loss.

Aim of the project
The aim of the project is to study the technical feasibility and the economic viability of a corrosion and scale-free geothermal doublet system for the built environment, manufactured in composite material. The project is aimed to offer basic information, for system developers and the geothermal heat sector in general, of the potential of using GRE as the base line construction material in comparison with traditional steel.

Short description of the activities
In this project, a technical feasibility study is carried out with partners from the supply chain and end users towards a corrosion-free geothermal system. The system and component requirements are defined by the well designers, drillers and operators together with composite companies and suppliers to investigate complete composite geothermal system design concepts. Current geothermal wells are mainly based on traditional oil and gas drilling and well construction technology. In this project attention is given to define functional requirements tailored to geothermal production and allow for alternative design space and define the appropriate base line for geothermal production conditions. Different conceptual designs are analyzed by experts of the consortium for critical technical performance, manufacturability, reliability, sustainability and safe use (strength, lifespan, circularity, costs). The results are developed and shared within the consortium and publicly reported to increase expertise development and increase production integration. Finally, based on the knowledge gained with the chain of collaborating companies a proposal for a pilot project is developed.

Results and conclusions
In the Com2Geo project the techno-economic feasibility of a corrosion and scale-free geothermal system for the built environment, constructed in composite material is investigated. Generalized functional system specifications of a doublet geothermal production system typical for Dutch conditions are defined and broken down to evaluate key safety and operational requirements. Next the main system components sand screen, the casing, production tubing, the wellhead, surface pipelines, the degasser, the filter modules and the heat exchanger are accessed for

technical and operational compliance when manufactured with GRE and steel. The assessment is conducted with subject matters experts from the partners of the consortium. A division of the maturity and availability of GRE products and GRE manufacturing technology is made to provide information for market readiness being part of the techno-economic evaluation. One of the main conclusions it that no technical bottlenecks are identified to design, manufacture, construct and operate a geothermal doublet system tailored to Dutch subsurface conditions providing required production capacity, system integrity and safety. Based on the material cost data (2022) and manufacturing costs of reference GRE products for example GRE pipes and vessels used in other sectors it is expected that the cost of material which part of the total CAPEX (components and installation) of a geothermal doublet is similar or lower to conventional cost of steel products and installation. Costs of operations (OPEX) and environmental impact is reduced while at the same time the longevity is increased from 10 to 30 years. Main cost saving identified are direct costs related to corrosion prevention (inhibitors/service), inspection (down time/equipment/services) and repair (down time/material/service). However also indirect costs as a result of the absence of corrosion and scale adds to the costs savings due to the lower flow resistance in the system which in turn reduces electricity need for pumping substantially. Recent developments, especially in recycling the blades of wind turbines in the wind industry, show that recyclability of (large) composite can be achieved. As this market of recycling of GRE blades of wind turbines is rapidly developing and pilot installations are currently built and tested recycling capacity for geothermal GRE components will be available within 10 years well before the decommissioning of the first built composite geothermal systems.

Based on LCA data of the TU-Delft estimates of 50 to 90% lower environmental impact have been found for composite compared to steel components. [1] It is expected that the environmental impact of infrastructure will become a condition of growing importance for project realization.

2.2 KPI table

KPI	
TRL at closure, Main phase	Fundamental Research
TRL at closure, Detailed level	TRL 3-5
Project achievements	1. The project has been completed in accordance with the original scope. All milestones have been achieved;
Follow-up	Follow-up research will be conducted within the MOOI Com2Heat project.
Number of peer-reviewed publications	1
Number of expected peer-reviewed publications	-
Number of non-peer-reviewed publications	-
Number of patents	No patents filed
Number of licences granted	-
Number of prototypes	No prototypes developed
Number of demonstrators	No demonstrators
Number of spin-offs/ spin-outs	No spin-offs / spin-outs (using the technology developed within the project)
Number of new or improved products/processes/services introduced	5 improved products of which 1 is market ready and 4 will be taken to a pilot phase in theCom2Heat project.
Impact	The project has created new economic opportunities by investigating the feasibility of composite products for geothermal well construction

2.3 Introduction

2.3.1 Background

In the Netherland the temperature of the subsurface is moderate to low and geothermal energy production from 2-3km depths are well below 100 ^{o}C. This is considered Low Temperature (LT) or Low Enthalpy (LE) geothermal energy. Although not suitable for electricity production it can play an important role in reducing CO_2 emissions for heating in the built environment and greenhouse horticulture. Experience from the 20-30 geothermal production systems currently teaches the sector that the Total Cost of Ownership of the infrastructure limits the full potential of geothermal development in the Netherlands. The project is aimed to contribute towards a reduction of the operational costs of geothermal production from low temperature sedimentary formation affordable sustainable heating and cooling in the built environment by reducing the costs of heat from geothermal energy for the built environment in the scope of the Multi-year Mission-driven Innovation Program MMIP4.

Geothermal wells are now being built in the Netherlands according to oil and gas industry standards. The drilling process and well construction including screens, wellheads, degasser, filter and heat exchanger is based on component made of steel. Steel is sensitive to corrosion and scale deposits from the circulating salt formation water and current production locations experience high costs due to unplanned maintenance due to corrosion and scale. Corrosion can cause loss of material strength and leakages. Inspections (logging) and repairs (well interventions) are expensive due to the limited access at great depths and the loss of production due to the heat supply interruption. To control the rate of corrosion and prevent the deposition of scale, chemicals (inhibitors) are injected directly into the system deep underground at the well inlet. The costs of continuously injecting these inhibitors are substantial. Although the method is widely applied, due to environmental requirements, this approach is under scrutiny, possibly resulting in upcoming stricter regulations. To avoid undetected risk of leakage the state regulator of the mines Staatstoezicht op de Mijnen (SodM) introduced a directive to install two casing and production tubing, double-skin solutions. Although this is more common for the oil and gas industry it adds quite some additional costs and restricts the production capacity and access for possible future intervention.

It is clear that a material that is not susceptible to corrosion and scale will reduce operational costs and also lower the risk of production downtime due to unplanned maintenance causing loss of production and costs of repair. All the components in the system that are exposed to the formation brine such as the, casing/tubing, heat exchanger, wellheads, degasser, pumps, valves, et cetera, are subject to deposits and corrosion. As a consequence, these components often need to be inspected, repaired or replaced before the predicted service interval. This is illustrated with data that in the Netherlands, in 3 of the 38 geothermal wells leaks due to corrosion have been detected after inspection. [1] Corrosion is causing the industry problems in many ways and composite materials have been used for pipes and vessels for decades in the oil and gas industry, the water sector and the chemical process industry to reduce the risks of leakage due to corrosion, to prevent scale deposition and thus to reduce operational costs, and to increase production with minimised downtime, see example case study of Radhakrishnan. [65]

Although the emerging geothermal sector could greatly benefit if corrosion and scale can be avoided it is at this point not clear what the potential is at geothermal system level and whether GRE can be applied for all components at the operational conditions of low temperature geothermal brine. Advantage of systems only partly constructed of material that is not sensitive for corrosion and scale.

Geothermal production systems made with materials not sensitive for corrosion and scale deposition can improve safety and reduce costs of operations which is a major step forward to improve the economics and speed-up the growth of sustainable heat production from geothermal sources.

The use of glass fibre reinforced composite has great potential for this application. Composite materials are not sensitive to corrosion and are also much less sensitive to scaling due to the smoother finish and the absence of iron atoms on which lime chemically binds. Furthermore, a full composite part is generally less sensitive to damage during installation or during interventions compared to a GRE-liner and has a longer lifespan than steel which is seen as an important spearhead for further innovation in the sector. [2] This type of materials offers the possibility to integrate sensors which can contribute to (operational) safety and production optimization. Finally, composite has a significantly lower density than steel (about 1/7), facilitating installation of the well and the above-ground components, reducing installation costs and risks, and offering additional benefits for construction sites in densely populated areas such as the Netherlands.

Thanks to these properties, a fully composite system can offer a “maintenance free” solution for operational cost reduction and provide both long-term operational and environmental safety.

2.3.2 State of the art

Current solutions for preventing corrosion and scale deposition in the geothermal sector are aimed at control with inspection, inhibitors and maintenance schedules. Also specific designs of components with redundancy such as corrosion allowance and double skinned well constructions. Composite materials is sometimes used as a liner / coating on the inside of a steel pipe for corrosion protection while the steel pipe provides the strength of the pipe for burst, collapse, tension and compression. However, this has some limitation. For example some traditional maintenance methods cannot be applied and corrosion of the steel from the outside is still a risk which could go undetected. Connection areas are also at risk as not all steel can be coated [3]. Existing solutions with coatings are vulnerable to delamination/chipping of the coating [3] and do not have the benefit of weight savings. A number of products have been developed by Huisman, such as production tubing and casing made fully out of composite [5] [4] [66]. There is also a number of projects that deal with composite solutions such as liners for well casing.

The development of fibreglass composite casing and tubing for geothermal production has been investigated by various groups and consortia in a European context, including within the European Geothermal programme.
In the CRECCIT project, the composite casing developed by Akiet [4] and the required installation technology were investigated. Huisman later took over the technologies developed.

In 2020, the GRE-GEO project started under the same European programme in which design rules, certification and installation of glass fibre composite tubing is being investigated [5].

In the GeoWell project, TNO and Huisman Geo, who are involved with the current project, explored high-temperature geothermal concepts alongside other partners. Corrosion-resistant materials along with composite tubing and flexible couplings were also investigated [6]. Recently, Huisman has won the European geothermal innovation award for their composite tubular and connection [10].

At individual component level, research on suitability of pumps types, designs and materials was carried out on the available solutions for the geothermal energy market with a focus on solutions to extend the lifespan from 2 to 5 years through maintenance [7]. The possibilities using plastic based heat exchangers have been investigated in a study by the University of Sannio in Italy [8].

2.3.3 Project developments

With the support of TKI Urban Energy, the Com2Geo project delivers a feasibility study and concept design of a corrosion and scale-free geothermal system for the built environment, made of glass fibre reinforced composite. All components of the geothermal system are examined individually and collectively, and innovations in this context are possible at the level of the system specification package, at the subsystem and at the component level.

There is experience within the industry with the use of composite materials at component level for geothermal applications, such as the use of composite casings and couplings. However, when considering the feasibility of using composite for the entire system, the project starts at the level of technology concept (TRL2). The feasibility study, the design of a case and a proposal for a pilot project are steps taken within the project to reach TRL3-4.

The design drivers and operational limitations considered are adapted from experience within the geothermal industry, existing standards applicable to oil and gas industry where explosion and strength safety play a dominant role, and specific considerations with regards to the efficient and sustainable use of composite materials. This last aspect is particularly important within the context of MMIP4 and a dedicated section of this report treats of the recyclability of the intended fibreglass composite installations, with an emphasis on the implications that the choice of material has on recyclability and on the economic and social aspects.

To ensure fitness for purpose, the partners in the project are subject matter experts and represent the production chain and end users. Based on the progress in the project it was decided to aim for a joint submission of a MOOI proposal called ‘Com2Heat’ to enable further development of the investigated system and its components into a pilot phase. VDL and TechnipFMC decided not to pursue their investigations within this new proposal. However several new partners joined as well and together formed a sounding board for the Com2Geo project, giving their feedback on the technical development of composite geothermal systems. The Com2Heat proposal has been granted and started 1st March 2023.

2.3.4 *Content and structure*

The structure of this report follows the work packages structures set out in the project initiation phase. In the first section, requirements for a composite geothermal system are established to cover the full lifespan of the system (WP1).
In the following part, conceptual design of geothermal doublet system components are designed (WP2) and the outcome is analysed critically against composite and conventional alternatives regarding the technical and economical merit, safety, and sustainability aspects (WP3).
Further, options for increasing the operational benefits of composite compared to conventional steel systems are explored (WP4) and the possibility of sensor integration in the composite parts is investigated (WP5).
A dedicated section then covers the aspects of composite material recycling towards a more circular and sustainable use of materials in the industry.
Finally, conclusions on the project are drawn to increase composite design expertise in the sector and to advance the application of composite in geothermal systems (WP6). Opening towards next steps is also suggested by means of a pilot project case design and proposal (WP7).

2.4 System requirements

2.4.1 System overview

The schematics presented in Figure 1 along with Table 1 give an overview of the different components coming into play in a doublet geothermal well system.

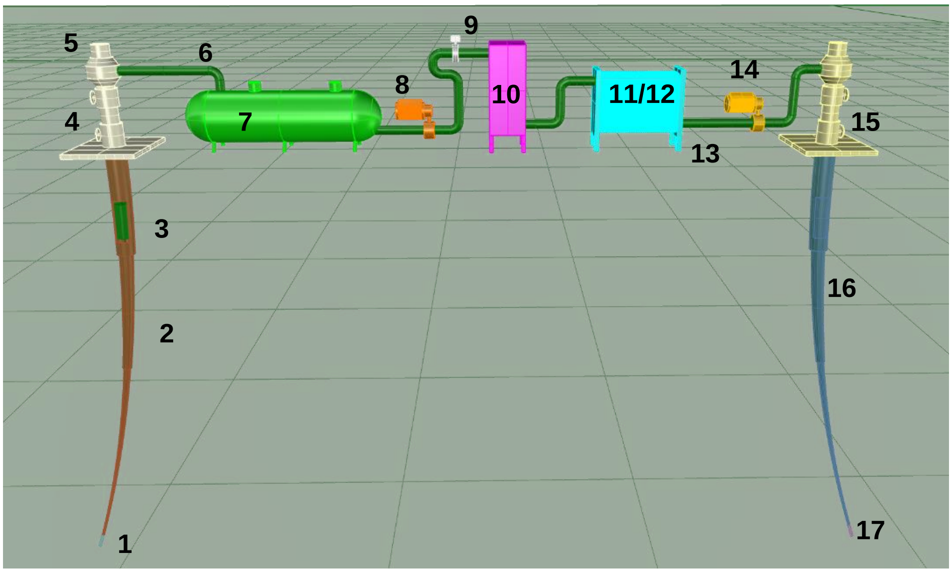


Figure 1 - Schematic overview of the system.

Table 1 - System components overview.

#	*Part:*	*System:*	#	*Part:*	*System:*
1	Well screen	Warm	**10**	Filters	Warm
2	Production casing	Warm	**11**	Heat exchanger	Warm
3	Electric submersible pump	Warm	**12**	Heating network connection	Warm/ Cold
4	Production wellhead	Warm	**13**	Piping - Cold water	Cold
5	Injection point	Warm	**14**	Injection pump	Cold
6	Piping - Hot water	Warm	**15**	Injection wellhead	Cold
7	Degassing	Warm	**16**	Injection casing	Warm
8	Booster pump	Warm	**17**	Well screen	Warm
9	Monitoring system	Warm			

In the context of this project, not all components will be treated separately,

- In cases where both components need to provide similar functions:
  - Well screens (1&17);
  - Casings (2 & 16);
  - Piping (6, 12 & 13);
  - Wellheads (4 & 15);
  - Pumps (3, 8 & 14) are not covered in this report.
- Or when the component is an ancillary to a main component of the system:
  - The injection point (5) part of the wellhead (4);
  - The Monitoring System (9) is installed on the pipelines (6, 12 & 13).

2.4.2 *Overarching system requirements*

The complete system has the set of overarching requirements described in Table 2.

Table 2 - System requirements.

#	Requirements:
S1	The system is of **doublet type**
S2	The system is designed for **Dutch subsurface conditions**
S3	The system produces ***300 m^3/h***
S4	The system captures water at **3km depth**
S5	The system operating temperature is ***100°C***
S6	The minimum lifetime of the system is ***30 year***
S7	The system is made out of **composite material components**
S8	The system is compliant with ge**othermal waters** (corrosion, acidity, scaling, salinity) without the use of corrosion inhibiters

2.4.3 *Component level requirements*

Additionally to the global requirements for the entire system, specific requirements for each component are drawn up in Table 3. The numbering refers to the ones established in section 2.4.1 considering the components grouping detailed there.

Table 3 - Component level requirement summary (for considered components, see section 2.4.1).

#	***Component***	***Requirement***
1	***Well screens***	
1.1	Prevents particles bigger than 100 microns to enter the system with the geothermal water.	Up to 100 µm;
1.2	Open area should be at least 10%, preferably 15%.	
1.3	The resistance to abrasion should be maximized, especially on the outer surface contacting the soil material.	
1.4	Chemical and thermal resistance should be ensured to the specific conditions of the brine.	
1.5	The lifetime of the part should at least match the lifetime of the system as the part cannot be replaced.	
1.6	The system should withstand the push/pull solicitations from the installation process.	
2	***Casings***	
2.1	The casing should withstand well pressures and forces due to installation (drilling) and operation	Tension-, Compression-, Burst-, and Collapse ratings sufficient to cope with Load Cases during construction and 30 years operations of typical low-enthalpy geothermal wells (injector and producer)

2.2	*Resistance against:*	
2.2.1	Mud	
2.2.2	*Cement*	
2.2.3	Corrosion	
2.2.4	Scaling from brine water deposit	
2.3	The casing should provide sufficient stability to unstable formations traversed, especially during drilling operations of the deeper section	
2.4	The casing should provide support to successive well elements (casing or well screen).	
2.6	The casing located nearest to ground level should provide support for the wellhead, blow-out preventers and other ancillaries near the ground level.	
2.7	The well casing should provide structural support to the ESP.	
2.8	The casing should provide integrity for the entire system lifetime and should ensure suitable end of life solution (efficient plug and abandonment strategy).	
4	***Well heads***	
4.1	The well can be accessed for maintenance without removing the well head.	
4.2	PSL2 quality level	PSL2
4.3	Material class FF based on API-6A for long exposure to a chemical environment at temperature.	API-6A-FF
4.4	*Resistance against:*	
4.4.1	Brine water (corrosion and chemicals)	
4.4.2	Outside environment	
4.5	206.8 bar (3000PSI) pressure to withstand for drilling operations 103.4 bar pressure to withstand in operation	Min 206.8 bar / 103.4 bar
4.6	Minimum lifetime of 25-30 years	25-30 years lifetime
4.7	Sealing between all connections (adequate surface finish and boundary penetration sealing)	Compatible with 90 °C, 1.07 SG NaCl with 2% CO_2 geowater
4.8	Geometry initially based on but not limited to metal components design	
4.9	Ability to connect to other API 6 components. Interfacing valves or fittings are excluded from the scope.	16’’ 84# casing; ESP hangers, BOP test plugs, and bowl protectors
4.10	Maximum height to fit in a cellar 2m	Max 2m high
4.11	Working temperature range [-18 to 121 °C]	-18 to 121 °C
4.12	Able to cope with being connected to components in materials with different thermal expansion factors	
4.13	Suitable for both the production and injection wells	
4.14	Internal TechnipFMC specification defined	SPC20085117
6	***Pipelines***	
6.1	Thermal insulation/conductivity to minimise losses	
6.2	Pressure to withstand?	Min 10 bar
6.3	Corrosion and chemical resistance	

7	***Degassing/separator***	
7.1	Thermal insulation/conductivity to minimise losses?	
7.2	Should withstand a pressure of 10 bar	Min 10 bar
7.3	Corrosion and chemical resistance	
7.4	Erosion resistance on the evaporation plates	
10	***Filters***	
10.1	Prevents particles bigger than 1 micron to enter the heat exchanger with the geothermal water.	Up to 1 μm
10.2	Thermal insulation to minimise losses	
10.3	Operating pressure	Min 10 bar
10.4	Corrosion and chemical resistance	
12	***Heat exchanger***	
12.1	Pressure to withstand (operating/pressurization)	Min 16 bar – max 24 bar
12.2	Flow	50-175m^3/h
12.3	Corrosion and chemical resistance	
12.4	Minimise scaling that would reduce the heat exchanger efficiency and reduce the flow	
12.5	Maximise conductivity between the two fluid systems	6 - 24 W/mK for conventional metallic systems
12.6	Thermal insulation to minimise losses with the outside of the system	
12.7	Inspectable and provision for drainage/pressure release/cleaning	

2.4.4 Regulatory and compliance framework

For the majority of the system components, no regulatory or certification framework exists for the use of composite materials. This is identified as an important aspect for the introduction of composite products for geothermal well systems.

However, the certification of geothermal wells made out of metallic components is often achieved, based on a conservative certification framework derived from oil and gas regional standards. These standards, along with relevant standards for GRP parts in other relevant industries could be used as a foundation to derive adequate procedures for the certification of composite components in geothermal wells.

The following references provide an initial base to carry out such an exercise.

Table 4 - Related standards and regulations.

Standard / Regulation		**Applicability**						
Code	Content	Well screen	Well casing	Pumps	Wellhead & injection point	Pipelines	Degassing unit and filters	Heat exchanger
GENERAL								
Norsok P-002 [9]	Process system design	√	√	√	√	√	√	√
Mijnbouwregeling 8.4 [10]	Dutch mining regulations	√	√	√	√	√	√	√
SYSTEM COMPONENTS								
API 6A [11]	Wellhead and tree	√	√	√	√			
API 6X [12]	Pressure containing equipment	√	√	√	√	√	√	√
API 6AF [13]	Flanges under combined loads	√	√		√	√	√	√
BS 6464 [14]	Reinforced plastic pipes, fittings and joints	√	√		√	√	√	√
ASTM D3517 [15]	GFRP pressure pipes	√	√		√	√	√	√
ASTM D5685 [16]	GFRP pressure fittings	√	√		√	√	√	√
ASTM D4024 [17]	Machine made GFRP flanges	√	√		√	√	√	√
ISO 10423:2022 [18]	Wellhead and tree	√	√	√	√			
ASME VIII div1 [19]	Pressure vessels construction		√		√	√	√	√
ASME VIII div2 [20]	Pressure vessels construction alternatives		√		√	√	√	√
NEN-EN 13445-3:2021 en [21]	Unfired pressure vessels		√		√	√	√	√
BSI PD 5500:2021 [22]	Unfired pressure vessels		√		√	√	√	√
ASME B31.3:2022 [23]	Process Piping	√	√		√	√	√	√
ISO 13703:2000 [24]	Piping systems	√	√		√			
NEN-EN 13480-3:2012 en [25]	Piping systems	√	√		√			
MATERIAL SELECTION								
NEN-EN-ISO 14692-1:2017 en [26]	GRP materials and terminology	√	√		√	√	√	√
Norsok M-630 [27]	Materials for piping	√	√		√	√	√	√
ISO 15156-1:2020 [28]	Crack resistant materials guidelines	√	√		√	√	√	√

2.5 System design & analysis

Based on the requirement and regulatory information gathered and summarised in the previous section, the consortium partners carried out design work on composite versions of the system components in order to assess the technical and financial feasibility of such system as well as its sustainability and safety. This section presents the main findings of this work.

However, not all the components of the system were designed. This can be motivated by the following reasons:
- the nature of the component such as pumps (ESP, Booster, Injection) and monitoring system where a good portion of the internal parts can only be made in metal (electrical components, motors, gears …). Although some of the remaining components could be manufactured out of composites.
- these components are fairly small with little gains to be made by using composites or where plastic materials are already in use such as the filters ahead of the heat exchanger.

2.5.1 Well screen

The water enters the system through the well screen which is the primary sand control mechanism. The well screen is designed to prevent sand particles from entering, and damaging, the system while maintaining a large open area to facilitate the inflow. Furthermore, it must be very wear resistant and contain non-clogging slot openings. This is very important since the well screen cannot be accessed during the entire lifetime of the well. Naturally, the screen must be resistant against chemical components that may be found in the geothermal brine and temperatures at the formation. The screen is typically installed around a perforated pipe with a large open area, which allows production of the filtered fluid.

The well screen consists of a mechanical filter, which prevents sand particles from entering and damaging the system. Over time, these particles build-up around the screen, creating a second, natural filter around the well screen itself. This natural sand pack functions as an additional filtering layer and increases the efficiency of the screen. Hence, the choice of filter is also dependent on the sand data analysis at the location. A typical well screen is the Wire Wrapped Screen (WWS). The V-shape of the wire provides the clogging protection and filtering, see Figure 2. The system is made of high grade steels, such as 316L, duplex or 825.

Given the formation specifics, a gravel pack can also be placed around the well screen at installation, to provide similar functionalities when a natural sand pack is not expected to form. Finally, a prepacked screen can also be used. Here, the mechanical filter is combined with a prepacked filter medium. This can be (coated) gravel or, glass or ceramic beads. An example of prepacked well screen from HP Well Screen is shown in Figure **2**.

The main challenges faced in creating a composite well screen are the mechanical strength and wear resistance of the filter media, when compared to conventional approaches. Important boundary condition here is the relatively high temperature (up to 100°C) at the reservoir that will influence the material behaviour. Furthermore, the perforated pipe should also be able to provide sufficient mechanical strength.

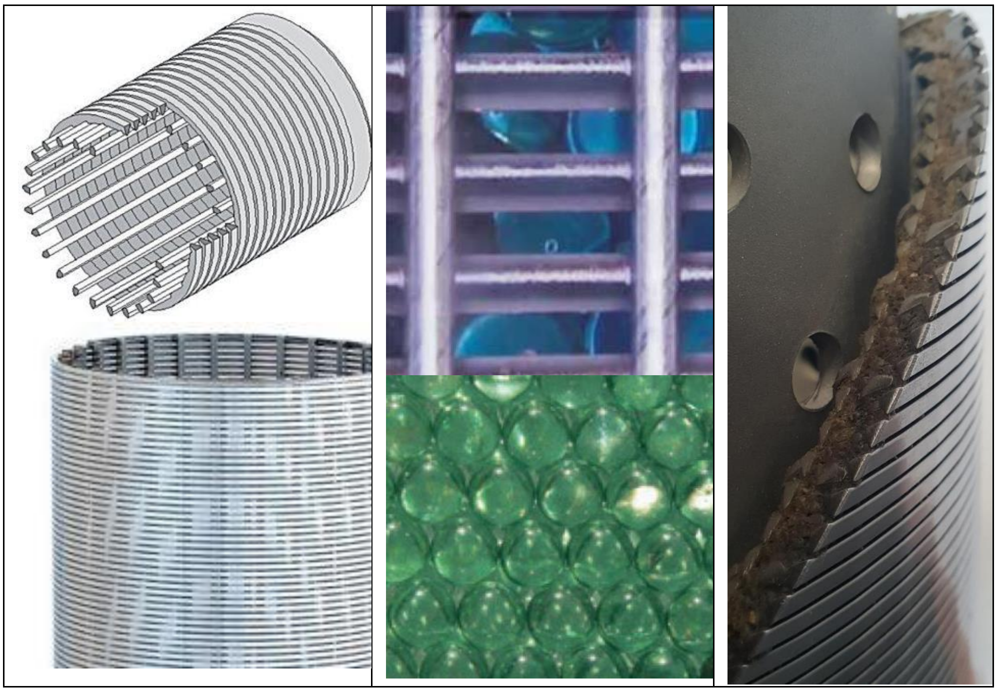


Figure 2 Various well screen lay-outs. Left: wire wrapped screen, middle: prepacked glass beads, right: prepacked gravel (source: www.hpwellscreen.com).

Summarizing the well screen requirements.

Open area:	15% (min 10%)
Slot opening screen:	250-350 micron
Slot opening GFRP gratings:	200-300 micron

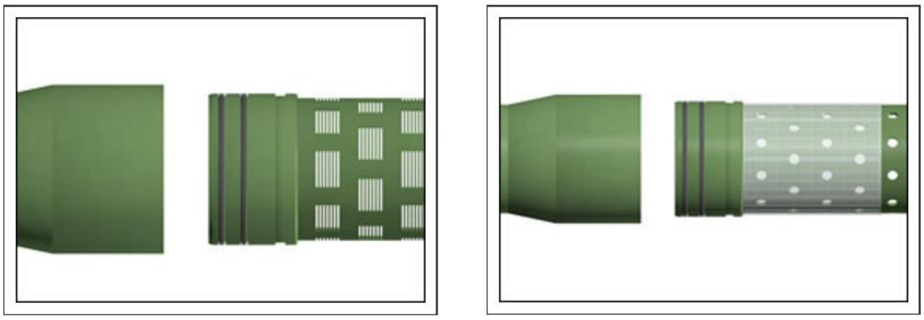
2.5.1.1 Alternative approaches

A series of brainstorm sessions, combined with a literature search led to the following list of alternative well screen designs. They include both *full GFRP approaches* to *hybrid approaches* where the corrosive parts are replaced by non-corrosive materials. Each of these designs features a slotted GFRP inner pipe, surrounded by a filtering layer based on:

1. A GFRP screen
2. Ceramic beads contained by GFRP gratings
3. Ceramic rings, combined with an outer GFRP protective shroud
4. Stainless steel wire screen with slotted/perforated GFRP pipe

The GFRP screen

Using a slotted GFRP pipe is already a solution used for screening by some companies [29]. As an example, a slotted GRP pipe and a V-shaped screen jacket are shown in Figure 3. These particular screens are used for water well applications.



a) Cut slot screens b) Pipe base V-Shaped screens

Figure 3 – Full GFRP well screens. [31]

These screens feature slot sizes in range 0.5-2.0 mm (V-shaped screen jacket) or 1 – 3.5mm (cut slot screens) and provide an open area in range 5-15% (for the cut slot screens) and larger for the jacket solution. Due to their composite nature, they are very suited for salt water environments [31]. However, they do not reach the very small slot size required for this geothermal application (0.1 mm) and are not suited for the high temperatures in geothermal applications.

Another solution is created out of PVC [32], which is also very suited for aggressive environments, provide long operational life and easy handling. Similar to the GPF solution above, This product is used for water wells and can feature slot sizes starting at 1.0 mm, for 10 inch (and larger) pipes. The product is suited for depths up to 600m. Similar to the GFRP screen, it is not directly suited for geothermal applications. Limiting factors are the slot size and the operating temperature.

Ceramic beads contained by GFRP gratings
This hybrid approach enables to redistribute the well screen requirements over the different elements and might improve the feasibility. The very fine slot opening is provided by the filtering medium, in this case the ceramic beads, and the GFRP screen is merely to keep the beads in place. Slotted FRP inner and outer gratings containing ceramic beads (0.8-1.2 mm). To keep them in place, a slot size of 0.25-0.4mm is required for the gratings.

This would relax some of the requirements, with regards to the full GFRP solution. The larger allowable slot size is in range of the full GFRP solutions presented above. The operating temperature, however, is still challenging. First of all, since the filtering takes place at the beads, the outer shell will encounter the full range of particles and should be sufficient wear resistant. Secondly, if gravel is to be used (instead of beats), it has to be baked in the filter to provide the final filtering medium, which would rise the temperature range the composite material should be suited for.

A literature search did not show any solutions in this direction.

Ceramic rings

An alternative approach is offered by 3M, which developed a filter consisting of ceramic rings over a slotted pipe, especially for High Temperature High Pressure environments (commonly defined as > 150°C and > 10,000 psi [33]). This solution is shown in Figure 4. This solution has been extensively tested and have since been deployed in numerous wells. The flexible V-stack provides a slot size of 150 to 350 micron [34], and is therefore more in range with the required slot seizes. The open area is in range 4 – 8% (for a 5 inch production tubing) and thus smaller than the 10-15% aimed for [37]. Furthermore, the ceramic material is highly wear resistant. Next to the ceramic filter, a metal pipe and shroud are required to transport the produced water and protect the filter.

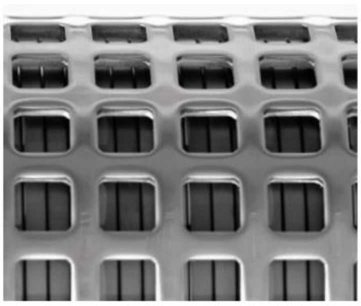


Figure 4 – Ceramic rings screen. [33], [34]

The ceramic ring solution is designed for high temperature high pressure applications, which is a situation far exceeding the geothermal application this research is conducted into. This brings the question whether this solution is economically feasible for geothermal applications. Furthermore, no mention of the open area is made in the documentation.

Stainless steel wire screen with slotted GFRP pipe

The final concept consists of the current stainless steel wire screen, mounted to a slotted GFRP base pipe. This will provide the same properties as the current application of the wire frame screens (in terms of slot opening, wear resistance and corrosion resistance). The most important update is the replacement of the steel slotted pipe by a GFRP slotted pipe. Here, it is important to understand the mechanical properties of a GFRP slotted pipe (at high temperatures) to see what the effect of the perforations is.

2.5.1.2 Design analysis

The design of the various composite alternatives to manufacture a well screen enabled to come up with a comparative table to assess the individual concepts, see Table 5.

Table 5 - Well screen design solutions analysis.

Design option:	***Advantages:***	***Disadvantages:***
Stainless steel (or Duplex) casing and wire screen.	• Known technology • Existing certification process • No issue with brine temperature	• Scaling of metal inner pipe. • Weight
GFRP screen	• No issue with corrosion or scaling. • Full, lightweight solution.	• Insufficient slot size • Strength at high temperature application
Ceramic beads contained by GFRP gratings	• Larger slots possible in GFRP • No corrosion	• Strength at high temperature application • Wear at high temperature
Ceramic rings	• Great wear resistance • Great with high temperature • No corrosion	• Design for much more extreme conditions and potentially expansive. • Small open area.
Stainless steel wire screen with slotted GFRP pipe	• Known filter technology • Existing filter certification process • No issue with brine temperature for the filter	• Unknown behaviour at elevated temperatures of slotted/perforated GFRP inner pipe

Within this project, a single concept is further investigated. Based on this analysis, the hybrid approach of a slotted GFRP pipe with the traditional stainless steel wire frame screen is chosen. This concept provides good corrosion resistance, sufficient slot opening and wear resistance and field proven for geothermal applications. By replacing the steel slotted pipe with a GFRP pipe, the screen is still corrosion resistant and fits the rest of the system while weight savings are achieved.

2.5.1.3 Design analysis

To investigate the feasibility of the stainless steel wire frame on a GFRP pipe, it is important to gain insight into the behaviour of a slotted GFRP pipe and the eventual loss of mechanical strength. To gain this insight, an exploratory Finite Element Analysis is performed on a representative GFRP pipe with different slotting patterns. The pipe has a diameter of 7 5/8 (19.37 cm) and a thickness of 14.2mm. For the analysis, the midsurface is modelled (single surface, located at the middle of the pipe wall).

Slotting patterns

Two slotting patterns are included in the analysis and compared to a GFRP pipe without perforations. and First of all, a pattern of holes in a 60 degree grid where the size and number of holes is varied. Secondly, a predefined pattern of straight slots. For each of these patterns, the main requirement is a 15% open area, which determined the exact hole dimensions. The tested patterns are (see also Figure 5):

- Non-perforated pipe
- Perforated pipe in a 60 degree patterns with 16, 20, 24 and 28 holes.
- Straight slots, with fixed dimensions.

The perforated pipe is designed such that the open area (percentage of the pipe that is open) is as close to 15% as possible, with a given number of holes. This determines both the hole size, as the distance between the holes. An overview of these distances is shown in Table 6. This table also shows the d/W ratio, which gives the ratio between hole size and the remaining material surrounding the hole. It is seen that for this pattern, the d/W ratio remains unchanged.

The slotted pipe is designed in a slightly different fashion. Here, the slot size (3 mm wide, 60mm high) and axial distance between the slots (60mm) are fixed. The number of slots (48) is determined such, that the open area is 15%. For reference, Table 6 also includes the d/W ratio of the slotted pipe.

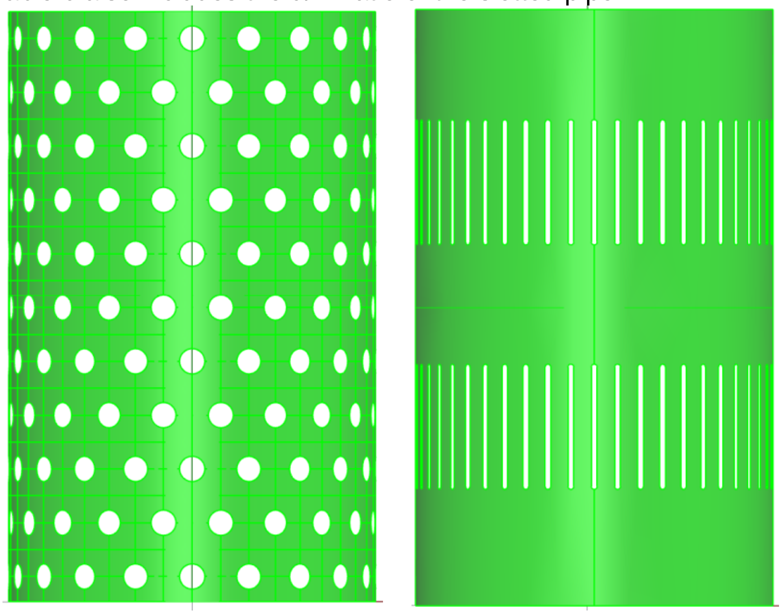
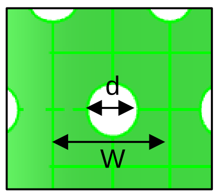


Figure 5 – (Left) Perforated pipe with 16 holes at a 60° pattern and (right) slotted pipe design.

Table 6 - Well screen base pipe main dimensions.

Variant:	Hole diameter [mm]	Distance between holes [mm]	d/W ratio [-]
16 holes	15.5	19.8	0.44
20 holes	12.4	15.8	0.44
24 holes	10.3	13.2	0.44
28 holes	8.8	11.3	0.44
Slotted	3.0	8.8	0.25



For the analysis, a representative material has been chosen, based on the material properties from Figure 6. This assumes a unidirectional lay-up, which is stacked in a 0, 0, 90 lay-up. In other words, two thirds of the fibres are in axial direction, one thirds in circumferential. Each ply is assumed to be 0.00125mm thick. This pattern is repeated over the entire thickness. The model is created out of shell elements, using the composite lay-up functionality in Abaqus.

The situation modelled in this comparison is one where to bottom end of the pipe is unable to move in vertical direction, for example because (a lower part) of the pipe is stuck. The top part of the pipe is moved upwards (in order to try and pull the pipe free), which puts the pipe in tension loading. This is achieved by prescribing a set movement to the top of the pipe, which is equal to 0.3 mm (over a total simulated pipe length of 300 mm). This displacement is applied to all pipe designs, after which the differences in stress at the holes is compared. This provides insight into the effect of the various patterns / approaches for creating a GFRP perforated pipe. The model is meshed using shell elements, with an average mesh size of 0.002 m. To avoid mesh sensitivity, an uniformly sized beam element with neglectable cross section, has been modelled at the holes. This element deforms with the hole's edge and provides a realistic stress distribution, independent of the mesh size around the hole.

Typical Mechanical Properties of a Unidirectional Lamina (SI System of Units)

Property	Symbol	Units	Glass/ epoxy	Boron/ epoxy	Graphite/ epoxy
Fiber volume fraction	V_f		0.45	0.50	0.70
Longitudinal elastic modulus	E_1	GPa	38.6	204	181
Transverse elastic modulus	E_2	GPa	8.27	18.50	10.30
Major Poisson's ratio	ν_{12}		0.26	0.23	0.28
Shear modulus	G_{12}	GPa	4.14	5.59	7.17
Ultimate longitudinal tensile strength	$(\sigma_1^T)_{ult}$	MPa	1062	1260	1500
Ultimate longitudinal compressive strength	$(\sigma_1^C)_{ult}$	MPa	610	2500	1500
Ultimate transverse tensile strength	$(\sigma_2^T)_{ult}$	MPa	31	61	40
Ultimate transverse compressive strength	$(\sigma_2^C)_{ult}$	MPa	118	202	246
Ultimate in-plane shear strength	$(\tau_{12})_{ult}$	MPa	72	67	68
Longitudinal coefficient of thermal expansion	α_1	μm/m/°C	8.6	6.1	0.02
Transverse coefficient of thermal expansion	α_2	μm/m/°C	22.1	30.3	22.5
Longitudinal coefficient of moisture expansion	β_1	m/m/kg/kg	0.00	0.00	0.00
Transverse coefficient of moisture expansion	β_2	m/m/kg/kg	0.60	0.60	0.60

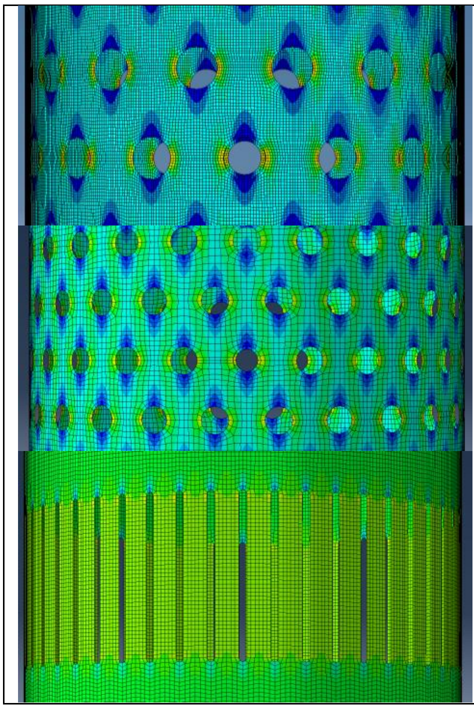
Source: Tsai, S.W. and Hahn, H.T., *Introduction to Composite Materials*, CRC Press, Boca Raton, FL, Table 1.7, p. 19; Table 7.1, p. 292; Table 8.3, p. 344. Reprinted with permission.

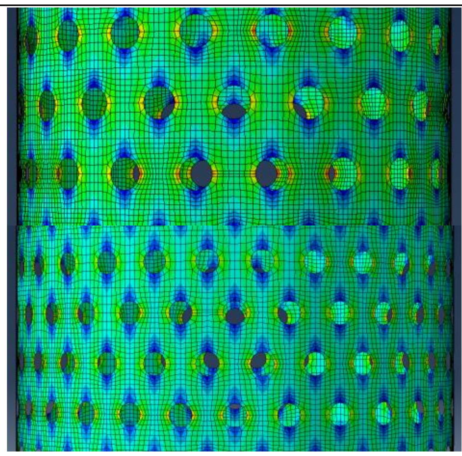
Figure 6 – Material properties for the model.

Results

Before going into the results in detail, it is important to note that this study compares the various layouts, without providing absolute numbers on the strength and failure of the pipe itself. The goal of the simulation is to gain insight into the effect of perforations on the mechanical properties of the pipe. However, to determine the absolute strength of the pipe, a more detailed analysis is required. This analysis should contain, among others, the material properties of the real pipe, a wider range of load cases and more realistic boundary conditions. For this reason, the report shows the normalized stresses. In all cases, these are (as expected for small deformations) well below the material ultimate strengths (see Figure 6).

Figure 7 gives an overview of the stresses in axial direction. The patterns seen are as expected: a stress concentration at the sides of the holes and a low stress at the top and bottom. This shows the stress path moving back and forth around the holes in the pattern. For the slotted pipe, the pattern is similar at the top and bottom of the slots, but uniformly in tension in between the slots, as expected. The figures shows some differences in severity in the perforated pipe simulations. This is due to mesh size effects at the stress concentration at the holes edge. The representative stress and strain are taken from the dedicated beam element at the holes edge.





This figure shows:

16 holes	20 holes
24 holes	28 holes
Slots	

Figure 7 – Overview of stress distributions in the slotted pipe.

Figure 8 compares the results from the unperforated pipe, the perforated pipes and the slotted solution. This figure shows the tensile stress, normalized to the tensile stress in the unperforated situation (‘no holes’). In this case, the stress is uniformly distributed with very minimal shear stress, as expected for a simple pull scenario on a pipe. A couple of insights are gained from this figure:

- For the perforated cases, the peak stress is almost the same for all cases. This seems counterintuitive, but is explained by the d/W ratios from Table 6. The ratio between the hole and the supportive material surrounding the hole is similar for all cases, which makes the stress build-up around the perforation very much comparable.
- The stress concentration around the slots is slower than in the perforated cases. Again, this is explained by the d/W ratio. In the slotted case, this is 0.25 where the perforated case has a d/W of 0.44. In other words, the slotted case features a relatively smaller hole, which induces less severe stress concentrations.
- When compared to the non-perforated situation, the slotted pipe features a maximum stress that is about 1.4 times higher. The perforated pipes are between 1.9 and 2.0 times higher.

Looking at these results, the slotted solution seems to be the preferable design for this specific load case. However, it is to be noted that his is a single, preferable load case and no definitive conclusions can be drawn without considering other load cases. In other load scenarios, different patterns might prove preferable (a 45 degree hole pattern might also be worth looking into). Nevertheless, the increase of stress due to the perforations is very reasonable and is in no way a showstopper for a perforated GFRP pipe.

Please do keep in mind that this scenario represents an idealized case and a single scenario. For example, the cutting process itself, with any influence it might have on the composite material, is not included. Similarly, the model assumes a perfect cylinder with a perfect lay-up all around.

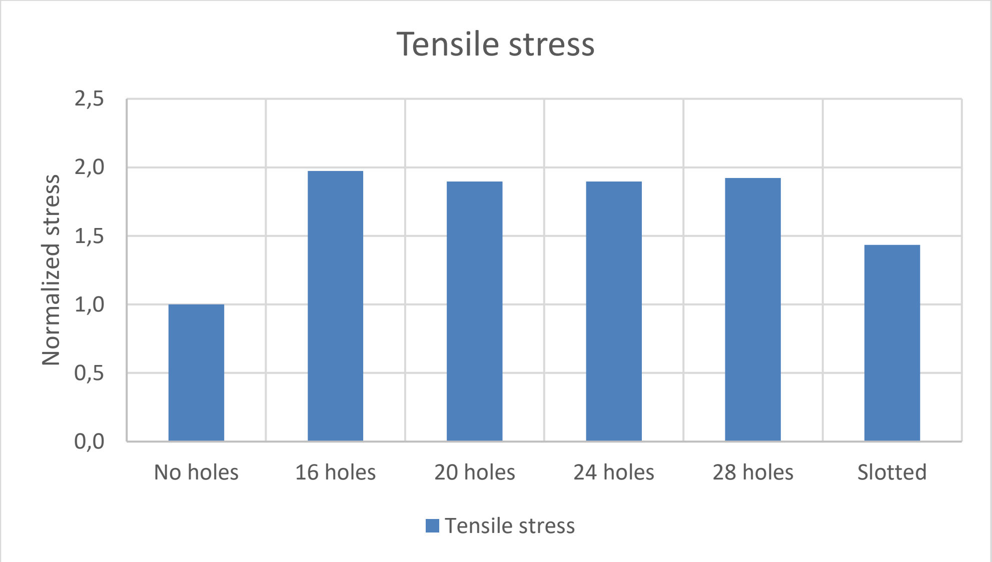


Figure 8 – Normalized stress concentrations at the hole / slots.

Conclusions

This analysis shows that, for this specific pull scenario, a perforated pipe has a stress multiplier of 1.4-2.0, with regards to the non-perforated situation. The slotted design is the best performing design (multiplier of 1.4), due to the relatively small diameter of the slot. The slotted designs have a multiplier of 1.9-2.0, where the number of holes in this pattern have no real influence. This means they can be chosen based on flow properties, instead of strength considerations. Finally, the stress increase due to the slots/perforations in the GFRP pipe is in range of expected values. Therefore, a perforated/slotted GFRP pipe is seen as a potential replacement of the steel pipe and should be investigated further. It is important to note that no definitive conclusions can be drawn without considering other scenarios and load cases.

Notes and recommendations

Please note that these insights are valid for this specific load case, where many more are to be considered. In other load cases, the slotted pipe might perform less than he perforated case (e.g. in a point load scenario) or the isotropic material behaviour might influence the structural behaviour in a different way. This analysis should be seen as a starting point for further development. In future analysis, it is recommended to:

- Update the material parameters to reflect the real pipe material at realistic environmental conditions (e.g. high temperatures, submerged).
- Include a wider range of load cases to span the various situations encountered.
- Estimate the ultimate strength of the material in these scenarios.
- Consider alternative hole patterns, for example a 45 degree pattern.
- Verify the results of the analysis with experiments.

Casing
In principle, the casing design chosen shall assure integrity for the full lifecycle of the well and ideally allows an efficient plug and abandonment once it reaches the end of its life. The circulation of corrosive brine (due to high salinity and dissolved gasses) requires a strong focus to prevent barrier failure using a risk (and cost) analysis looking at both prevention and mitigation measures.

2.5.1.4 *Composite component design*

The main drive for the use of composite tubulars is to tackle the corrosion issues on the future geothermal wells in the Netherlands and abroad, so that well integrity is assured and better profitability can be achieved by reducing operational expenses. In the Netherlands, most geothermal well design consist of three sections (top hole casing, intermediate liner and a sand screen section) but variations are possible primarily depending on the geology.

Wells can be single skin or (partly) double skin as depicted in the well schematics below, see Figure 9. For design of the casing Well Engineering Partners have written their own manual [30]. Here, a hypothetical scenario is used to represent a typical Dutch doublet in a relevant environment. Two well designs are considered, and both have an average depth to the mid aquifer of 2,100 m true vertical depth (TVD) but differ in tubular layout (see Figure 9).

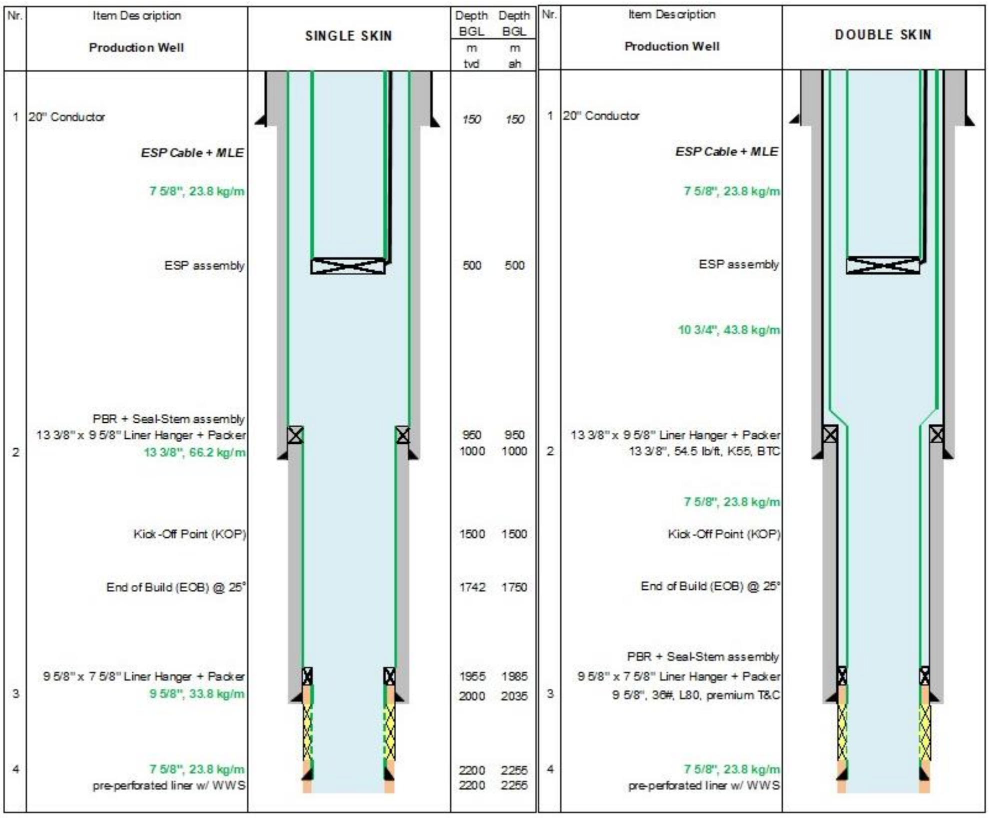


Figure 9 - Tubular scheme of two scenarios considered in this study.

Both designs will eliminate casing corrosion. The single skin design will be significant cheaper to construct and has no annulus that has been introduced to

mitigate casing corrosion effects. The double skin design is similar to the designs used for steel casing. Both the use as injector and producer have been considered. Moreover, a distinction is made between design level 1 (DL1) and design level 2 (DL2). An overview of the load cases considered is laid out in Table 7.
DL1 is the most conservative design and only applies to all sensitive and high-risk wells with none or limited relevant offset data. Most potential geothermal wells in the Netherlands fall into the DL2 category. For DL2 a less conservative approach is required since there is more certainty about geology and the risk of producing hydrocarbons is negligible.

For the two scenarios the burst, collapse, and axial loads have been determined with Wellcat and StressCheck software and compared to the load rating of composite tubulars. The forces acting on the casing are calculated by a series of load cases which depend on geology (e.g. presence of salt or gas), available information and risk (e.g. wildcat well), well type/use (e.g. injector or producer well). A good description of well casing loads can be found in the StressCheck^{TM} training manual [31].

Table 7 - Applicable load cases including duration estimation.

Stage	Load Type	Load Condition	Load Application Duration	
			Short Term (hours)	Long Term (years)
Drilling	Burst	Displacement to Gas (DL1)	24-36	-
	Burst	Displacement to Gas Limited by Fracture at Shoe (DL1)	24-36	-
	Burst	Green Cement Pressure Test (DL2)	1-12	-
	Collapse	Full evacuation (DL1)	24-48	-
	Collapse	Cementing (DL2)	1-5	-
	Axial	Running in Hole (Shock Loads) (DL2)	12-24	-
	Axial	Overpull Force (DL2)	24-36	-
	Axial	Green Cement Pressure Test (DL2)	1-12	-
	Axial	Service Loads (DL2)	1-48	-
Completion	Axial	Running in Hole (Shock Loads) (DL2)	12-24	-
	Axial	Overpull Force (DL2)	24-36	-
Production Injection	Burst	Injection down casing (DL2)	-	25-30
	Collapse	Full Evacuation (DL1)	24-48	-
	Collapse	Salt Squeeze (DL1)	-	25-30
	Axial	Running in Hole (Shock Loads) (DL2)	12-24	-
	Axial	Overpull Force (DL2)	24-36	-
	Axial	Service Loads (DL2)	-	25-30
Well Intervention Workover Abandonment	Burst	Pressure Test (DL2)	1-2	-
	Axial	Running in Hole (Shock Loads) (DL2)	12-24	-
	Axial	Overpull Force (DL2)	24-36	-

The risk analysis determines the strategy on handling corrosion and the choice of material. Monitoring of the well is an important aspect of it. In traditional casing design, the strength reduction of steel-based materials is based on estimates of yearly corrosion rate, wear calculations, etc. Most of these are done according to standards coming from the oil & gas industry.
Such standards do not exist yet for downhole composite tubulars which load bearing capacity depends more on load duration and temperature. Therefore, a duration estimation (short term vs. long term) needs to be made per load case and per design level (DL1 or DL2) as shown in Table 7. Furthermore, due to the absence of standards, availability of detailed information from the supplier on material behaviour under a load in the foreseen environment is critical.

The GRE tubular load ratings used in this study, as shown in Table 8, were based on the available data for a standard range of tubulars at the time of the research (2021) and were used for comparison with the load cases analysed. It is important to note that the load ratings used in this study do not necessarily reflect the highest possible load ratings achievable with composite tubulars. The load ratings analysed in this study are for composite tubulars designed to fit inside conventional steel casings, which limits the available geometrical options.

Load ratings for composite tubulars can be significantly improved by customizing wall thicknesses and connection geometry to specific needs, leading to enhanced performance. It should be noted that customizing composite tubulars to meet all load cases was not the focus of this study.

Table 8 - GRE tubular load ratings used in this study. Source: Huisman

HCT - Nominal size	**7 5/8**	**9 5/8**	**10 3/4**	**13 3/8**	
Dimensions (OD * ID)	206.4 x 167.1	262 x 218.5	298 x 248.2	372 x 311.4	mm
Length	11.7	11.7	11.7	11.7	m
Long term load ratings					
Application temperature	85				°C
Assumed load duration	20				years
Collapse rating	86	73	75	71	bar
Burst rating	100	88	95	100	bar
Axial tension rating	12	16	18	23	mt
Axial compression rating	16	20	23	29	mt
Short term load ratings (to be adhered during running)					
Application temperature	85				°C
Assumed load duration	50				hours
Collapse rating	194	165	169	162	bar
Burst rating	227	200	215	226	bar
Axial tension rating	30	39	44	56	mt
Axial compression rating	39	50	57	72	mt

Table 9 and Table 10 show the results. Some of the design level 1 (DL1) load cases exceed the tubular load rating. For all other load cases the tubular rating is sufficient within the mentioned operational limits (For example: the running speed is limited to 0.3 m/s for the single skin 9 5/8 section to limit axial shock loads).

Table 9 - Results Single Skin Well.

Single Skin					
OD (in)		**13 3/8**	**9 5/8**	**6 5/8**	**7 5/8**
Load Type		**Surface Casing**	**Intermediate Liner**	**Production Liner**	**Suspension Tubing**
Burst	**DL1[1]**	*Design load exceeds the pipe rating with 44%.[2]*	*Design load exceeds the pipe rating with 17%.[2]*	-	-
	DL2	Pipe rating can withstand the short- and long-term loads.	Pipe rating can withstand the short- and long-term loads.	-	-
Collapse	**DL1[1]**	Pipe rating can withstand the short- and long-term loads.	*Design load exceeds the pipe rating in 31% (w/o squeezing salt).[2]*	-	-
	DL2		Pipe rating can withstand the short-term loads	-	-
Tensile		Pipe rating sufficient for: 1) 5 mt Overpull 2) RIH at 0.1 m/s	Pipe rating sufficient for: 1) 15 mt Overpull 2) RIH at 0.3 m/s	Pipe rating sufficient for: 1) 15 mt Overpull 2) RIH at 1 m/s	Pipe rating sufficient for: 1) 15 mt Overpull 2) RIH at 1 m/s
Compressive		Pipe rating sufficient for: 1) a lightweight cement 2) internal pressure is sustained during hardening of the cement. Without the above limitations the loads exceed the rating with 235%	Pipe rating sufficient for: 1) a lightweight cement 2) internal pressure is sustained during hardening of the cement. Without the above limitations the loads exceed the rating with 218%	Pipe rating can withstand all loads.	Pipe rating can withstand all loads.

1. *DL1 is the most conservative design and only applies to all sensitive and high-risk wells with none or limited relevant offset data. Most potential geothermal wells in the Netherlands fall into the DL2 category.*
2. *Pipe ratings are highly customizable and can be improved to meet more demanding load cases. Customization of tubulars was not within the scope of this study.*

Table 10 - Results Double Skin Well.

Double Skin				
OD (in)		**10 ¾ x 7 5/8**	**6 5/8**	**7 5/8**
Type		**Protective Tieback**	**Production Liner**	**Suspension Tubing**
Burst	**DL1**[1]	Pipe rating can withstand loads with a minimum safety factor of 2.15 and 1.26, respectively.	-	-
	DL2		-	-
Collapse	**DL1**[1]	*Design load exceeds the pipe rating in 4%.*[2]	-	-
	DL2	pipe rating can withstand the short and long-term loads	-	-
Tensile		If tieback can redistribute ballooning deformations between hang of point and packer, the pipe rating can withstand all loads. When this is not the case the loads exceed the 10 ¾ pipe rating with 75%	Pipe rating sufficient for: 1) 15 mt Overpull 2) RIH at 1 m/s	Pipe rating sufficient for: 1) 15 mt Overpull 2) RIH at 1 m/s
Compressive		Pressure Test and Injection Down Casing loads: of the main part above the packer can withstand all loads	Pipe rating can withstand all loads.	Pipe rating can withstand all loads.
		Pressure Test and Injection Down Casing loads of the small part below the packer exceed the 7-5/8" pipe rating with 126% - see **note** below[2]		

1. *DL1 is the most conservative design and only applies to all sensitive and high-risk wells with none or limited relevant offset data. Most potential geothermal wells in the Netherlands fall into the DL2 category.*
2. *Pipe ratings are highly customizable and can be improved to meet more demanding load cases. Customization of tubulars was not within the scope of this study.*

The calculations made during the design of a well result in various load combinations. In combination with the load bearing capacity of the composite product, this results in a load envelope plot. An example is shown in Figure 10.

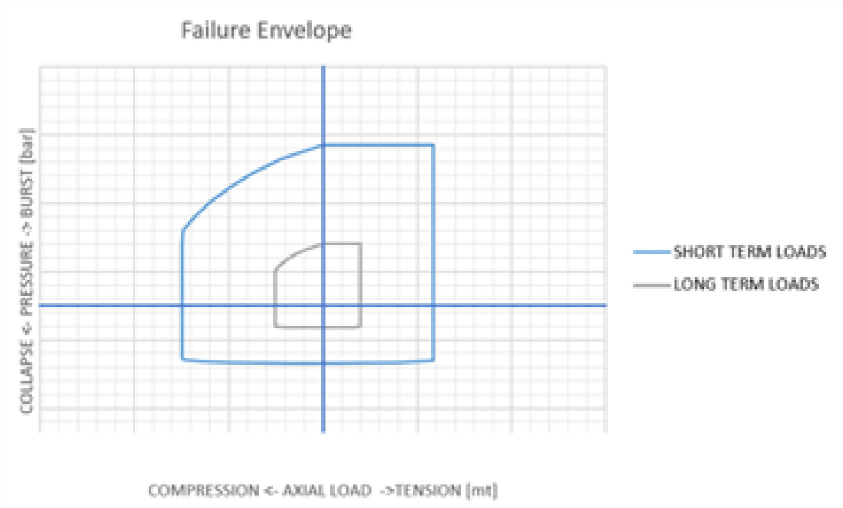


Figure 10 - An example of a load bearing envelope plot for composite casing for both short and long term loads. Source: Huisman

As described above, shifting from conventional steel- to composite materials, fibre reinforced polymers tackle corrosion problems at the core and reduces scaling tendency to a minimum, providing durable, carefree and efficient solutions. Specifically for well construction purposes, Huisman has developed and tested a composite casing system.
This solution consists of fibre reinforced polymer pipes, connected through a special connection piece, see Figure 10. This connection consists of a threaded fibre reinforced polymer pin and metallic collar (box). Depending on the application, the material of the collar can be altered. For applications where the product is run as tubing, in most cases it will be sufficient to have a steel collar with the same material quality as the primary casing. For other applications, where it is expected that external corrosion might be an issue, the collar material can be altered (e.g. to CRA, titanium or composite).

Figure 11 - Running of a composite tube (source: Huisman HCT Brochure).

When performing the calculations for composite tubulars a well engineer must keep in mind the differences between composites with steel:
• Composite ratings strongly depend on temperature;
• Composite tubular ratings depend on the duration of the loading;
• Composites are anisotropic and show different ballooning effects then steel;
• Not all casing design software is suitable for incorporating composite properties and customized pipe dimensions;
• Be sure that ratings provided by suppliers include the strength of the coupling, long-term load effects. For the Huisman composite tubulars this is incorporated. In addition, temperature deration factor or derated rating vs temperature data, and thermo-mechanical properties should be given by suppliers;
• No standards defining criteria, methods etc. exist for downhole composite tubulars;

2.5.1.5 *Design analysis*

For the two studied scenarios, the currently available composite tubular can be installed and used within specification hence it is suitable, for use in most geothermal wells in the Netherlands (design level L2) if the following loads are considered and addressed:
1. Overpull should be decreased when compared to steel.
2. Running speeds must in most cases be reduced to prevent excessive shock loads.
3. The cementation of long sections needs special attention. A possible solution is to maintain the inside pressure during hardening of cement.
4. The tie-back liner must be able to redistribute any thermal expansions and ballooning deformations over the length between the hang of point and packer.

This report shows what is possible with composite tubulars when taken sufficient care during installation and operation, and it opens the way to significant reduction of operational costs for geothermal systems by reducing corrosion, down-time and scaling while maintaining a large internal flow area. This is further emphasised by the findings from a similar study by EBN on non-alloy based tubulars [32]. They concluded that:

- The roughness/friction reduction with composites compared to carbon steel will result in increased flow (carbon steel and corroded carbon steel in the order of 0.045mm – 0.09mm and 0.15mm – 4.0mm respectively while glass reinforced epoxy stands in the order of 0.006mm);
- The weight reduction will drive some handling benefits;
- Increased range of options for monitoring with epoxy matrix being more transparent to a greater range of electromagnetic logging techniques;
- Operational cost benefits as no corrosion inhibitors have to be used;
- Reduced carbon footprint with a full composite string and the elimination of corrosion related workovers.

A risk assessment should always be made to ensure well design objectives are met.

2.5.2 *Wellhead*

The composite wellhead design work carried out by TechnipFMC to fulfil the requirements identified in section 2.4. The work takes its foundation on the design of metallic wellheads with subsequent considerations for the specificities of composite material properties, the various manufacturing process options available and cost aspects. Shown below in Figure 12 is a typical range of wellhead designs via standardization and modular approach. For geothermal applications, the goal is to create a compact composite wellhead design, where the height is limited to reduce weight and costs, easier access and reduced footprint.

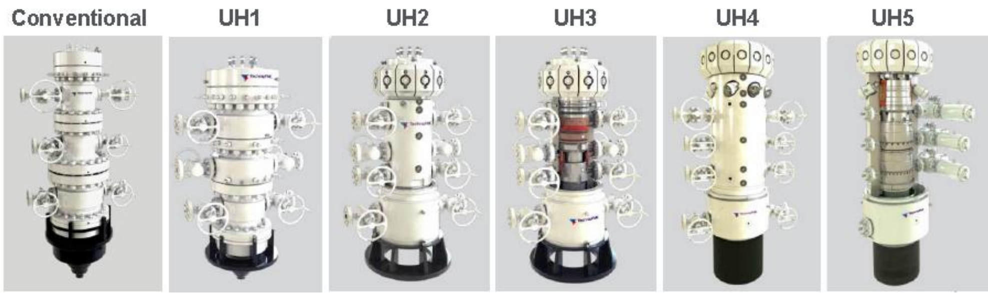


Figure 12 - Typical range of modular and standardized wellhead designs for different classes.

2.5.2.1 *Composite component design*

Metal components typically follow subtractive manufacturing process allowing for components to be machined out from a basic forged shapes to multiple degrees of complexity while maintaining homogeneous material properties to meet the requirements in the governing standards.
Fibre reinforced composites offer the possibility of tailored material properties to suit the material geometry and application. This can also present challenges with realising complex geometries and achieving material performance comparable to metals. Composite materials can be produced with a broad range of manufacturing methods whose choice is highly determined by production volume, level of complexity, secondary machining and cost perspectives. The production volume and manufacturing complexity also influence the amount of automation and the labour costs. Some important aspects to consider for composite part productions are the need for specific moulds, additional set ups, application of coatings or machining operations in the hardened composite part.

With respect to the production of wellheads, it is found that infusion and filament winding with glass-fibre epoxy could be cost effective candidates. However, geometrical simplifications are needed on the design to enable the use of such manufacturing processes.

Strength of carbon or glass fibre composites can match steel, stiffness is found to be less, especially when fibres need to be oriented in all main directions (quasi-isotropic), typically resulting in 1/5th-1/3rd of the stiffness of steel. Composite materials typically have a much higher strength to weight ratio than metal components, however, to achieve similar load bearing capabilities it is expected that geometries will increase resulting in thicker/larger components. The hardness or scratch resistance of most composites is less than metals. Sand erosion and potential scratching during workovers need to be taken into account in the design.

Design features such as holes and discontinuities can lead to stress concentrations and due to the orthotropic nature of composites, they can be more pronounced than in metal components. Special attention must therefore be paid to connections because of the potential stress concentrations. Design for many interfacing components in a wellhead (e.g. flange connections and studs) are defined by the controlling standard and designed based on metal components and would be required to be capable of withstanding the same loadings.

Carbon and Low-allow steels do require coatings and corrosion resistant mediums that may become damaged during handling or worn overtime on the external surfaces that are exposed to the environment, the internals are also more susceptible to scaling and corrosion. Composite materials do not face the same issues and can be installed without coatings. To enhance protection against erosion, UV degradation, and osmosis (depending on the matrix/resin/manufacturing method combination) special resins or coatings can be integrated in composites as well.

2.5.2.2 Design analysis

Composite materials within wellhead equipment present a positive direction for future components as there are many options that could be utilised to eliminate issues faced by typical metal components, particularly with regards to weight, chemical/corrosion resistance, durability and design flexibility.
A range of composite materials capable of fulfilling all the design criteria set out was not able to be identified preventing further research in to how the components would need to be altered based on initial metal component design. A contributor to this being the material selection, geometries and design criteria are heavily controlled by API 6A for the design of wellheads and wellhead equipment which currently includes wellheads used for geothermal wells.

Currently the standard does not provide guidance for alternative materials (e.g. composites) or means to allow for comparable testing or qualification to metal components. Also, complexity of the bodies and the range of secondary machining operations required to satisfy interfacing geometry for additional equipment (e.g. flanged, gaskets, fittings).
Extensive research and development in to incorporating composites into API 6A would be required to drive the development of the testing and qualification to meet the same level of scrutiny metal components are subjected to within API 6A (e.g. hydrostatic, gas, temperature cycling, chemical exposure, mechanical load cycling) with additional validation testing for in field conditions, alongside deeper understanding of compositing material manufacturing limitations to allow for an overhaul of how components are designed to meet the design criteria.

2.5.3 Piping

In this project, no emphasis was given to investigating FRP piping design. Indeed this type of large scale, high requirements piping are already well developed for use in a number of industries:

- Chemical industry
- Oil and Gas industry
- Water systems
- Sewer systems

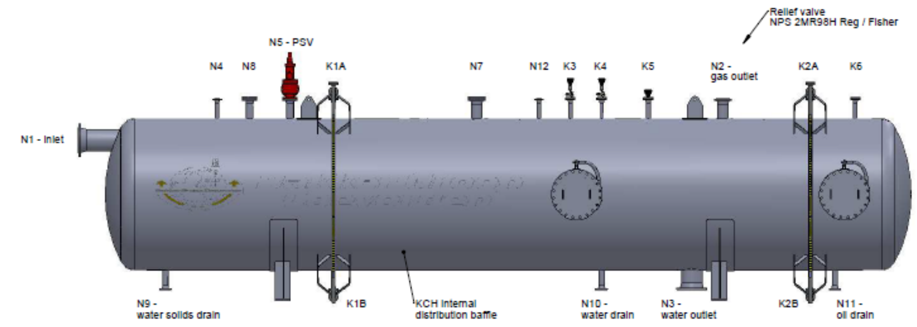
The main benefits of such pipes in a geothermal well system are their chemical resistance, corrosion resistance, long life, thermal and UV stability, low heat conductivity, light weight, low maintenance requirements, and design shape flexibility.

The potential drawbacks of such pipes are their ability to interface with other components of the system in a water and air tight fashion while being removable. However, this is something which is also the case in the aforementioned industries using GFRP piping solutions. Therefore, industrial solutions have already been developed, tested and certified such as a close tolerance bell and spigot assembly complete with O-rings, sleeve assemblies, FRP flanges, or by bonding a metallic flange on the ends of the pipe. [33] Using metallic components in conjunction with FRP parts can lead to some complications due to differing thermal expansion rates (typically $10.8 \times 10^{-6}[1/_{\circ C}]$ for steel [34] and $5 \times 10^{-6}[1/_{\circ C}]$ longitudinal, $25.1 \times 10^{-6}[1/_{\circ C}]$ transversal for GFRP composites [35]). This drawback is also present in other industries and can be accommodated with careful design.

The initial cost of a FRP pipe is generally higher than an equivalent steel pipe, that is due to generally higher material and manufacturing/processing costs.
However, this has to be balanced over the life of the component. First of all, the lesser weight of the FRP part can lead to lighter and less expansive support structure. Then it can lessen transport and installation costs by requiring cheaper, lower weight capacity handling equipment. Finally, in comparable industries, FRP pipes have shown a significant reduction in maintenance costs [36]. With the democratization of the technology and the lowering of costs, for a number of applications FRP pipes make be a cost effective solution when compared to conventional steel equivalents [37].

2.5.4 Degasser

The degassing takes place in a degasser or separator, where geo-gas is separated from the geothermal water. As operated by ECW in the Netherlands, the separator is a large vessel and, typically measuring 13,4 meter x 2,7 meter diameter and with an internal volume of 73m^3.
The two-phase geothermal water enters the system at a nominal pressure of 10 bars. Dissolved carbon-dioxide and methane gas are then encouraged to separate from the hot geothermal brine by spraying it onto plates. Subsequently the gas is captured using a pump connected to an outlet on top of the tank while the hot liquid exits the degassing unit in a more stable state and continues its journey in the geothermal system.
The vessel is also equipped with a distribution baffle, to ensure a stable, flat liquid surface and a stable level in the degasser vessel. Finally, a vanepack, placed in front of the gas extraction outlet to dry the gas and return some liquid to the degasser chamber.
The separator and its connections is shown in Figure 13. These vessels are traditionally made out of coated carbon steel. The unit is as such pressurized to and subjected to both brine and sand particles.



Conn. nr.	Size	Press. rate	Facing	Service	Type / mark
N1	12"	150#	RF	Inlet	Inlet Device / KCH
N2	6"	150#	RF	Gas Outlet	D40 Vanepack / KCH
N3	12"	150#	RF	Water Outlet	
N4	2"	150#	RF	Degas Annulus	
N5	4"	150#	RF	Press.safety valve	5262.5902 4"x6" / Leser
K1+K2	2"	150#	RF	Ball valves (4)	FA2 RVS316 150 2" / Eriks
N7	6"	150#	RF	Spare	Blinded
N8	4"	150#	RF	Spare	Blinded
N9	4>3"	150#	RF	Water solids drain	
N10	4>3"	150#	RF	Water drain	
N11	4>3"	150#	RF	Oil drain	
N12	3"	150#	RF	Nitrogen	
K1A/B	4>2"	150#	RF	Level gauge	D-150 h.o.h.3655mm / Hadro
K2A/B	4>2"	150#	RF	Level gauge	D-150 h.o.h.3655mm / Hadro
K3	2"	150#	RF	Pressure indicator	In-line pressure transm.2051 / Rosemount
K4	2"	150#	RF	HPS	D1T-H150SS-EXI / Barksdale
K5	2"	150#	RF	Radar	Guided wave radar 5302 / Rosemount
K6	2"	150#	RF	Radar	
M1	24"	150#	RF	Manhole	
M2	24"	150#	RF	Manhole	

Figure 13 - Schematical picture of the separator and its connections.

Outlets at the bottom of the tank allow the degassed brine to pass to the next component in the geothermal system. The fluid level in the separator is kept at 50% which is controlled by using measuring levels. At the same time the pressure is controlled by means of pressure measurements and pressure valves. Nitrogen is used to prevent ignition of a potential explosive gas accumulation. The vessel needs to be periodically drained to remove excess of sand or other particles. Proper sand screens downhole are needed to prevent both erosion and sand accumulation in the separator, but also to prevent the filters to silt up. Moreover, the replacement of the filters also brings in oxygen, which traditionally further accelerates the corrosion of the system.

The two-phase brine and the present sand particles can cause erosion of the coating and thereby cause the onset and progression of corrosion of the carbon steel. Since the separator pressurized it is subjected to the Pressure Equipment Directive [38] which prescribes obligatory inspections. To enable these inspections access hatches must be present. Figure 14 shows the damage found by ECW during one of these required inspections.

Figure 14 - Damage found by ECW during one of prescribed 4-yearly inspections of the separator.

The encountered damage in the separator must be solved to pass the 4-yearly inspection of the pressurized vessel. The costs of repainting the separator are significant, which drives the wish for an alternative, for example a composite tank.

A detailed design was not conducted for this part. Feasibility is demonstrated by existing design and build of pressurized composite tanks and separators technology [39].

However, the dimensions for geothermal applications are larger and therefore require the certification of a newly developed vessel. This for example includes a 1000 hour pressure test under realistic conditions as stated in the norm for pressurized tubing (ISO14692).

2.5.5 *Heat exchanger*

After the separator the geothermal production fluid is passes through the filter unit and the heat exchanger. A booster pump is used to prevent degassing of remaining gas in the flow media and consequent pressure drops further along the process. The filter unit that filters the flow media down to a particle level of 1 μm (micron/mu) is needed to prevent pollution of the heat exchanger and the injector well. Different types of heat exchangers can be used such as tube or plate exchangers. The plate heat exchangers are generally preferred over tube exchangers as they require about 1/5 of the of the space for tube exchangers. [49]

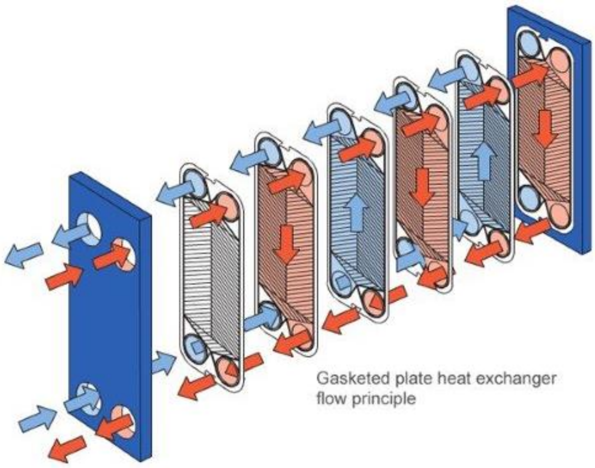


Figure 15 - Working principle of a plate heat exchanger. [50]

Figure 15 shows a picture of the working principle of a plate heat exchanger. According to operator ECW, leakage as a result of corrosion due to the brine is a common failure mode and regular maintenance is needed. Inhibiters are added to reduce corrosion issues as well. The plates in the exchanger are stacked alternately and provide by a hot and cold circuit flow to optimize the heat exchange between the production well supply and the heat network fluid. The thermal difference between the plates causes mechanical stress. In combination with the corrosive environment, this can cause both stress- and crevice-corrosion and cracking. To minimize these issues, the plates are typically made of stainless steel or titanium.

2.5.5.1 *Composite component design*

In order to avoid corrosion the use of composites can come into play. The challenge for the use of composite in heat exchangers is the thermal conductivity. Especially the polymers exhibit a very low thermal conductivity that is commonly less than 1 W/mK, when compared to stainless steel (16-24 W/mK) or titanium (5.8-23 W/mK). [51] It should be noted however that for titanium the highest value is based on pure titanium, and drops to the lower value for alloys that are used in practice.
By adding conductive particles, e.g. metals or nanotubes, the conductivity of epoxy can be improved (up to 4.8 W/mK according to [51]). A list of possible fillers and their specific thermal conductivity can be found in Table 11 below. [52]

While glass fibres are generally good isolators carbon fibres can exhibit a very high thermal conductivity. This is particularly the case in fibre direction and the challenge is to take advantage of this by creating a fibre orientation in thickness- / z-direction. [53] Especially pitch-based fibres exhibit a very high thermal conductivity of 320-800 W/mK. [52]

Table 11 - Comparison of PAN- and pitch-based carbon fibre thermal conductivity and an overview of the thermal conductivity of different fillers. [52]

Table 1. Comparison of polyacrylonitrile (PAN) and pitch-based carbon fibers data values from [11–13].

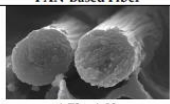
Property	PAN-Based Fiber	Pitch-Based Fiber
Morphology		
Density (g/cm³)	1.73—1.93	2.10–2.19
Axial Thermal conductivity (W/mK)	14–100	320–800
Radial Thermal conductivity (W/mK)	0.5–10	0.5–10

Table 2. Thermal conductivity of different fillers.

Filler	Epoxy Resin	Carbon nanotubes (CNTs)	Carbon nanofibers (CNFs)	Carbon Black	CNT Buckypaper	Graphene	Graphite	Copper	Born Nitride	Aluminium	Aluminum Oxide	Aluminum Nitride	Aluminun, Pure
Thermal conductivity (W/mK)	0.17	2000–6000	1950	6–174	15–45	5300	100–400	483	30–400	240	20–29	180–200	200

2.5.5.2 *Design analysis*

By creating a 3D woven carbon fibre architecture (4 – 7.2 W/mK) or by partially graphitizing the matrix of a carbon carbon composite (20-50 W/mK) part of the high fibre and/or filler thermal conductivity value can be obtained in a laminate. [54] Of special interest are the so called ZRT-materials, a Z-direction composite technology that recently came available at industrial scale. An increase in thermal conductivity to around 10 W/m-K for PAN-based carbon is claimed, and pitch based CFRP laminate can reach up to 250 W/mK (with thermoforming) using 100% reclaimed feedstock [55]. It has been developed both as ZRT thermoplastic films and thermoset prepregs for thermal/electrical conductivity and local reinforcement. In addition to polycarbonate, Boston Materials has made ZRT thermoplastic composite films using PPS, PEEK, LM-PAEK, PEI, PA-6, PA-12 and bio-PA. The ZRT thermoplastic films and thermoset prepregs can be handled similar to existing composite manufacturing processes. In Figure 16 both the manufacturing process of ZRT films and a micro-dimple thermoformed plate for a non-metallic heat exchanger application is shown. Strength and stiffness of the composite panel can be obtained by adding in-plane carbon fibre fabrics as outer layers. Manufacturing is expected to come at competitive costs compared to existing metal plate forming as a (semi-)automated process is expected to be possible.

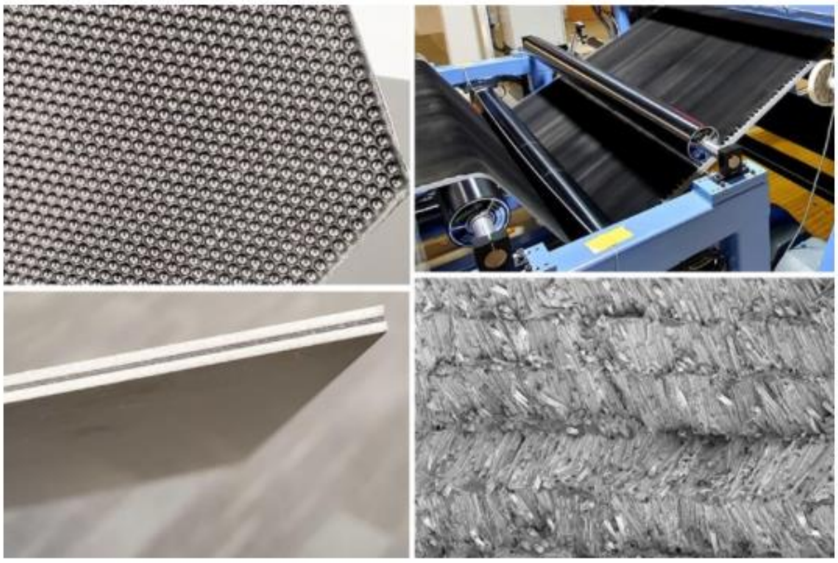


Figure 16 - The manufacturing process of ZRT films (top right) based on z-direction oriented carbon pitch-fibres (bottom right) and use of the material in sandwich sheet and micro-dimple thermoformed plate for non-metallic heat exchanger (top left). [55]

2.6 Total Cost of Ownership

The operational advantages of a completely composite geothermal system in comparison to a conventional metal geothermal system have been investigated and summarised in Table 12 below. Material price and eco-costs data in the table are based on the book of Vogtländer. [1] Specific data given by the partners is referred to a such. An estimated delta costs is given as a comparison between conventional metal and composite system components.

From the results in the table several observations can be made:

- Based on the material cost data and experience with existing composite components it can be seen that composite solution can compete on CAPEX with existing stainless steel and titanium solutions. Low and medium grade steel solutions come at lower costs compared to composite solutions. In case of low-grade steels however double wall solutions are required for the well structure to mitigate potential leakage. The complete composite system is expected to come at comparable costs as conventional systems.

- Composites can offer a large benefit on OPEX by reducing or removing operational costs and by the increased longevity (from 10 to 30 years). ECW estimates the benefits at 1530k per year per doublet (including depreciation). For a carbon steel casing and composite inner liner benefits of 1330k per year per doublet is expected.

- Eco-cost benefits for composite components are estimated to range from at least 50 to 90% in comparison to conventional metal components. Operational advantages such as drag reduction can generate further energy savings and thus further enlarge the benefits.

One of the additional benefits of the use of composites is the potential of sensor integration. A comprehensive review can be found in an article by Rocha et al. [56] By embedding the fibres into the composite the structural health of the component can be monitored and operational conditions can be assessed such as for example temperature, pressure or flow in the system. Further benefits of non-metallic tubulars is transparency to a greater range of EM logging techniques. [41]

Table 12 - Total Cost of Ownership (TCO) of Composite versus Metal Geothermal Energy Systems – CAPEX.

CAPEX	*Metal*	*Composite*	*Estimated Delta costs:*
Total system	Generally lower material costs. Double barrier well structure designs increase costs significantly.	Generally higher costs compared to low-medium grade steel depending on manufacturing automation and size of series. Competitive or cheaper than stainless steel and titanium solutions. Costs savings due to use of smaller installation rigs	The CAPEX of the composite system components are estimated to be lower compared to existing stainless steel or titanium components, but 1.5 to 3 times higher than low grade steel components. The complete composite system is expected to come at comparable costs as conventional systems.
Material	Low-medium carbon steel (density 7800 kg/m3), 2.730 – 6.240 euro/m3, Stainless steel 35.100 – 39.000 euro/m3	Composites (GFRP-epoxy) 4.000 – 20.000 euro/m3.	
Wellscreen	Use of stainless steel induces high material cost	Base pipe cost of product (GRE) lower than SST or High alloys. [HP Wellscreen]	Savings in base pipe are applicable as cost of product (GRE) are lower than SST or High alloys. [HP Wellscreen]
Casing	Installation costs higher due need of a larger rig. In case of low-grade steels double wall solutions are required to mitigate potential leakage	Largely reduced weight and enlarged buoyancy compared to metals (2000 kg/m3 for glass-fibre composite versus 7800 kg/m3 for steel)	CAPEX for full composite tubulars ~ 1.5 to 3X that of metal (e.g. L80). However most probably lower CAPEX than for high CR and/or GRE Lined alternatives. [Huisman]
Wellhead	Currently standardized solutions from oil and gas used. Cost for a traditional wellhead (without inlay) is in the range of 85K Euro's. CRA (corrosion resistance alloy) inlay on (wetted) sealing area's plus hangers out of CRA in the range of 160K Euro's. [TechnipFMC]	The cost of a composite wellhead is expected to be competitive to traditional wellhead without inlay. Whereas a wellhead with CRA inlay will double in costs. Life time as well as the performance in this case is expected to be similar.	Estimated cost reduction of 25%+ if the wellhead is manufactured out of composite versus a standard LCS wellhead and 50%+ compared to a version with CRA inlay on (wetted) sealing area's plus CRA hangers.
Pipeline		Composite piping already existing in the market and commonly preferred due to higher longevity. Currently no standardization and relatively expensive connection methods. 300k total for 1 doublet (GRE-ISO14692 + few pieces stainless in the high pressure injection line because of design limitations at the moment). [ECW]	Composite piping lower CAPEX than stainless steel. Fitting prices comparable to stainless steel. High welding process costs for stainless steel result in an estimated cost difference between -25% and -33% for composite. [ECW]
Degasser	1 piece, total 300k for 1 doublet 350m3/h (carbon steel with coating) [ECW]	Higher costs expected for composite degassser with respect to carbon steel version.	-
Filter	4+7 pieces, total 260k for 1 doublet 350m3/h (stainless steel 316) [ECW]	Comparable or lower costs expected for the filter in comparison with stainless steel.	-
Heat exchanger	High material cost as a result of the use of titanium or stainless steel. 4 pieces, total 360k for 1 doublet 350m3/h (stainless steel 316) [ECW]	High material costs using carbon-fibre with enhanced heat transfer properties, but expected to be competitive.	-

Table 12 (continuation) - Total Cost of Ownership (TCO) of Composite versus Metal Geothermal Energy Systems - OPEX

OPEX	*Metal*	*Composite*	*Estimated Delta costs:*
Total system	Expected product lifetime of about 15 years down-hole, corrosion inhibiters (80kE annually) needed and regular maintenance and repair of several components.	Expected product lifetime of about 30 years.	With composite casing and 30 years lifetime (750k*2)+20k+10k = 1530k/year.doublet (see casing, degasser and filter delta costs). With carbon steel casing and composite inner liner and 30 years lifetime (650k*2)+20k+10k = 1330k/year.doublet. [ECW]
Wellscreen	No maintenance during 15 years using stainless steel	The product lifetime is expected to be extended to 30 years. Maintenance or replacement might however be needed as the wellscreen becomes a super filter over time due to particals building up on the outside and thus will get constipated. OPEX for the screen product remain the same, current design does not show early maintenance. For the installation, weight may be less and required handling (RIG) capacity may be slightly less, potentially saving installation cost.	-
Casing	Wells need repair during the expected design lifetime of 15 years (up to 30% show leakage). Cost of liners estimated 800kE annually.	Cost savings depend strongly on well design and parameters (base case for metal and composite). Following can be assumed: - Annual electricity saving for ESP and injection of ~€40k to ~€250k. Lower drag due to enhanced smoothness and less scale formation saves energy costs. - Annual savings on inhibitors ~€50k to ~€100k - Saving on workovers (e.g. for replacing metal double barriers). [Huisman]	Carbon steel casing and 10 years lifetime = 1000k/year depreciation + 40k more electricity + 50k inhibitor. Composite casing and 30 years lifetime = 333k/year depreciation. Difference ca. 750k/year.well. If you place an composite inner liner in a carbon steel casing the difference is less because of the extra costs (casing and inner liner) and the higher electricity costs due to more drag. Difference ca. 650k/year.well. [ECW]
Wellhead	3K Euro's per annum to check the integrity of the well for both, steel and composite.	Potential weight savings and smaller rigs needed during installation and maintenance. With regards to annual maintenance there is no difference in cost between a steel version or a composite version.	The risk of integrity failures with a LCS version is much higher and might lead to work-overs for example on the intermediate casing section. This will result in considerable downtime as well as huge additional cost with higher risks.
Pipeline		Higher longevity of composite pipeline	-
Degasser	Re-coating vessel 80.000kE, every 4 year pressure inspection (pressure equipment directory)	The inspection will stay the same (PED). No cleaning/re-coating.	Estimated saving 20k/year.doublet
Filter	Regular inspection needed as a result of corrosion	The inspection will stay the same (PED). No repair/replacement.	Estimated saving 10k/year.doublet
Heat exchanger	Regular replacement of plates needed as a result of corrosion (bi-annual) or use of titanium plates to overcome corrosion.	Low maintenance due to non-susceptibility to corrosion. Maintenance on the gaskets remains for both titanium and composite product.[ECW]	-

Table 12 (continuation) - Total Cost of Ownership (TCO) of Composite versus Metal Geothermal Energy Systems – ECO-costs & TCO

ECO-costs	***Metal***	***Composite***	***Estimated Delta costs:***
Total system	Low-medium carbon steel: eco-costs 5000-8000 euro/m3, Stainless steel: 30.000 euro/m3, Titanium: 100.000 euro/m3	Glass-fibre composites (GFRP-epoxy): 1000 euro/m3 carbon-fibre composites (CFRP-epoxy): 2000 euro/m3	Large reductions in eco-costs of >90% are possible
Wellscreen	High eco-costs as a result of use of stainless steel		Large reductions in eco-costs of >90% are possible
Casing	Typically low-medium carbon steel	CO_2 emissions for production of 1meter GRE tubular are approx. 50% lower than for 1 meter of steel tubular. Plus further CO_2 savings due to electricity savings. [Huisman]	Reduction in eco-costs of >50% possible
Wellhead	Low-medium carbon steel or stainless steel		Reduction in eco-costs of >50% possible
Pipeline	Typically low-medium carbon steel		Reduction in eco-costs of >50% possible
Degasser	Typically low-medium carbon steel		Reduction in eco-costs of >50% possible
Filter	Typically low-medium carbon steel		Reduction in eco-costs of >50% possible
Heat exchanger	High eco-costs as a result of typical use of stainless steel or titanium		Especially high reductions possible when replacing titanium (>90%)

4. Total Cost of Ownership and LCA key cost drivers

In order to properly compare the costs of a complete composite geothermal system compared to a system built of a steel or other metals it is imperative to consider the TCO. This is especially true because of the many different drivers that impact the TCO. On the OPEX side, the use of a complete composite system will overcome the need of corrosion inhibiters and the significant costs, estimated at 50 to 100kE yearly for a geothermal doublet according to ECW, associated with this type of corrosion reducing methods. Another important factor that determines the TCO is the expected production and lifetime of the system. While in principle, geothermal wells can be operated endlessly, the limiting factors currently are the rising cost of operation that occur due to leakage (corrosion) or scale that causes production drops and require expensive work-overs. While a large variety in well operation exists, commonly an economic lifetime of 10-15 years is used.

2.7 Recycling

The use of composite material is growing rapidly, partly due to its low weight and corrosion resistance, an example being the wind turbine blades. There are also more and more companies developing technology for the reuse of plastic composites. Although the heating infrastructure has an intended lifespan of 30 years, companies that focus on the reuse of composite plastics will be involved in the development of the composite products to ensure that the reuse of composite material is an integral part of the life cycle of the heating infrastructure. With the rapid growth of wind energy, the amount of waste resulting from decommissioned wind farms will rapidly grow as well [47]. It is still common for contractors in various countries to store the blades or dump them in a landfill until cost-effective recycling options become available or landfill is no longer an attractive alternative. With the increasing need to address the issues of blade waste in a sustainable way, the wind energy industry is driving forward the composite material recycling and circularity developments. Currently, OEMs, such as LM Windpower (GE), Vestas and Siemens Gamesa are exploring the development of recyclable blades [48], [49], [50], [51]. Such developments may be transferrable to the design of sustainable composite parts for a geothermal plant.

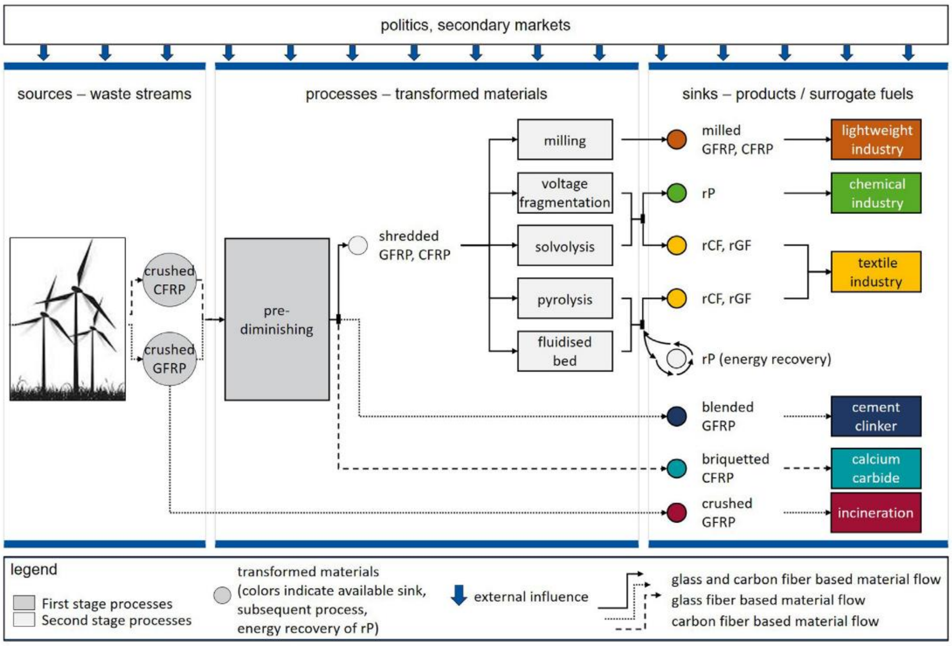


Figure 17 - Recycling and recovery options for GFRP and CFRP for wind turbine rotor blades. [52]

Different recycling routes can be followed for the wind turbine blades and similar options will be available for the processing of composite waste from geothermal applications. Figure 17 shows an overview of the options for recycling and recovery of glass-fibre and carbon reinforced polymers (GFRP and CFRP) as given by Sommer and Walther. [52]. The current generation of blades is still mostly reinforced with glass fibre, but the use of carbon fibre is expected to increase due to the increasing blade sizes and loads. This is related to the higher performance (especially the higher strength and stiffness over density ratio) of carbon fibre over glass fibre. The same holds for the resins used that tend to shift from polyester and vinylester to epoxies for the higher loaded parts.

2.7.1 Recycling options

The selected material also impacts the recycling routes, which in summary are: shredding, pyrolysis, solvolysis, upgrading glass fibre, and reuse of the large composite components for structural purposes.

Shredding

Large glass fibre components can be reduced in size by mechanical processing (shredded, cut and ground to small particles) and reused in a different form as a filler or as a reinforcement in concrete, reinforced plastics or other products. In this case it is estimated that about 80% recycling/downcycling is achieved due to material losses in the processing [47]. Much of the thermoset composite products are nowadays processed in this way. However, there seems to be little demand for the regained materials (grinded resin powder, short fibres, aggregates, fibre reinforced shards) and materials are not reused in the manufacturing of new large scale composite components.

Pyrolysis

Using pyrolysis polymers can be 'cracked’ at high temperature (450-700 °C) in a chamber with a limited amount of oxygen, reducing the polymers to fibres, oils and gasses. At high temperatures, the strength of the glass fibres reduces, which has consequences for the possible application of the recovered fibres, while carbon fibres are less sensitive to degradation. The required heat and the reuse of the recovered materials (oils, gasses, fillers and fibres) can result in a feasible solution for carbon fibre recycling [53].
Recent research by TNO with Brightlands Materials Centre has shown that using low-temperature pyrolysis can lead to an acceptable quality of recovered glass fibre that can be used in recyclable injection moulded products [54]. To reduce the heating cost, the ‘fluidized-bed’-technology (a microwave technology) is being explored as well, but not yet commercially available. Recently Shell decided to invest in recycling company Bluealp for converting hard-to-recycle plastic in pyrolysis-oil of which durable chemicals can be made [55].

Solvolysis

Solvolysis is a recycling technique in which the composite resin dissolves at lower temperatures [56]. The results at lab scale are promising and sometimes combined with the pyrolysis process. Commercial application has been limited up to now [57], but it is a promising route that allows for regaining the weaves as well as the monomers. The process also prevents the formation of carbonised material that contaminates the fibre surface after pyrolysis and can diminish fibre-matrix bonding.

Upgrading glass fibre

A consortium consisting of Aker Offshore Wind (Lysaker, Norway), Aker Horizons (Norway) and the University of Strathclyde (Scotland) developed a process developed at lab scale by Strathclyde for thermal recovery and post-treatment of glass fibres from GFRP scrap to achieve near-virgin quality glass fibre. Together they work on the scale-up and commercialization of the process. [58]

Reuse of the large composite components for structural purposes
Full recycling is also possible, if the entire part can be reused in a second life for structural applications such as infrastructure or architectural products. [59]

2.7.2 *Design for recycling*

Design for recycling is important for new composite components in order to make optimal use of the existing and future recycling options in the early development stage. Besides material selection, this also includes the manufacturing and assembly method. The use of specific chemistry, for example, can make the parts more suitable for recycling. Fisher and Lejeail [60] describe a reversible chemistry based on Diels–Alder reactions that are activated by temperature. Washing of the separated fabric using a bio-based solvent acetic acid reclaims fibres with an almost virgin quality and purity. Taynton and Kaffer [61] developed a resin that uses exchangeable imine-linked chemical bonds, called vitrimer. Due to the reversible chemistry the cured materials can be depolymerized and separated from the fibres under mild conditions. The second generation resins can contain recycled resin loadings of 30-40%.

Various core materials can be used. For example, in the wind turbine blade industry, besides traditional core materials such as balsa, PVC, and SAN, the thermoplastic PET is amongst others attractive for its recyclability and the fact that it can be made with recycled content (typically, from waste PET bottles) [62].
From a recycling perspective the use of a single polymer for both fibre and matrix is attractive. The developed single-polymer composites based on polyolefins or polyalkenes, such as polyethylene (Kaypla, Dyneema) and polypropylene (Pure) do offer the recyclability, but are also susceptible for creep.

A recent development of a single polymer composite uses liquid crystalline polymers. Liquid crystalline polymers (LCPs) are a special type of thermoplastics with a high degree of crystallinity. At ETH Zurich the self-assembly of liquid crystalline polymer molecules during extrusion resulted in novel material with highly oriented properties. The printed material matched the stiffness and strength of carbon fibre-reinforced polymers. Additional features of the process include recyclability, automated manufacturing and lower carbon footprint. Moreover, the used 3D printing technique allows for production of complex geometries [63], [64].

The developments in the wind industry show that recyclability of (large) composite structures can be achieved. For geothermal application however the operating conditions are much different. The operating temperature is higher and exposure to brine is present. For example, reversible chemistry for depolymerization of the cured materials would therefore require adapted or new methods. Thus dedicated recycling routes will need to be developed.

2.8 Conclusions & recommendations

The Com2Geo project has investigated the feasibility of a corrosion and scale-free geothermal system for the built environment, manufactured in composite material. The system requirements for such a system have been determined and the main components (well screen, casing, wellhead, piping, degasser, filter and heat exchanger) have been studied in detail. The study also gave insight in the technology development status with an identification of products that are commercially available, existing products not ready for commercialisation, and products which still have to be developed. Intermediate results have also been published and presented at a scientific conference [67].

Further development is required at both a system level and at a component/ product level. At a system level, an adaptation is needed of the design requirements that are often adopted from the oil and gas or processing industry. These requirements are geared to the production of explosive and chemically reactive products. A closer look at the production of geothermal energy and the pumping of water for heat distribution below 100 °C shows that there is room for solutions with composite material for all components without consequences for safe production.

At a component level, various routes are identified for various components of the system. An overview:

- **Well screen.** For the well screen, a hybrid approach is identified as the most promising result where an existing stainless steel / Duplex screen is combined with a slotted/perforated GFRP pipe. Initial analysis show that this is a promising replacement of a steel pipe, but more design loads are to be considered.
- **Casing.** This report shows that composite tubulars are suited for most of the potential geothermal wells (the DL2 category) in the Netherlands. Some of the design level 1 (DL1) load cases currently exceed the tubular load rating, which is the most conservative design and only applies to all sensitive and high-risk wells with none or limited relevant offset data.
- **Wellhead**. The use of composites is expected to both increase the lifetime and reduce the costs, as current wellheads demand coatings or inlays to enhance longevity. Currently however the standard does not provide guidance for alternative materials (e.g. composites) or means to allow for comparable testing or qualification to metal components.
- **Piping.** For the piping systems, GFRP are found feasible as they are already being used in comparable industries.
- **Degasser**. Potential feasibility of the degasser is found in existing designs of pressurized composite tanks and separators, albeit at a smaller scale. This means that additional research and retesting would be required.
- **Heat exchanger.** Composite plate are found to be feasible replacements for metal plate exchangers, when special attention is paid to the heat conductivity. This can be achieved by using z-axis oriented laminates using pitch carbon fibre.

Based on the material cost data and experience with existing composite components it is expected that the total composite system CAPEX is comparable to conventional metal solutions. That is, the composite (component) solutions can compete with existing stainless steel and titanium solutions. Low and medium grade steel solutions come at lower costs compared to composite solutions. In case of low-grade steels however double wall solutions are required for the well structure to mitigate potential leakage. Maintenance costs and environmental impact can be strongly reduced for composite solutions. At the same time longevity is expected to increase from 10 years for a conventional system to 30 years for a composite system.

Recent developments, especially in the wind industry, show that recyclability of (large) composite structures can be achieved. Though, for geothermal application the operating conditions (temperature, pressure and exposure to brine) are much different and dedicated recycling routes will need to be developed.

The results show the potential and feasibility of using composite components and identify the technical challenges that need to be investigated further. Within this work, no showstoppers are found, which highlights the need for further development of this technology.

2.9 References

[1] SodM, 2019. [Online]. Available: https://www.sodm.nl/jaarverslag2019/geothermie. [Accessed 15 February 2023].

[2] R. Steffens, “Innovatie Roadmap Geothermie,” Royal Haskoning, 2018. [Online]. Available: https://kennisbank.ebn.nl/wp-content/uploads/2018/11/20180604-rapport-innovatie-routekaart-geothermie-final.pdf.

[3] P. Wood, “Corrosion Review and Materials Selection for Geothermal Wells,” *Wood Group Intertech Ltd.,* 2017.

[4] *Creccit project - Cost Reducing Enhanced Composite Casing Installation Technology,* 2014-2018.

[5] *Geothermica GRE-GEO project - Glass Fiber Reinforced Epoxy Casing System for Geothermal Application,* 2020-2023.

[6] *Geowell Project,* 2016 - 2019.

[7] H. van 't Spijker and P. Ungemach, “Definition of Electrosubmersible pump (ESP) design and selection workflow,” *Kennisagenda,* 2015-2016.

[8] F. Ceglia, “Modelling of Polymeric Shell and Tube Heat Exchangers for Low-Medium Temperature Geothermal Applications,” 2020.

[9] NORSOK, “Norsok P-002: Process system design,” August 2014. [Online]. Available: https://www.standard.no/en/nyheter/nyhetsarkiv/petroleum/2014/p-002-process-system-design-edition-1-august-2014/. [Accessed 9 January 2023].

[10] Dutch Government, “Mijnbouwregeling Afdeling 8.4,” Overheid.nl, 01 January 2022. [Online]. Available: https://wetten.overheid.nl/BWBR0014468/2022-01-01/0/Hoofdstuk8/Afdeling8.4/informatie. [Accessed 9 January 2023].

[11] American Petroleum Institute, “API 6A: Specification for Wellhead and Tree Equipment,” 01 November 2019. [Online]. Available: https://www.api.org/products-and-services/standards/important-standards-announcements/spec-6a. [Accessed 09 January 2023].

[12] American Petroleum Institute, “API 6X: Design Calculations for Pressure-containing Equipment,” September 2008. [Online]. Available: https://global.ihs.com/doc_detail.cfm?document_name=API%20STD%206X&item_s_key=00620054. [Accessed 09 January 2023].

[13] American Petroleum Institute, “API 6AF: Technical report on Capabilities of API flanges Under Combinations of Load,” March 2014. [Online]. Available: https://global.ihs.com/doc_detail.cfm?document_name=API%20STD%206X&item_s_key=00620054. [Accessed 09 January 2023].

[14] British Standards Institution, “BS 6464: BS specifications for Reinforced plastic pipes, fittings and joints for process plants,” 01 July 2014. [Online]. Available: https://global.ihs.com/doc_detail.cfm?document_name=BS%206464&item_s_key=00108397. [Accessed 09 January 2023].

[15] ASTM International, “ASTM D3517: Standard specification for “Fibreglass” Pressure pipes,” 19 February 2020. [Online]. Available: https://www.astm.org/d3517-19.html. [Accessed 09 January 2023].

[16] ASTM International, “ASTM D5685: Standard specification for “Fibreglass” Pressure pipe fittings,” 25 February 2020. [Online]. Available: https://www.astm.org/d5685-19.html. [Accessed 09 January 2023].

[17] ASTM International, “ASTM D4024: Standard specification for Machine Made “Fibreglass” Flanges,” 21 July 2022. [Online]. Available: https://www.astm.org/d4024-22.html. [Accessed 09 January 2023].

[18] Technical Comittee ISO/TC 67/SC 4, “ISO 10423:2022: Petroleum and natural gas industries — Drilling and production equipment — Wellhead and tree equipment,” March 2022. [Online]. Available: https://www.iso.org/standard/79588.html. [Accessed 09 January 2023].

[19] The American Society of Mechanical Engineers, “ASME VIII div1: Rules for Construction of Pressure Vessels Division 1,” 2021. [Online]. Available: https://www.asme.org/codes-standards/find-codes-standards/bpvc-viii-1-bpvc-section-viii-rules-construction-pressure-vessels-division-1/2021/print-book. [Accessed 09 January 2023].

[20] The American Society of Mechanical Engineers, “ASME VIII div2: Rules for Construction of Pressure Vessels Division 2-Alternative Rules,” 2021. [Online]. Available: https://www.asme.org/codes-standards/find-codes-standards/bpvc-viii-2-bpvc-section-viii-rules-construction-pressure-vessels-division-2-alternative-rules/2021/print-book. [Accessed 09 January 2023].

[21] CEN, “NEN-EN 13445-3:2021 en: Unfired pressure vessels - Part 3: Design (Issue 1:2021),” 01 May 2021. [Online]. Available: https://www.nen.nl/en/nen-en-13445-3-2021-issue-1-2021-en-283142. [Accessed 09 January 2023].

[22] British Standards Institution, “BSI PD 5500:2021: Specification for unfired pressure vessels,” 15 September 2022. [Online]. Available: https://knowledge.bsigroup.com/products/pd-5500-2021-a2-2022-specification-for-unfired-pressure-vessels-1/standard. [Accessed 09 January 2023].

[23] The American Society of Mechanical Engineers, “ASME B31.3:2022: Process Piping,” 2023. [Online]. Available: https://www.asme.org/codes-standards/find-codes-standards/b31-3-process-piping/2022/print-book. [Accessed 09 January 2023].

[24] Technical comittee ISO/TC 67/SC 6, “ISO 13703:2000: Petroleum and natural gas industries — Design and installation of piping systems on offshore production platforms,” December 2000. [Online]. Available: https://www.iso.org/standard/22676.html. [Accessed 09 January 2023].

[25] CEN, “NEN-EN 13480-3:2012 en: Metallic Industrial Piping - Part 3: DEsign and calculation,” 01 July 2012. [Online]. Available: https://www.nen.nl/en/nen-en-13480-3-2012-en-173656. [Accessed 2023 January 2023].

[26] Technical comittee ISO/TC 67/SC 6, “NEN-EN-ISO 14692-1:2017 en: Petroleum and natural gas industries - Glass-reinforced plastics (GRP) piping - Part 1: Vocabulary, symbols, applications and materials,” 01 September 2017. [Online]. Available: https://www.nen.nl/en/nen-en-iso-14692-1-2017-en-238666. [Accessed 01 January 2023].

[27] NORSOK, “Norsok M-630,” 05 September 2010. [Online]. Available: https://www.standard.no/pagefiles/18204/m630u5.pdf. [Accessed 09 January 2023].

[28] Technical Comittee ISO/TC 67, “ISO 15156-1:2020: Petroleum and natural gas industries — Materials for use in H2S-containing environments in oil and gas production — Part 1: General principles for selection of cracking-resistant materials,” November 2020. [Online]. Available: https://www.iso.org/standard/79658.html. [Accessed 09 January 2023].

[29] Gruppo Sarplast S.r.l., “Sarplast,” [Online]. Available: http://www.sarplast.com/eng/products-casings.php. [Accessed 2022].

[30] G. Og and C. Vera, “Casing Design Manual, M-01 V4.0. Hoogeveen: Well Engineering Partners (WEP) BV,” Internal document, 2022.

[31] StressCheckTM, *Chapter 2: Theory, Calculations, and References - Detailed Mechanical Design.*

[32] EBN. SGS Nederland B.V., “KIRA Non-Alloy Based Tubulars Literature Review,” 2021.

[33] FRP Systems, “Pipe & Fittings,” Shout-Media.ca, [Online]. Available: https://frpsystems.com/products/pipe-fittings/. [Accessed January 2022].

[34] G. Xu and Et al., “Measurement of expansion coefficients of four steel types,” *Ironmak. Steelmak.,* vol. 40, pp. 613-618, 2013.

[35] G. B. Vaggar, S. C. Kamate and P. V. Badyankal, “Thermal Properties Characterization of Glass Fiber Hybrid Polymer Composite Materials,” *International Journal of Engineering Technology,* vol. 7, pp. 455-458, 2018.

[36] Hebei Weitong FRP Co., Ltd., “Is FRP Cost Effective Compared to Steel?,” 09 February 2022. [Online]. Available: https://www.frpwt.com/news/is-frp-cost-effective-compared-to-steel.html. [Accessed 08 January 2023].

[37] K. Yu, E. V. Morozov, M. A. Ashraf and K. Shankar, “A review of the design and analysis of reinforced thermoplastic pipes for offshore applications,” *Journal of Reinforced Plastics and Composites,* 2017.

[38] “Pressure Equipment Directive,” 15 April 2022. [Online]. Available: https://ec.europa.eu/growth/sectors/pressure-equipment-and-gas-appliances/pressure-equipment-sector/pressure-equipment-directive_nl.

[39] Tankwell, "Composite Lightweight Containers," 2022. [Online]. Available: https://tankwell.nl/. [Accessed 09 January 2023].

[40] “Sondex Plate Heat Exchanger - Working Principles,” 19 April 2022. [Online]. Available: Sondex Plate Heat Exchanger - Working Principles - YouTube https://youtu.be/Jv5p7o-7Pms.

[41] “Hoe platenwisselaars werken,” 19 April 2022. [Online]. Available: https://www.alfalaval.com/nl/microsites/platenwarmtewisselaars/tools/hoe-platenwarmtewisselaars-werken/.

[42] “List of thermal conductivities,” 19 April 2022. [Online]. Available: https://en.wikipedia.org/wiki/List_of_thermal_conductivities.

[43] M. Martins and e. al, “Highly Conductive Carbon Fiber-Reinforced Polymer Composite Electronic Box: Out-of-Autoclave Manufacturing for Space Applications,” *MDPI,* vol. 6, p. 23, 2018.

[44] G. Gardiner, Composite World, 2021. [Online]. Available: https://www.compositesworld.com/articles/z-direction-composite-properties-on-an-affordable-industrial-scale. [Accessed 15 February 2023].

[45] K. Sharp, A. E. Bogdanovich, J. Schuster and D. Heider, “Through-Thickness Thermal Conductivity in Composites Based on 3-D Fiber Architectures,” *SAE Transactions Vol. 116, Section 1: JOURNAL OF AEROSPACE, Published By: SAE International,* pp. pp. 1098-1102 (5 pages) , 2007.

[46] “Boston Materials,” [Online]. Available: https://www.bomaterials.com/products/. [Accessed 15 February 2023].

[47] L. Bank, E. Delaney, J. McKinley, R. Gentry and P. Leahy, “Defining the landscape for wind blades at the end of service life,” CompositesWorld, 2021. [Online]. Available: https://www.compositesworld.com/articles/defining-the-landscape-for-wind-blades-at-the-end-of-service-life. [Accessed 9 December 2021].

[48] A. Durakovic, “First Fully Recyclable Wind Turbine Blade Rolls Out,” OffshoreWIND.biz, 2021. [Online]. Available: https://www.offshorewind.biz/2022/03/17/first-fully-recyclable-wind-turbine-blade-rolls-out/. [Accessed 21 March 2021].

[49] A. Durakovic, “Danish wind turbine manufacturer Vestas is leading a new initiative aiming to make blades fully recyclable,” OffshoreWIND.biz, 2021. [Online]. Available: https://www.offshorewind.biz/2021/05/17/vestas-leads-project-to-make-wind-turbine-blades-fully-recyclable/ . [Accessed 9 December 2021].

[50] A. Durakovic, “Siemens Gamesa Launches Recyclable Offshore Blade,” OffshoreWIND.biz, 2021. [Online]. Available: https://www.offshorewind.biz/2021/09/07/siemens-gamesa-launches-recyclable-offshore-blade/. [Accessed 9 December 2021].

[51] “Siemens Gamesa unveils recyclable wind turbine blade,” Offshore, 2021. [Online]. Available: https://www.offshore-mag.com/renewable-energy/article/14209879/siemens-gamesa-unveils-recyclable-wind-turbine-blade. [Accessed 9 December 2021].

[52] V. Sommer and G. Walther, “Recycling and recovery infrastructures for glass and carbon fiber reinforced plastic waste from wind energy industry: A European case study.,” *Waste Management,* vol. 121, p. 265–275, 2021.

[53] T. Vandenhaute, M. Kaufmann, L. De Vriese, B. Waeyenbergh, T. Martens, K. Vallons and G. Luyckx, “Recyclage van composieten, white paper,” Sirris – Leuven, Leuven, Belgium, 2016.

[54] H. van der Mijle Meijer, A. Codou, C. Mariusz and N. Saraswati, “Glass fibre reclamation from thermoset wind turbine blade material for use in thermoplastic composite products,” TNO, Petten, 2021.

[55] Shell, “Shell investeert in plastic recycling technologiebedrijf Bluealp,” 9 Sep 2021. [Online]. Available: https://www.shell.nl/over-ons/shell-moerdijk/nieuwsberichten-shell-moerdijk/nieuwsberichten-2021/shell-investeert-in-plastic-recycling-technologiebedrijf-bluealp.html. [Accessed Nov 2021].

[56] R. Fonte and G. Xydis, “Wind turbine blade recycling: An evaluation of the European market,” *Journal of Environmental Management,* vol. 287, no. 112269, 2021.

[57] H. Mason, “Siemens Gamesa launches recyclable wind turbine blade,” CompositesWorld, 9 Sep 2021. [Online]. Available: https://www.compositesworld.com/news/siemens-gamesa-launches-recyclable-wind-turbine-blade. [Accessed Jan 2022].

[58] G. Nehls, “European partnership drives forward novel process development for GFRP recycling,” CompositesWorld, 2021. [Online]. Available: https://www.compositesworld.com/news/european-partnership-drive-forward-novel-process-development-for-gfrp-recycling. [Accessed 9 December 2021].

[59] [Online]. Available: https://www.designboom.com/design/denmark-repurposing-wind-turbine-blades-bike-garages-09-27-2021/. [Accessed 17 February 2023].

[60] M. Lejeail and H. Fisher, “Development of a completely recyclable glass fiber-reinforced epoxy thermoset composite,” *Journal of Applied Polymer Science,* no. DOI: 10.1002/app.49690, 2020.

[61] J. Sloan, “Vitrimers: The reprocessable thermoset,” CompositeWorld, 2020. [Online]. Available: https://www.compositesworld.com/articles/vitrimers-the-reprocessable-thermoset. [Accessed 9 December 2021].

[62] J. Sloan, “Core for composites: Winds of change,” CompositeWorld, 2010. [Online]. Available: https://www.compositesworld.com/articles/core-for-composites-winds-of-change. [Accessed 9 December 2021].

[63] T. Jeewandara, “3-D printing hierarchical liquid-crystalpolymer,” PhysORG, 2018. [Online]. Available: https://phys.org/news/2018-10-d-hierarchical-liquid-crystal-polymer.html. [Accessed 9 December 2021].

[64] S. Gantenbein et al, “Three-dimensional printing of hierarchical liquid-crystal polymer structures,,” *Nature,* no. DOI:10.1038/s41586-018-0474-7, 2018.

[65] G. Radhakrishnan, A. L. Sharma, E. Venkataraman and A. Fernandes, “Enhanced Life Cycle Costing Approach to Tubing Material Selection - New Coses and Revenue Drivers Identified for Experience with Non-Metallic Downhole,” *Abu Dhabi International Petroleum Exhibition & Conference,* no. SPE-192775-MS, 2018.

[66] L. S. Duthie, H. Al-Marri, H. A. Saiood, A. Latta and G. Radhakrishnan, “Effective Corrosion Mitigation Exploiting Glass Reinforced Epoxy Lined Tubulars in Offshore Producing & Injection Wells,” *Materials Science,* 2019.

[67] H. e. al., “Exploration of a geothermal system fully constructed from composite materials,” *GRC Transactions,* vol. 46, 2022.

[68] T. Sivasankaraiah and L. Bhaskara Rao, “Strength degradation of glass epoxy composites under hygrothermal.,” Material Principles, 2021.

3 Project execution

To study the feasibility of composite geothermal systems both partners from the composite industry and from the geothermal industry joined the project. Heatmatrix left the consortium early in the project and was replaced by TechnipFMC. Several meetings were organised by TNO and by partners amongst each other that encouraged a good knowledge exchange and joint investigation. Visits to production locations of Huisman Geo (Figure 18) and VDL Fibertech helped to support technical discussions and create shared insight. Dedicated meetings took also place at WEP, ECW and HP Wellscreen. Based on the achieved progress a joint paper was prepared and presented at the Geothermal Rising Conference. Based on this progress it was decided to aim for a joint submission of a MOOI proposal called 'Com2Heat' to enable further development of the investigated system and its components into a pilot phase. VDL and TechnipFMC decided not to pursue their investigations within this new proposal. However several new partners joined as well and together formed a sounding board for the Com2Geo project, giving their feedback on the technical development of composite geothermal systems. The Com2Heat proposal has been granted and started 1st March 2023.

Figure 18 - Visit to Huisman. Picture taken on top of the Huisman Innovation Tower.

4 Financial report

The financial report can be found in a separate Excel file. Except for the replacement of Heatmatrix by TechnipFMC no changes or deviations to the original budget were made.

5 Signature

Delft, 11th May 2023

TNO

ValidSigned by Michiel Hagenbeek
on 2023-05-12 09:34:00

M. Hagenbeek
Author & Project manager

ValidSigned by Sander Dragt
on 2023-05-12 09:14:40

R.C. Dragt
Author

ValidSigned by Loris Pergod
on 2023-05-11 16:26:19

L. Pergod
Author

ValidSigned by Tom Basten
on 2023-05-12 07:58:25

T.G.H. Basten
Research Manager Naval and Offshore Structures