IEA Technology Collaboration Programme

International Energy Agency
Technology Collaboration Programme on Energy Storage
(ES TCP)

Task 39 - Large Thermal Energy Storages for District Heating

Subtask B: Components and Materials Database

Deliverable B: Subtask B main report

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CONTENT

LIST OF ABBREVIATIONS

TES	Thermal energy storage
LTES	Large thermal energy storage
KPI	Key performance indicator
PTES	Pit Thermal Energy Storages
TTES	Tank Thermal Energy Storage
ATES	Aquifer Thermal Energy Storages
BTES	Borehole Thermal Energy Storages
DH	District heating
TSS	Thermal storage structure

DEFINITIONS

Experts involved in Subtask B agreed on the following definitions to be able to communicate between experts from different fields of science.

Name	Example
Structure:	Pit storage, borehole storage, …
Systems:	Lid/cover (in Pit storage), piping system
Components:	Insulation layer, piping
Subcomponents:	Pipes, insulation, fixations
Materials:	Polymer, stabilizer, soil, metal

INTRODUCTION

Thermal Energy Storage (TES) is a key enabling technology for the realization of a carbon-neutral energy system. Integration of large thermal storage (LTES) into a District Heating (DH), a mature technology for heating buildings, is essential for energy efficiency in society. DH is an excellent solution for several reasons e.g. creating a carbon-neutral energy supply, shaving the peak hours in thermal as well as electric grids, and enabling a more flexible system operation.

Task 39 "*Large Thermal Energy Storages for District Heating*" aims to determine the aspects that are important in planning, designing, decision-making, and realizing very large thermal energy storages for integration into district heating systems and industrial processes, given the boundary conditions for different locations and different system configurations.

The key objectives of the Task are:

- Definition of several representative application scenarios, the connected boundary conditions, and Key Performance Indicators
- Improve LTES materials and materials performance measurement methods.
- Prepare guidelines for obtaining proper water quality.
- Compare the performance and accuracy of simulation models for LTES.
- Derive validation tests for LTES simulation models.
- Generate information packages for decision-makers and actively disseminate the information.

Four types of storage are considered, Pit Thermal Energy Storage (PTES), Borehole Thermal Energy Storage (BTES), Aquifer Thermal Energy Storage (ATES), and Tank Thermal Energy Storage (TTES).

The Task is organized around 4 Subtasks (ST). Subtask A works on application scenarios, Key Performance Indicators (KPI) definition, the assessment of storage concepts in the scenarios, and the detailing of integration aspects. Subtask B aims at composing a database of materials needed for a LTES, specifying those materials that meet the off-standard conditions of a LTES. Subtask C is dedicated to a round-robin of the numerical simulation of LTES storages with real case data sets. Subtask D has as a goal to develop and distribute information packages for decision-makers.

This report aims to present the outcomes of the activities in WP B. The activities of WP B were planned to focus on four topics:

- Material database for LTES.
- Guidelines for proper water quality and procedures for obtaining this water quality.
- Guidelines/recommendations for corrosion protection.
- Proposal for novel hygrothermal and mechanical test methods.

However, the topic 'Proposal for novel hygrothermal and mechanical test methods' was not treated at all. A few test methods were compiled, one of them is described under 2.3. In the coming chapter activity and outcomes of the other topics are presented.

In general, the follow-up task (Task45) will take up the progress described in this report to further improve the level of detail of the content.

MATERIAL DATABASE FOR LARGE THERMAL ENERGY STORAGE

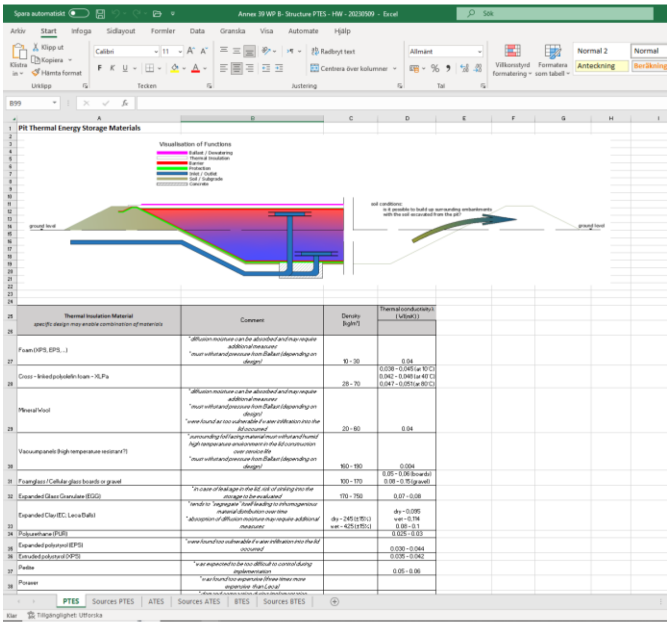
Materials and component properties are essential for the planning, design, and performance of thermal energy storage. The performance of each component/material is directly coupled to the lifetime and cost/benefit analyses of a thermal storage structure.

1 Material and component data

Material and component data are gathered and structured. Density, thermal conductivity, specific heat capacity, and the other relevant material properties for materials involved in the structure of thermal storage are presented in an EXCEL file for further utilization in the database.

A differentiation of the technologies PTES, BTES, and ATES has been made. Each type either differs fully or in parts from the other, both in terms of components but also used materials for their construction. A status of available materials was gathered and listed. With the help of schematic drawings of each storage type, a principal visualization of their composition is intended. Especially for the PTES technology a large choice of materials has been gathered, of which however a few already have been proven inadequate in the past. For nearly most materials a comment section has been filled in to reveal closer information, often gathered by experience from projects.

Since the technologies have a different maturity level further information requires gathering. ATES is in comparison to PTES quite mature, so the confidence in information is quite strong, also because an established combination of materials seems to be used in many existent plants.



Pit Thermal Energy Storage Materials

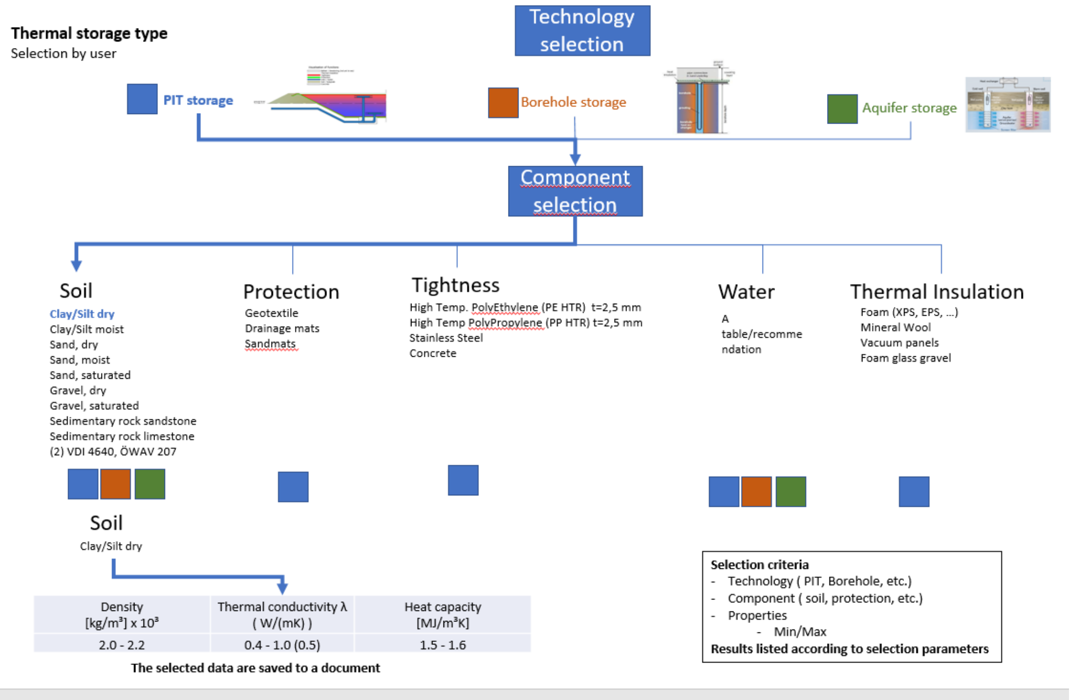
Thermal Insulation Material *specific design may enable combination of materials*	Comment	Density [kg/m³]	Thermal conductivity λ [W/(mK)]
Foam (XPS, EPS, ...)	**diffusion moisture can be absorbed and may require additional measures* **must withstand pressure from Ballast (depending on design)*	10 - 30	0.04
Cross - linked polyolefin foam - XLPe		28 - 70	0,038 - 0,045 (at 10°C) 0,042 - 0,048 (at 40°C) 0,047 - 0,051 (at 80°C)
Mineral Wool	**diffusion moisture can be absorbed and may require additional measures* **must withstand pressure from Ballast (depending on design)* **were found as too vulnerable if water infiltration into the lid occured*	20 - 60	0.04
Vacuumpanels (high temperature resistant?)	**surrounding foil facing material must withstand humid high temperature environment in the lid construction over service life* **must withstand pressure from Ballast (depending on design)*	160 - 190	0.004
Foamglass / Cellular glass boards or gravel		100 - 170	0,05 - 0,06 (boards) 0,08 - 0,15 (gravel)
Expanded Glass Granulate (EGG)	**in case of leakage in the lid, risk of sinking into the storage to be evaluated*	170 - 750	0,07 - 0,08
Expanded Clay (EC; Leca Balls)	**tends to "segregate" itself leading to inhomogenious material distribution over time* **absorption of diffusion moisture may require additional measures*	dry - 245 (±15%) wet - 425 (±15%)	dry - 0,095 wet - 0,114 0,08 - 0,1
Polyurethane (PUR)			0.025 - 0.03
Expanded polystyrol (EPS)	**were found too vulnerable if water infiltration into the lid occured*		0.030 - 0.044
Extruded polystyrol (XPS)			0.035 - 0.042
Perlite	**was expected to be too difficult to control during implementation*		0.05 - 0.06
Poraver	**was found too expensive (three times more expensive than Leca)*		

Figure 1. Excerpt of material data example excel-file for PTES

Material development for PTES on the other hand is still ongoing, to cover all aspects of handling the different challenges coming with the operation. The construction method is partly above ground, with the use of large earth dams to partially gain very large volumes. Therefore, other aspects, such as certain construction parts or landscape design also interface to some extent and reveal potential for further investigation.

2 Structure of the database

The proper design of the database aims to provide up-to-date accurate information on LTES materials and components. The design process consists of different steps, which include i) defining the purpose of the database, ii) finding and organizing the information into tables, iii) selecting the information to be included in each table, and iv) establishing the relationship between them. These steps allow us to provide the information when it is needed. The wireframe of the database is presented in Figure 2 and Figure 3. A wireframe is a schematic, a blueprint, useful to help you and your programmers and designers think and communicate about the structure of the software or website you're building.



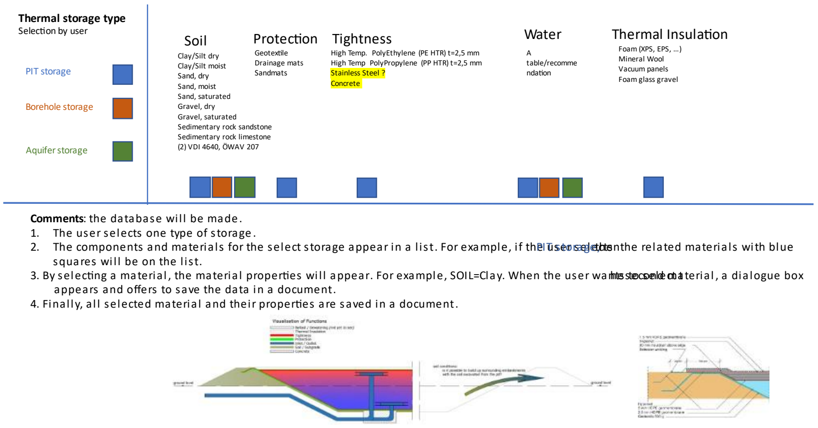
Density [kg/m³] x 10³	Thermal conductivity λ (W/(mK))	Heat capacity [MJ/m³K]
2.0 - 2.2	0.4 - 1.0 (0.5)	1.5 - 1.6

The selected data are saved to a document

Selection criteria
- Technology (PIT, Borehole, etc.)
- Component (soil, protection, etc.)
- Properties
    - Min/Max

Results listed according to selection parameters

Figure 2. Structure of the database



Comments: the database will be made.

1. The user selects one type of storage.
2. The components and materials for the select storage appear in a list. For example, if the user selects PIT storage, then the related materials with blue squares will be on the list.

3. By selecting a material, the material properties will appear. For example, SOIL=Clay. When the user wants to select a material, a dialogue box appears and offers to save the data in a document.
4. Finally, all selected material and their properties are saved in a document.

Figure 3. Structure of the database

i) The purpose of the database is to provide access to up-to-date crucial data needed for the design of different LTES. That means materials and components properties for being used in different LTES systems such as PTES, BTES or ATES are targeted candidates.

ii) The participants in this activity were grouped to identify the materials, components, and properties of the different LTES. That allowed us to start creating a list of the main relevant properties needed for design and system assessments, see Chapter 2.1.

iii) A further discussion on the information gathered led to select the information to be included in each table.

iv) Finally, it was established that the relationship between the tables and data will lead to different searching modes in the database.

As an example, in Figure 2, it can be seen the information flow created within the database, from the search 'soil properties for PTES' to the results of the search. The search will lead to a set of 'soil + properties table' that can be further ranked according to different criteria such as minimum/maximum thresholds or increasing/decreasing property values.

The database will be hosted on the Supergene Energy Storage Network+ website https://supergenstorage.org/, an energy storage platform that supports the energy storage community joining (experts) and disseminating (knowledge) through academia, industry, and policy. The Supergen Energy Storage Network+ website is linked to the https://ukesto.supergenstorage.org website where UK energy storage facilities and databases are showcased.

3 Measurement methods

The methods presented in this chapter are based on the research that has been performed by Ph.D. students involved in the activities of ST B.

3.1 Method for lifetime estimation of polymer liners as a water barrier in PTES

To develop and screen novel material formulations in a highly accelerated manner, a testing and assessment approach based on miniaturized specimens was implemented at the Institute of Polymeric Materials and Testing (University of Linz, AT). In a series of associated funded research projects (e.g., SolPol-1/2, 4/5 and 6, giga_TES) polyethylene (PE) and polypropylene (PP) liner material formulations were concepted, manufactured, and assessed as to their ageing behavior in hot air or water. Comprehensive data sets were generated and published in peer-reviewed publications such as Grabmayer et al., 2014 & 2015; Povacz et al., 2016, Grabmann et al., 2017 & 2018 and Peham et al., 2023. Special attention was given to the acceleration of the ageing mechanisms by elevated temperature and specimen miniaturization.

As to lifetime estimation, a method based on cumulative damages was used (Wallner et al., 2016). The lifetime assessment is based on a) simulated temperature loading profiles (Fig. 4, left) for LTES, and b) extrapolated experimental aging data on the micro-specimen level (Fig. 4 right). These data were weighted and accumulated considering a cumulative damage model.

Similar failure times for comparable sample thicknesses were observed in the 2016 Danish study by Paranovska and Pedersen. In different aging setups (water and air on each side vs. more critical medium) the lifetime of polymer liners used for water-based thermal energy storage was investigated over 10 years (Paranovska et al. 2016).

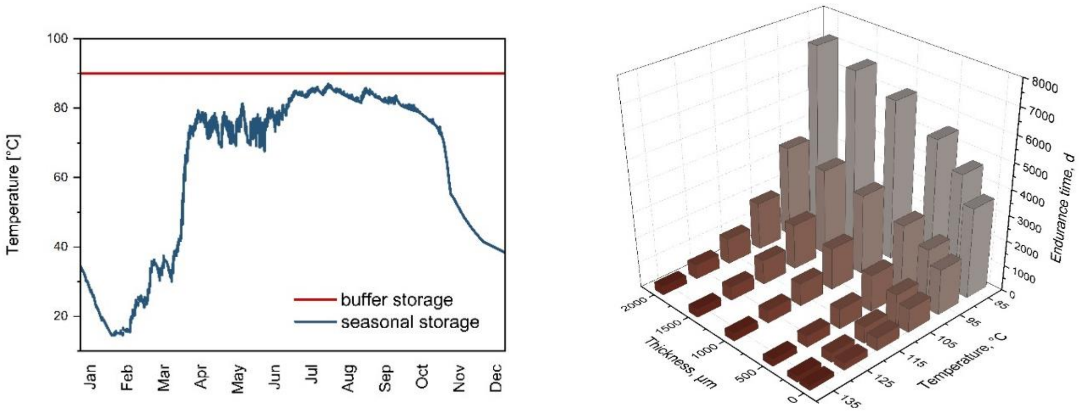
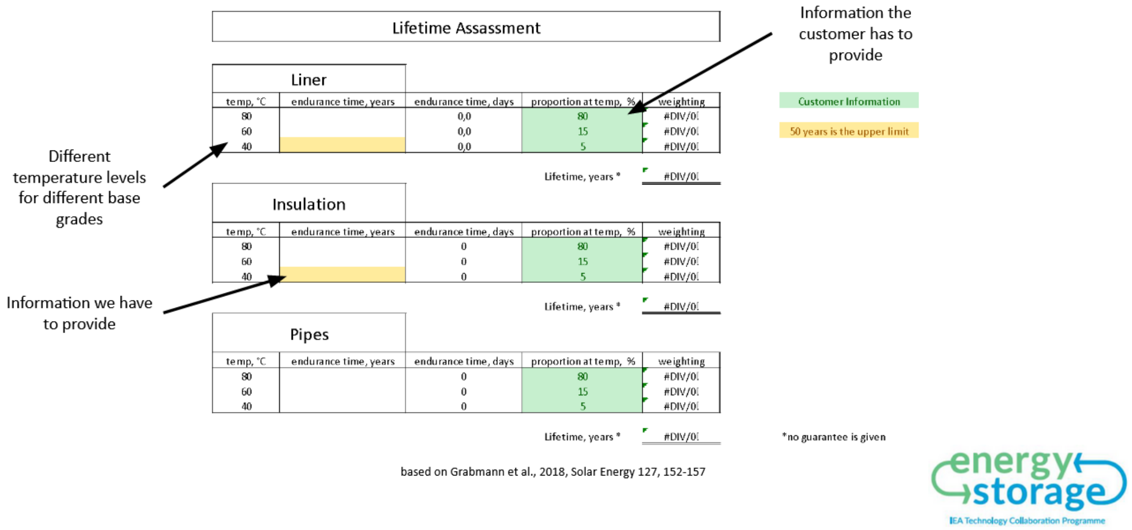


Figure 4. Temperature loading profiles of a buffer and seasonal storage (left) & endurance times (evaluated and extrapolated) dependent on thickness and temperature (Grabmann et al., 2018) (right)

In IEA ECES Task 39, the complexity of the lifetime assessment was reduced by consideration of the more critical environment (hot air or water) and, temperature-dependent endurance times for PE and PP liners of the service-relevant thickness (Fig.5). Instead of complex temperature profiles, time distributions based on three operating temperature levels have to be defined by the user.



Lifetime Assassment

Information the customer has to provide

Customer Information

50 years is the upper limit

Different temperature levels for different base grades

Information we have to provide

Liner

temp, °C	endurance time, years	endurance time, days	proportion at temp, %	weighting
80		0,0	80	#DIV/0!
60		0,0	15	#DIV/0!
40		0,0	5	#DIV/0!

Lifetime, years * #DIV/0!

Insulation

temp, °C	endurance time, years	endurance time, days	proportion at temp, %	weighting
80		0	80	#DIV/0!
60		0	15	#DIV/0!
40		0	5	#DIV/0!

Lifetime, years * #DIV/0!

Pipes

temp, °C	endurance time, years	endurance time, days	proportion at temp, %	weighting
80		0	80	#DIV/0!
60		0	15	#DIV/0!
40		0	5	#DIV/0!

Lifetime, years * #DIV/0!

*no guarantee is given

based on Grabmann et al., 2018, Solar Energy 127, 152-157

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Figure 5. Adapted, user-friendly lifetime estimation tool for polymeric materials in pit thermal energy storages

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Wallner et al. (2016). Solar Energy 125, 324-331.

4 Granular bulk insulation and factors affecting the thermal performance

Considering their large size, LTES are often built underground, to minimize their impact on the surroundings. In the presence of a groundwater table which is below the bottom of the storage, LTES systems (like the “Danish pits”) were built in an excavated ground without lateral insulation, whereas the cover was insulated. However, if unfavorable hydrogeological conditions were selected, the walls and the bottom of the storage can be insulated to reduce the thermal losses from the TES and minimize the groundwater overheating; however, this affects the economic feasibility of the storage.

The thermal performance of the insulation materials in a TES might deteriorate due to long-term exposure to high temperature, high pressure, and high moisture. The deterioration leads to an increase in the heat losses of a TES with the consequence of an increased temperature of the surrounding ground and in this case groundwater. Thus, the long-term thermal performance of the insulation materials is a key parameter for the efficiency of the TES and for complying with potential local regulations to avoid the temperature exceedance of the groundwater (Dahash et al. 2021).

Among the different types of insulation materials structures, granular bulk insulation is supposed to be a suitable material that can be applied as TES insulation, thanks to the ease of installation without the need for scaffolding, as the grains can be poured and adjusted to any geometrical irregularity. Foam glass gravel is an interesting candidate, already employed in existing TES systems (e.g. Munich - Ackermannbogen, Eggenstein-Leopoldshafen (International Energy Agency (IEA) 2015)). Other suitable materials are perlite, expanded clay, and expanded glass granules. As pointed out in (Ochs 2009), however, when comparing the theoretical estimated heat losses with measured heat losses in the operation phase, the measured heat losses can be 30 % to 50 % higher than the estimated ones. In the absence of failures or changes in the operating conditions, the main reason for this discrepancy can be the overestimation of the insulation performance during the design phase. The high temperatures involved, the insulation thickness, and consequently convection as well as the presence of moisture are the main contributors to the performance of an insulation material and the influence of these parameters should be included in the design phase. However, the lack of knowledge and data on the behavior of insulation materials at high temperature /moisture content/pressure is one of the main barriers to incorporating these aspects in the TES design phase.

Because of the presence of open porosity (i.e. voids between the grains) the use of granular bulk insulation can be unfavorable from the point of view of the insulation performance in the presence of upward and horizontal heat flux (as in the TES cover or the TES wall, respectively), since the formation of natural convective transfer (that naturally establishes as a consequence to the air density gradient), would represent a non-negligible part of the total heat flux. Bianchi Janetti et al. (Bianchi Janetti et al. 2015) showed that, for upward heat flux and temperature differences higher than 10 K, the thermal conductivity of uncompacted granular bulk materials (i.e. foam glass gravel) drastically increases from the nominal values because of this convective component. Additionally, increasing moisture content contributes in increasing the effective thermal conductivity of the material, since the additional term related to the latent heat transfer needs to be considered (Ochs, 2009)(Tosatto et al. 2023). Degradation of a buried TES envelope can be linked to moisture penetration (from both the surroundings and leakages from the TES).

Within the TES design phase, it is to be clarified whether thermal insulation of the lateral walls is needed and in which form. The choice of the most suitable envelope materials is related to the envelope element (i.e. cover, vertical walls), the costs (for the material itself and its installation) and to other specific requirements (e.g. presence of groundwater, temperature range, desired U-value). A deep knowledge of the insulation material properties under the operational boundary conditions is a key factor to develop design solutions able to maximize the insulation performance and longevity of the envelope elements and to develop measures that prevent these degradation effects such as moisture barriers or sinks and convection barriers.

4.1 Assessment of the convection risk

Nominal or rated values of the thermal conductivity from e.g. technical datasheets are commonly defined for a specific temperature and (no or low) moisture content. To extend the knowledge of materials' properties, tests at operational boundary conditions are recommended, but it is also possible to derive some preliminary indications from the available data (porosity, nominal thermal conductivity) and expected application.

The calculation of the Rayleigh number (Ra) for a specific material is a useful indicator for the possibility of the formation of convective heat transfer. In the case of porous materials, the Darcy-modified Rayleigh formulation is suggested (*VDI-Wärmeatlas. Fc4 Wärmeübergang Durch Freie Konvektion in Geschlossenen Fluidschichten.* 2006):

$$Ra = \frac{g\,\beta_a}{\nu_a} \cdot \frac{L\,K\,\Delta T}{a}$$

The single contributions on the development of convective heat flux depend on:

- Fluid characteristics:
    - ν_a is the fluid (i.e. air, a) kinematic viscosity, [m^2/s]
- Geometry and configuration:
    - g is the gravitational acceleration, [m/s^2]
    - $\beta_a$is the coefficient of thermal expansion, [1/K]
    - ΔT is the temperature difference between the two sides of the insulation, [K]
    - L is the characteristic length, [m]
- Material characteristics:
    - K is the material permeability, [m^2]
    - a is the material thermal diffusivity, $a = \frac{\lambda}{\rho_a \cdot c_{p,a}}$, where λ is the bulk thermal conductivity (without convection), [W/(m·K)]

It should be noted that the estimation of the permeability of the material (K) can be challenging and can strongly affect the final value of Ra due to the linear dependence. More specifically, in case of bulk materials, the permeability strongly depends on the degree of compaction, which can vary across the dimensions of the sample depending on the mechanical stress on the sample. An empirical formula for the evaluation of the permeability of a bulk material was developed by Ergun (Ergun 1952), and depends on the mean grain diameter (d_m) and on the bulk macro-porosity (ψ):

$$K = \frac{d_m^2 \psi^3}{A \cdot (1-\psi)^2}$$

As suggested in (Baehr and Stephan 2011) and (Ochs 2009), the empirical factor A can be set to 150. The permeability of materials can also be obtained by means of comparison of numerical results (i.e. from finite-element tools) and measured data as suggested in (Tosatto, Bianchi Janetti, and Ochs 2023).

The bulk macro-porosity ψ can be defined as following (Ochs 2009):

$$\psi = \frac{\psi_{tot} - \psi_{grain}}{1 - \psi_{grain}}$$

where:

- $\psi_{tot} = 1 - \frac{\rho}{\rho_s}$ is the total porosity
- ψ_{grain} is the grain porosity
- ρ is the bulk density, [kg/m^3]
- ρ_s ist he density of the solid matrix, [kg/m^3]

Once the material properties and its behaviour at the specific operation conditions are known, it is possible to develop design solutions that help minimising or prevent convection. The implementation of simulation tools to support the design of robust TES envelope solutions is a valid help but it must be based on reliable insulation material properties, i.e. the actual performance of the material under real TES conditions. Overall, the adoption of effective thermal insulation is an important feature in the construction of buried TES systems in order to support the integration and expansion of renewable energy sources in DH systems with minimal impact on the surrounding environment.

4.2 Example

Considering the specific case of foam glass gravel, it is possible to give some indications concerning the Rayleigh number threshold, above which the convective heat transfer strongly affects the performance. From the results of the studies proposed by Ochs et al. (Ochs, Bianchi Janetti, and Klesnil 2015), it is possible to suggest that in the presence of upward heat flux, a Rayleigh number higher than 50 represents the critical threshold for the development of convective heat flux. Further investigations are recommended to suggest critical Rayleigh numbers for other materials.

An example of the calculation of the Rayleigh number is presented in Table 1, which shows the case of a 0.5 cm thick foam glass gravel layer on a 60 °C heating plate and with 20 °C on the top. Two configurations were analysed (non-compacted and with a 30 % degree of compaction) and in both cases the development of convective heat flux was observed.

The comparison with experimental data from literature (Ochs, Bianchi Janetti, and Klesnil 2015) (Tosatto et al. 2023) confirms the theoretical approach. In the uncompacted sample, presence of convection is dominant and results in a Rayleigh value above 200, while in the compacted sample, the lower share of open porosity allows to drastically reduce the impact of convection, but with the specific thickness and temperature difference, it is still not sufficient to prevent it. Therefore, design solutions aimed at preventing convection are here required (i.e. convection brakes).

Table 1 Example of the calculation of Rayleigh number for the specific case of two foam glass gravel (FGG) samples.

Fluid characteristics (air)			
ρ_{air}	[kg/m^3]	1.25	
$c_{p,air}$	[J/(kg·K)]	1005	
μ_{air}	[kg/(m·s)]	0.000019	
Geometry and configuration			
L	[m]	0.5	
$T_{ambient}$	[°C]	20	
$T_{hot\ side}$	[°C]	60	
Material Characteristics			
		Non compacted FGG	*Compacted FGG 30%*
λ	[W/(m·K)]	0.1	0.1
d_{grain}	[m]	0.01-0.06	0.01-0.06
ψ	[-]	0.32	0.20
K (Ergun)	[m^2]	5.7E-07	1.1E-07
Rayleigh number			
Ra	[-]	293	57

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GUIDELINES FOR PROPER WATER QUALITY AND PROCEDURES FOR OBTAINING THIS WATER QUALITY

The water is used as the heat transfer fluid in DH-network as well as a storage medium, e.g. in PTES. The challenges considering water quality in a DH-network very similar to the challenges in a thermal storage structure (TSS). Thus, in this report existing knowledge obtain by DH researcher and energy providers who run a DH-network is used.

The water in a TES should have a sufficient quality to fulfil the following functions:

- avoid or minimize corrosion in metallic based components for example, diffuser system, pumps and heat exchangers installed in a thermal storage structure.
- avoid bacteria growth in the storage.
- avoid harmful influence on the service life of the polymer and other materials for a LTES.

The water in a TSS could be circulated by an open or a close system. In an open system, the water is in contact with atmospheric air. Thus, oxygen cannot be kept out of the water, and it will increase the risk for corrosion damages.

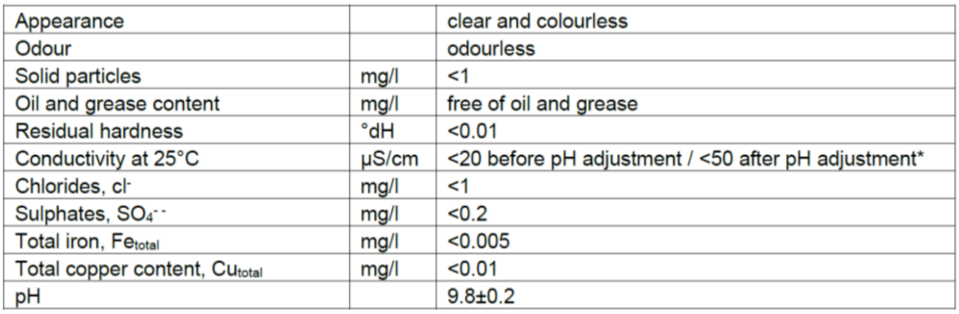
Furthermore, the temperature of the water is assumed to be between 5°C and 95°C in a TSS. The temperature level in a TSS is of importance for estimation of the lifetime of a TSS considering all material and especially metallic and polymetric material.

In the following chapters several recommendation and specification related to water quality in TES and DH will be presented.

1 Bobach Solutions

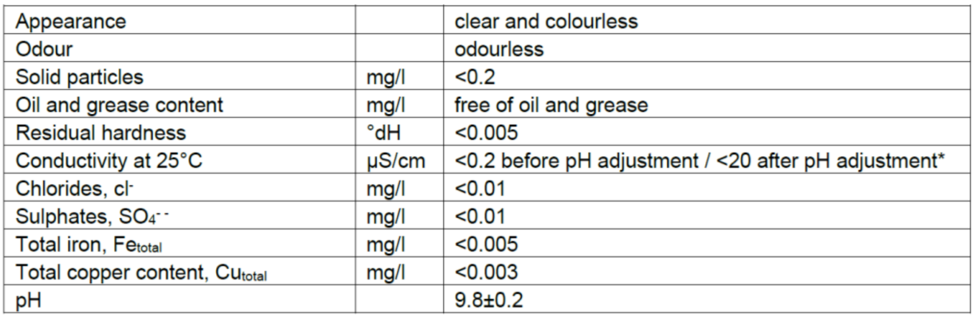
Bobach Solutions presented the experience and guidelines for requirements to water quality for PTES in the guideline (Requirements for water quality in pit thermal energy storages, Bobach, 2022). In this report, experiences from existing PTES are presented. Furthermore, water quality requirement for different material type of diffuser is stated.

Table 1 Minimum required water quality for PTES with stainless steel diffuser system. Maximum chloride content is adjusted according to the requirements from temperature (95 C) and steel grade (AISI 304/316), Minimum conductivity is adjusted as well. Conductivity increases because of PH adjustment by sodium hydroxide is accepted.



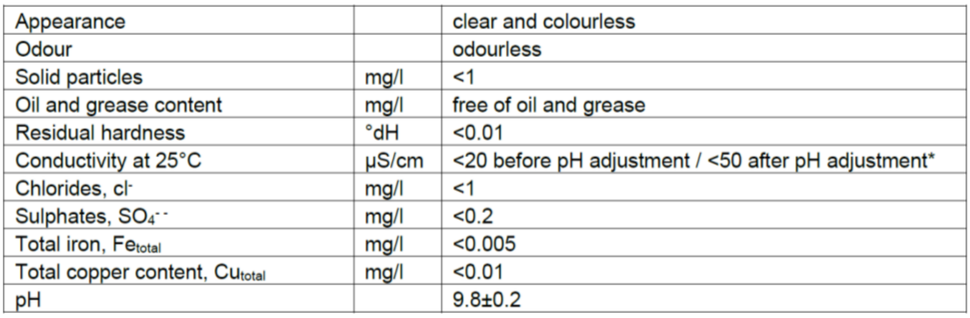
Appearance		clear and colourless
Odour		odourless
Solid particles	mg/l	<1
Oil and grease content	mg/l	free of oil and grease
Residual hardness	°dH	<0.01
Conductivity at 25°C	µS/cm	<20 before pH adjustment / <50 after pH adjustment*
Chlorides, cl^-	mg/l	<1
Sulphates, SO_4^{--}	mg/l	<0.2
Total iron, Fe_{total}	mg/l	<0.005
Total copper content, Cu_{total}	mg/l	<0.01
pH		9.8±0.2

Table 2 Minimum required water quality PTES with carbon steel diffuser system where corrosion should be minimized as much as possible. Conductivity increases as a result of PH adjustment by sodium hydroxide is accepted.



Appearance		clear and colourless
Odour		odourless
Solid particles	mg/l	<0.2
Oil and grease content	mg/l	free of oil and grease
Residual hardness	°dH	<0.005
Conductivity at 25°C	µS/cm	<0.2 before pH adjustment / <20 after pH adjustment*
Chlorides, cl^-	mg/l	<0.01
Sulphates, SO_4^{--}	mg/l	<0.01
Total iron, Fe_{total}	mg/l	<0.005
Total copper content, Cu_{total}	mg/l	<0.003
pH		9.8±0.2

Table 3 Minimum required water quality PTES with carbon steel diffuser system where corrosion should be kept below 0.2 mm/year. Conductivity increases because of PH adjustment by sodium hydroxide is accepted.

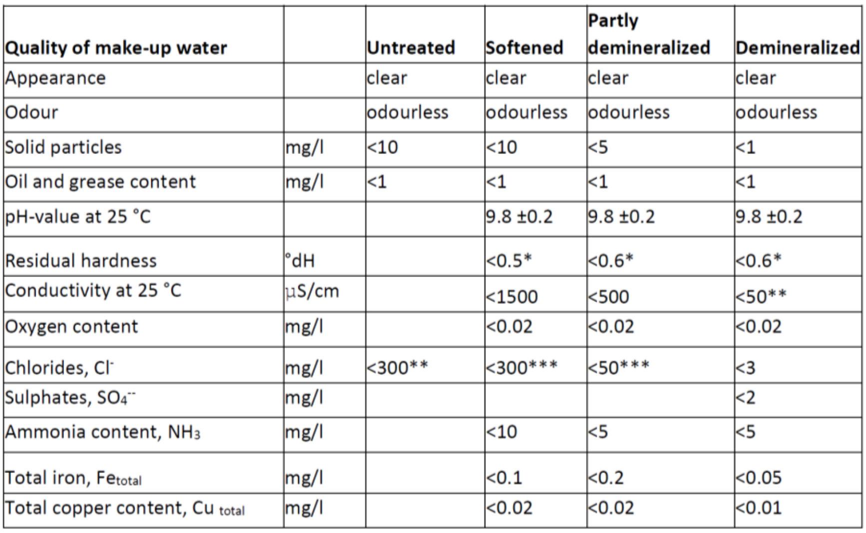


Appearance		clear and colourless
Odour		odourless
Solid particles	mg/l	<1
Oil and grease content	mg/l	free of oil and grease
Residual hardness	°dH	<0.01
Conductivity at 25°C	µS/cm	<20 before pH adjustment / <50 after pH adjustment*
Chlorides, cl^-	mg/l	<1
Sulphates, SO_4^{--}	mg/l	<0.2
Total iron, Fe_{total}	mg/l	<0.005
Total copper content, Cu_{total}	mg/l	<0.01
pH		9.8±0.2

2 District heating

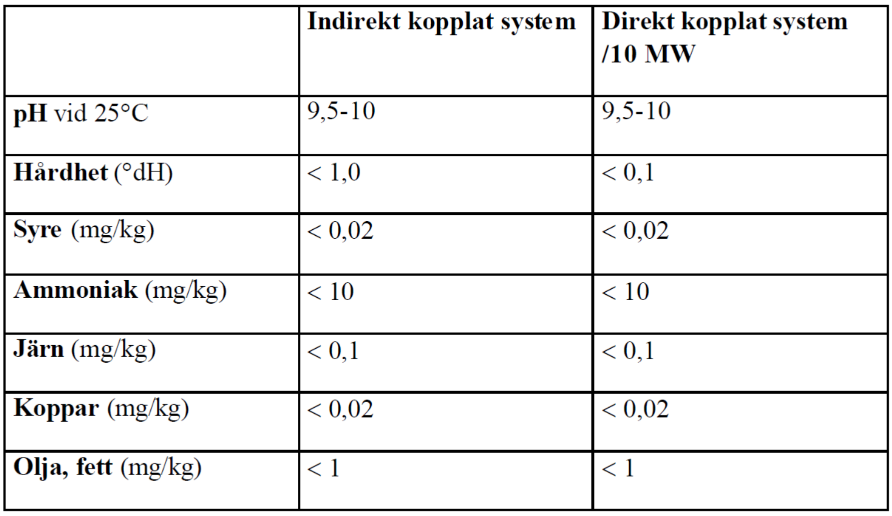
Several district heating companies have the same challenge concerning corrosion of metalic material thus, they have their own guidelines. The water quality in Danish, Swedish and German district heating system are presented in following tables.

Table 4 water quality in Danish district heating by Danish district heating association



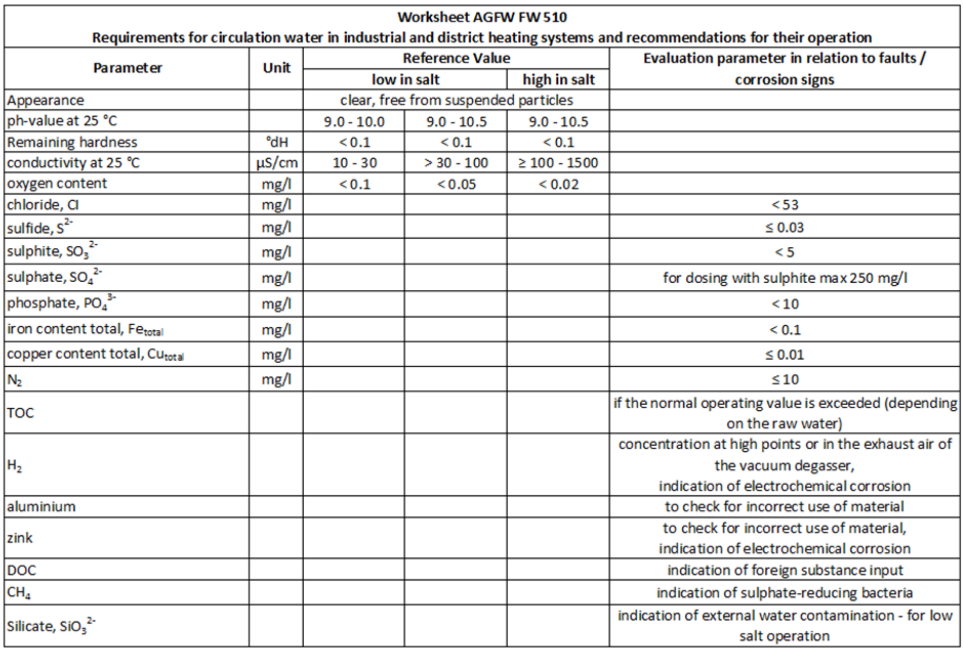
Quality of make-up water		Untreated	Softened	Partly demineralized	Demineralized
Appearance		clear	clear	clear	clear
Odour		odourless	odourless	odourless	odourless
Solid particles	mg/l	<10	<10	<5	<1
Oil and grease content	mg/l	<1	<1	<1	<1
pH-value at 25 °C			9.8 ±0.2	9.8 ±0.2	9.8 ±0.2
Residual hardness	°dH		<0.5*	<0.6*	<0.6*
Conductivity at 25 °C	µS/cm		<1500	<500	<50**
Oxygen content	mg/l		<0.02	<0.02	<0.02
Chlorides, Cl^-	mg/l	<300**	<300***	<50***	<3
Sulphates, SO_4^{--}	mg/l				<2
Ammonia content, NH_3	mg/l		<10	<5	<5
Total iron, Fe_{total}	mg/l		<0.1	<0.2	<0.05
Total copper content, Cu_{total}	mg/l		<0.02	<0.02	<0.01

Table 5 water quality in Swedish district association by (Bjurström&Carlsson, 2001)



	Indirekt kopplat system	**Direkt kopplat system /10 MW**
pH vid 25°C	9,5-10	9,5-10
Hårdhet (°dH)	< 1,0	< 0,1
Syre (mg/kg)	< 0,02	< 0,02
Ammoniak (mg/kg)	< 10	< 10
Järn (mg/kg)	< 0,1	< 0,1
Koppar (mg/kg)	< 0,02	< 0,02
Olja, fett (mg/kg)	< 1	< 1

Table 6 Requirements for circulation water in industrial and district heating systems and recommendations for their operation in Germany (Arbeitsblatt AGFW FW 510)



Worksheet AGFW FW 510
Requirements for circulation water in industrial and district heating systems and recommendations for their operation

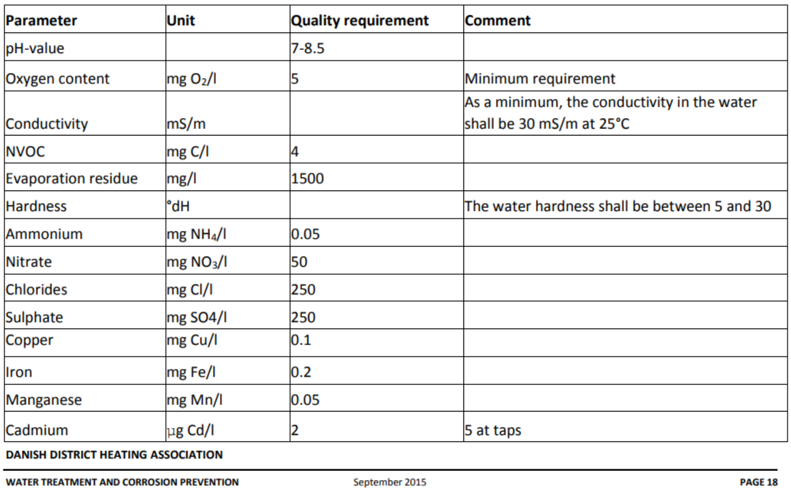
Parameter	Unit	Reference Value			Evaluation parameter in relation to faults / corrosion signs
		low in salt		high in salt	
Appearance		clear, free from suspended particles			
ph-value at 25 °C		9.0 - 10.0	9.0 - 10.5	9.0 - 10.5	
Remaining hardness	°dH	< 0.1	< 0.1	< 0.1	
conductivity at 25 °C	µS/cm	10 - 30	> 30 - 100	≥ 100 - 1500	
oxygen content	mg/l	< 0.1	< 0.05	< 0.02	
chloride, Cl	mg/l				< 53
sulfide, S^{2-}	mg/l				≤ 0.03
sulphite, SO_3^{2-}	mg/l				< 5
sulphate, SO_4^{2-}	mg/l				for dosing with sulphite max 250 mg/l
phosphate, PO_4^{3-}	mg/l				< 10
iron content total, Fe_{total}	mg/l				< 0.1
copper content total, Cu_{total}	mg/l				≤ 0.01
N_2	mg/l				≤ 10
TOC					if the normal operating value is exceeded (depending on the raw water)
H_2					concentration at high points or in the exhaust air of the vacuum degasser, indication of electrochemical corrosion
aluminium					to check for incorrect use of material
zink					to check for incorrect use of material, indication of electrochemical corrosion
DOC					indication of foreign substance input
CH_4					indication of sulphate-reducing bacteria
Silicate, SiO_3^{2-}					indication of external water contamination - for low salt operation

3 Water supplies and qualities

Conventionally, drinking water is used for production of make-up water for district heating systems. Drinking water has a well-defined quality with known limit values for contents of several substances. Drinking water is e.g. ground water, which is pumped up, oxidized, and filtered to produce the water. Usually, substances like iron and manganese are removed, but also methane, aggressive carbon dioxide, nitrite, ammonium, and phosphor as well as certain tracers.

The most common requirement for drinking water for some countries is presented in Table 7.

Table 7 the most relevant quality requirements for drinking water cf. executive order No. 1310 of November 11, 2015, of Danish Ministry of Environment. Where nothing else is stated in the table, the highest allowable values are used.



Parameter	Unit	Quality requirement	Comment
pH-value		7-8.5	
Oxygen content	mg O_2/l	5	Minimum requirement
Conductivity	mS/m		As a minimum, the conductivity in the water shall be 30 mS/m at 25°C
NVOC	mg C/l	4	
Evaporation residue	mg/l	1500	
Hardness	°dH		The water hardness shall be between 5 and 30
Ammonium	mg NH_4/l	0.05	
Nitrate	mg NO_3/l	50	
Chlorides	mg Cl/l	250	
Sulphate	mg SO4/l	250	
Copper	mg Cu/l	0.1	
Iron	mg Fe/l	0.2	
Manganese	mg Mn/l	0.05	
Cadmium	µg Cd/l	2	5 at taps

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Guidelines/recommendations for corrosion protection

Corrosion protection is relevant for all metal parts in direct contact with the storage medium and heat transfer fluid in the TES. That is diffusers, pipes, heat exchangers, pumps, and valves. In this context, the heat transfer fluid is always water with some degree of treatment as discussed above. The necessary precautions to avoid corrosion are highly connected to the level of water treatment and the ability to keep the water quality in a controlled state. The guidelines and recommendations for corrosion protection are based on experience from traditional DH systems as well as experience from existing LTES.

For TTES made of steel, the exact same recommendations as given for DH systems (pipe network) can be used. The main reason for this is that the oxygen level in the water can be kept at a minimum. In pressurized steel tanks there is no contact to atmospheric air from the surroundings and in pressure-less steel tanks atmospheric air is kept away from the water surface by a layer of steam or nitrogen. In the end this means that regular carbon steel can be used, and no further corrosion protection is needed if the water quality is maintained at typical levels given by the district heating organisations (oxygen content, pH-level, conductivity etc.).

For open system storages like PTES the requirements for corrosion protection are higher as the water has contact to atmospheric air and oxygen in the water cannot be avoided.

1 Recommendations for corrosion protection in PTES – Bobach Solutions

There has been a variety of approaches to corrosion protection in PTES projects that has been realized until now. The experience from some of these projects are described in the guideline (Requirements for water quality in pit thermal energy storages, Bobach, 2022).

The approaches in the existing PTES projects can be divided into three categories:

1. Carbon steel combined with low level of water treatment.
2. Coated carbon steel combined with low level of water treatment.
3. Stainless steel combined with high level of water treatment (chloride content < 1mg/l).

Finally, the combination of carbon steel combined with high level of water treatment is interesting. This combination is realized in a PTES project in Høje Taastrup, DK put into operation 2022, so at the time of writing there is no long-term experience available with this combination.

Summarizing the experiences from the existing PTES, the only safe approach to avoid corrosion is the combination of stainless steel and a high level of water treatment. This approach has been used in Dronninglund, DK since 2013 and Langkazi, Tibet since 2018 without any signs of corrosion. The steel quality used in those projects are Stainless steel AISI316. Stainless steel AISI304 or 316 can be used only if the chloride content is less than 1mg/l to avoid stress corrosion cracking at elevated temperatures as seen in Figure 6.

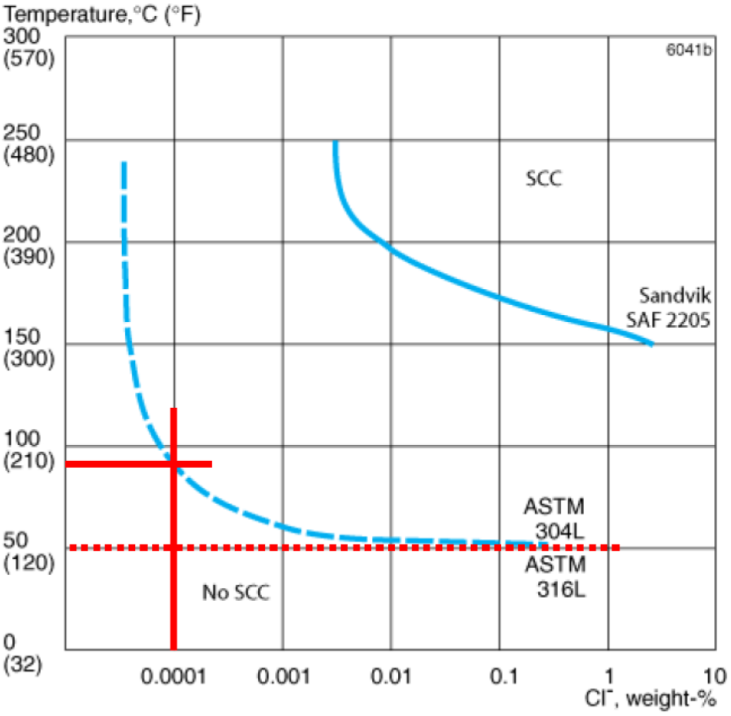

Figure 6. Resistance to stress corrosion cracking in neutral water with 8 ppm oxygen