TEST METHODS FOR COMPONENTS USED IN VERTICAL GEOTHERMAL HEAT EXCHANGERS

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Test methods for components used in vertical geothermal heat exchangers

Abstract:
This report treats the development of test methods for performance test of components used in vertical geothermal heat exchangers (GHX). The aim of the method proposals, attached to this report, is to help evaluate their performance in laboratory conditions, whilst subjected to relatively realistic environment. Such test methods are missing presently. This is of great concern since the number of GHX’s rapidly increases presently which might endanger the quality of ground water and the reliability of the heat exchanger itself, unless performance of the components used are adequately evaluated. The methods also enable national requirements regarding performance of GHX-components to be set up.

The project focused on the most commonly used components in the Nordic countries and on those that was regarded most important to keep the environmental impact to a minimum as well as to keep the functionality and reliability of the GHX to a maximum. Thus, the resulting method proposals are:

1. Leakage performance of well tops when subjected to hydrostatic pressure load and their ability to withstand mechanical lift force due to build up of ice on the collector wall.
2. Leakage performance of cast case sealing when subjected to hydrostatic pressure load. A concrete block kept in a thermally controlled environment simulates the borehole.
3. Leakage performance of non-cast case sealing and plug sealing when subjected to hydrostatic pressure load. A concrete block or steel pipes kept in a thermally controlled environment simulates the borehole.
4. Ability of collectors, i.e. plastics pipes, to resist external hydrostatic load in constant temperature.

The method proposals were developed from theoretical and practical investigations, in close contact with experts and key persons in the area.
Description of the project work

The project was formally launched at the first expert group meeting held in Borås at SP the 21st January 2004. Thereby a detailed plan was set up on how the project was to be realized. It was decided that the project should be initiated with a literature study and gathering of information. Besides studying relevant literature (that was found quite unusual), reports etc. it also incorporated interviews with key-persons and other experienced parties in this field of knowledge. Further, extensive searches on Internet were performed. The aim of the initial study was:

1. To identify components used in vertical geothermal heat exchangers (GHX);
2. To identify occurring or possibly occurring problems in GHX’s, such as environmental impact and malfunctioning;
3. To investigate if any existing standards or test methods may be adopted for these applications;
4. To investigate if any relevant research in this area has been conducted in the past and if so, if it would be usable in this project.
5. To identify other relevant information’s, such as environmental conditions in GHX’s.

Based on the gathered information the test method proposals where set up, as well as recommendable test parameters. Due to the nature of GHX’s these should however only be regarded as guidelines and may never be considered as insurances against malfunctioning in real applications since to many factors divers substantially between different GHX’s and locations.

Theoretical analyses and calculations were performed to evaluate feasibility, security, uncertainty and other parameters crucial for the method proposals. Also some experiments were conducted to evaluate the method proposals and to detect important factors overseen in the theoretical analyse.

The second expert group meeting was held at SP in Borås the 22nd November 2004 in which the conducted work was presented and discussed. The proposals were then discussed and evaluated with the members in the expert group, but later also with other experts in the area.
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Appendix A. Method proposal: Well tops used on drilled wells – sealing capability when subjected to hydrostatic pressure and resistance against lift force.

Appendix B. Method proposal: Performance test of cast case sealing used in drilled wells when subjected to hydrostatic pressure.

Appendix C. Method proposal: Performance of non-moulded case sealing and plug sealing when subjected to hydrostatic pressure.

Appendix D. Method proposal: Buckling resistance of plastics pipes when subjected to hydrostatic pressure.
## Abbreviations and Definitions

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<td>BHE</td>
<td>Borehole Heat Exchanger: A vertical drilled hole in which heat transfer occur between bedrock or/and gravel and a secondary heat carrier circuit or brine, i.e. borehole heat exchanger or vertical geothermal heat exchanger. Thus acting as heat source or heat sink for heat pumps or similar device producing heat or cold.</td>
</tr>
<tr>
<td>GHX</td>
<td>Geothermal Heat Exchanger: another denotation for BHE.</td>
</tr>
<tr>
<td>SDR</td>
<td>A value defining the relation between diameter and wall thickness in pipes.</td>
</tr>
<tr>
<td>MRS</td>
<td>Minimum required strength of pipe material when subjected to 50 years load duration at 20°C.</td>
</tr>
<tr>
<td>MDPE</td>
<td>Medium Density Polyethylene.</td>
</tr>
<tr>
<td>HDPE</td>
<td>High Density Polyethylene.</td>
</tr>
<tr>
<td>LDPE</td>
<td>Low Density Polyethylene.</td>
</tr>
<tr>
<td>PE</td>
<td>Polyethylene.</td>
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<table>
<thead>
<tr>
<th>Term</th>
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<tr>
<td>Active depth</td>
<td>Depth of BHE’s filled with water or other material enabling heat transfer between bedrock and heat carrier fluid or brine.</td>
</tr>
<tr>
<td>Water table</td>
<td>Depth of ground water.</td>
</tr>
<tr>
<td>Aquifer</td>
<td>Ground water magazine.</td>
</tr>
<tr>
<td>Artesian aquifer</td>
<td>Ground water magazine in which the hydrostatic pressure is higher than the atmospheric pressure or low enough to cause drainage of the aquifer when in contact with the atmosphere.</td>
</tr>
<tr>
<td>Static water level</td>
<td>Undisturbed water level in a BHE or well, i.e. the water level when no water is evacuated as in the case with BHE.</td>
</tr>
<tr>
<td>Hydrotite</td>
<td>Chloroprene rubber.</td>
</tr>
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</table>
1 Introduction and background

1.1 Background

Nordtest granted funding for this project the year of 2003. The objective of the project has been to develop test methods for components used in vertical geothermal heat exchangers (GHX). Besides Nordtest, financial support has also been given by FAB Föreningen för Avancerad Brunnsbörning, Uponor AB, SP Sveriges Provnings- och Forskningsinstitut and SGU.

The Nordtest method proposals, attached to this report are the results of experiments, calculations and discussions carried out during the year 2004 by personnel from SP in close cooperation with other concerned parties such as manufacturers of components and branch organizations.

A reference group consisting of Dag Henning Saether, Norskt byggforskningsinstitutt (NBI), Claus S. Paulsen, Dansk Teknologisk institutt (DTI) and Antero Aittomääki, Tamperes Tekniska Universitet (TUT) have been supporting the project. The reference group where gathered at two occasions. Crucial information has also been obtained from Göran Risberg (SGU), Anders Nelson (Geotec), Göran Hellström (LUT) and Hans Alexandersson (Pemtec), among others.

1.2 Introduction

To enhance the understanding of the problems and aspects of this report an understanding of the function and construction of the BHE is a necessity. The aim of the following section is to give the reader a brief description of BHE as well as of possible risks, components and other aspects of interest.

A BHE is a relatively expensive component, which if constructed inadequately not only may render the whole system useless or inefficient, but also may endanger the natural resource that a clean ground water constitutes. No standardised methods enabling evaluation of performance and reliability regarding components used exist presently, with some exceptions. This is of great concern, especially in Sweden, since the market of ground coupled heat pumps and thus BHE’s is undergoing a rapid expansion with more than 33 000 new installations in Sweden alone last year.

The need of test methods is thus revealed mainly by two major concerns; pollution of the relatively clean ground water in the Nordic countries and the functionality and reliability of the BHE. However, since BHE’s are constructed and designed mainly “on-site” the functionality and efficiency is strongly depended on human competence, and other local aspects, that are likely to vary between installations. The test methods proposed here should therefore not be regarded as insurance against malfunctions, but merely act as tools to help evaluate the performance of individual components. Such tools are lacking today, as stated earlier.

It is hoped that this project will provide means to establish bases for national standards and regulations regarding construction and design of BHE’s in order to maintain the credibility and effectiveness of BHE’s and not least to protect the still relatively clean ground water in Sweden and the rest of the Nordic countries.
1.2.1 Design and function of the BHE

The general design used in almost every BHE constructed in the Nordic countries is illustrated in figure 2.1.

![Figure 2.1. General design of the BHE.](image)

In the upper part of the BHE, located in unconsolidated ground and further down at least two metres into solid bedrock, the borehole is supported by a casing (B), usually made of steel. If the depth of the unconsolidated ground is shallow, less than two metres, plastics pipe, usually polyethylene may be used [20, pp10.1]. The casing prevents the hole from caving in as well as surface water from reaching the upper, usually crackled segments of the bedrock. At the upper end of the casing a well top is mounted (A). The purpose of the well top is to act as a barrier against surface water and other residue and to a certain degree to prevent water to exit in case of artesian aquifers in conjunction with the BHE. The lower part of the casing end in a sealing (C) that prevents infiltration through the gap between the bedrock and the casing.

The collector (F) is the “cold side” of the heat exchanger and contains the heat carrier fluid, usually ethyl alcohol. The most commonly used collector type, the single U-pipe illustrated in the figure, ends in a U-bend protected by a plastics casing (E). A concrete pilot weight is attached to the collector to weigh it down. Grouting material, usually water, transports the heat between the bedrock and the collector. If the hole is dry, i.e. the water table is deep; the hole may be backfilled with some other material than water to enable heat transfer between the collector and bedrock. Backfilling or grouting may also be done to completely seal off the BHE from the surrounding. In this case an impermeable grout such as cement is used. However, this is almost never done in the Nordic countries [28, 29] but relatively common in the USA. In some states it is even legislated to backfill BHE’s in order to achieve permits of construction.

To prevent different layers of ground water to mix different types of plug sealing may be used (D).

The total depth of the BHE is normally somewhere between 100 – 200 m of which at least the upper 6 m is cased.
1.2.2 Environmental risks and malfunction causes for BHE’s

The environmental hazard of BHE’s is confined to pollution of, or disturbances in, ground water aquifers. Such aquifers in solid rock may be considered effectively sealed from the surface and often also from each other. When constructing a BHE this barrier is penetrated enabling polluted water to infiltrate unless sealed sufficiently. A number of scenarios are possible:

1. Infiltration of surface water through the well top or through the gap between the casing and bedrock in case of malfunctioning case sealing.
2. Mixture of different aquifers of which one or more may be polluted or saline, contaminating the fresh water.
3. Leakage of heat carrier fluid.
4. Drainage or disturbance of aquifers.

SGU has received reports of polluted fresh water wells over the years [29]. If this is due to BHE’s or some other source of contamination is not definite, however, strong suspicions have been raised in some cases.

Due to the nature of BHE’s causes for malfunctioning and sometimes even the malfunction itself are not always easy to define or even to detect. Further, if malfunction occurs they are often hard, in some cases even impossible to cure sufficiently with less than backfilling the entire BHE and constructing a new one. Possible, and in some cases not unusual malfunctions or flaws of BHE’s are however:

1. Leakage of heat carrier fluid;
2. Freezing causing the collector to deform and thus preventing the system to work periodically;
3. Compressive deformation of the collector system due to difference in density between the ground water and heat carrier fluid in deep BHE’s or when backfilling with heavy grouts such as cement;
4. Malfunction of sealing causing pollution;

As indicated most of these can be derived back to construction and dimensioning of the BHE, i.e. the human factor, such as freezing. Some of the above listed malfunctions may, however, result from inadequate material.

1.2.3 Components - an overview

A great variety of components and designs exist and will probably be developed in the future. The following section is only intended to work as an overview in which the most common components are briefly described.

1.2.3.1 Well tops

The presently occurring models may be divided into three groups, based on design, function and how they are intended to be assembled, as listed below.

A. Internally mounted models with sealing capability.
B. Externally mounted models with sealing capability
C. Externally mounted models without sealing capability
Internally and externally mounted models are assembled on the inside or outside of the casing respectively. Sealing capability means in this context that the model is likely to act as water sealant. Models that only prevent gravel and other residue from infiltrating the BHE are not regarded as having sealing capability. However, the grading is not based on tests, but merely on visual inspection and the intended function of the different models.

1.2.3.1.1 Type A

This design consists of three basic components; metal frames, rubber sealants and mounting screws or bolts. When installed the lid is placed inside the steel casing whereby the bolts/screws are tightened. The two metal frames are pressed together as a result of this, which causes the rubber sealants located at contact with the casing and the collectors to expand and thereby to seal off against the casing and the collectors.

Some models of this concept are also equipped with supporting screws, which are tightened against the casing to prevent separation due to pullout. Some examples are shown in figure 2.2.

1.2.3.1.2 Type B

The construction of this type varies somewhat but the most commonly occurring is simply a rubber hood, secured to the casing and the collectors by usage of hose clamps. In some versions this design is equipped with a supportive metal frame underneath the hood to strengthen the design. Due to the relatively low cost of this well top it should be regarded as the most commonly used model today. This well top may be viewed to the right in figure 2.2.

This design also comprises models with function similar to type A but externally mounted instead. These models are however unusual since internally mounted models are more practical when constructing the BHE [26].

1.2.3.1.3 Type C

This design is not equipped with any sealants at all to prevent water from passing through. They usually consist of a plastics cap secured to the casing by screws tightened against the outer surface of the casing. Models with or without through holes for collectors are available. An example is given in figure 2.3.
1.2.3.2 Case sealing

Two main principles to obtain water sealing between the casing and the surrounding bedrock may be recognised:

1. Cast case sealing;
2. Non-cast case sealing.

However, the latter has not obtained any great success on the market yet, due to a relatively high cost [26] and thus the cast case sealing is by far the most commonly used sealing presently.

1.2.3.2.1 Cast case sealing

The case sealing itself usually consists of cement paste or in Norway bentonite clay [32]. In Sweden and Finland cement is however always used [13, 17], since bentonite loses in performance regarding sealing capability if dehumidified or frozen.

Two methods to construct the case sealing may be recognized. The most commonly used method is to mechanically press out the moulding material into the annulus of the casing by usage of a special tool. At the same time the casing is brought to rest against the borehole bottom, i.e. casing shoe. To facilitate the procedure the casing is lifted somewhat as the grout is forced into the gap between casing and bedrock. Sometimes accelerators are used to speed up the hydration of the grout. According to most manufacturers no substantial hydration time, i.e. time to set is necessary before continuing with the constructing, and thus valuable time is saved, why this is the preferred method amongst most BHE-constructors.

The second method differs from the previous one only in that the grouting material is not physically pressed out in the annulus of the casing but allowed to fill up the gap according to the principle of communicating vessels. This method is very uncommon since the grouting material must hydrate substantially before the construction can continue.

1.2.3.2.2 Non-cast case sealing

The only model found of this design is a member of the “Aquatät”-family [23], equipped with Hydrotite sealants that expand when subjected to water. Sealing capability is supposedly achieved between the casing/sealing, bedrock/sealing and collector/sealing. The sealing is assembled as illustrated in figure 2.4. According to the manufacturer the sealants are sufficiently expanded after 24 hours and thus sealing performance obtained.

Figure 2.4 Assembled non-cast case sealing.
1.2.3.3 Collectors

Two main principles of collector design may be recognized; co-axial and U-pipe collectors, illustrated in figure 2.5.

Figure 2.5 Principle sketch of the single U-pipe collector (to the left) and the coaxial collector.

The by far most commonly used collector in Sweden as well as the rest of the Nordic countries is the simple U-pipe, due to the simplicity, security and low cost of the design. However, if the BHE works as heat sink as well as heat source, i.e. recharging of the BHE is conducted periodically, a double U-pipe is sometimes used, which in simple terms may be described as two single U-pipes.

Some variations of the U-pipe, the triple and quadruple coiled U-pipe are illustrated in figure 2.6.

Figure 2.6 Triple coiled (left) and quadruple coiled U-pipes.

U-pipe collectors normally consist of polyethylene pipes of dimensions 40 x 2,4 mm or 32 x 2,0 mm classified to PN6. The quality of the polyethylene normally conforms to MDPE 80 [26, 27, 28, 29], although high density and PE100 materials are growing more popular. The collector system, pipes and couplings, are fused together before delivery to the actual site of installation and delivered in coils.

The coaxial collector exists in a great variety of designs of which some are illustrated in figure 2.7.
1.2.3.4 Plug sealing

Two major designs are used; cast plug sealing and non-cast sealing. The latter is unusual though, due to the cost being somewhat higher than is the case with cast sealing.

1.2.3.4.1 Cast plug sealing

The cast plug sealing may in simple terms be described as a segmental grouting/backfilling creating a plug to prevent flow and leakage from a polluted or saline aquifer entering the BHE and eventual fresh water aquifers present.

The grout used normally consists of cement, concrete, bentonite or some other mixture based on cement, bentonite and some additive. In addition some kind of device or support may be used to guide the grout to the right location in the BHE. If a deep segment is to be sealed the bottom of the borehole may act as cast foundation. If a shallower segment is of interest a plastics plate or similar may be used. Some examples on installation and construction of cast plug sealing may be viewed in figure 2.8.

![Figure 2.8](image)

Figure 2.8. Different ways to obtain sealing by use of cast plug sealing.

1.2.3.4.2 Non-cast plug sealing

In common for all non-cast plug sealing is the principle of function, which is based on expansion of the whole plug or of sealants mounted to it, when subjected to water or expanded by other means. The plug itself may consist of wood or plastics equipped with sealants at one or two locations, i.e. single or double sealing. The wooden sealing should be regarded as quite unusual nowadays, although it has been used in the past to some extent and might still be.

Aquatät is a group of plastics plug- and case sealing equipped with Hydrotite sealants. Hydrotite is a rubber material that slowly swells when immersed with water, up to ten times the original
volume according to the manufacturer [23]. A number of different designs and dimensions are available. Some examples are illustrated in figure 2.9.

![Double sealing (left) and single sealing (right).](image)

**Figure 2.9.** Double sealing (left) and single sealing (right).

### 1.2.3.5 Backfilling

As stated previously backfilling is done to either enhance the heat transfer in dry BHE’s (thermal backfilling) or to obtain a complete seal (grouting). At present thermal backfilling is by far most common in the Nordic countries and the material is normally sand.

However extended research on suitable materials has been conducted during the years among others by M.L. Alan [2,3] and thus the knowledge in this subject is relatively good. A good or suitable material is among other things governed by:

1. High thermal conductivity;
2. Low permeability;
3. Good adhesion to the collector and bedrock;
4. Capability to withstand freezing and drought;

In addition the grout must be pumpable and have a relatively high rate of hydration etc. The backfills and grouts used, except water, are cement; sand; cement/sand; bentonite; cement/bentonite; bentonite/graphite and bentonite/sand.
2 Aim of the new Nordtest method proposals

The aim of the Nordtest method proposals is to enable evaluation of the different components used presently in BHE’s regarding their performance when assembled as intended. The methods should be usable as tools to enable national requirements to be set up or to help evaluate products during development or to secure quality in production. To enhance the security, repeatability and quality of results of the test should be performed under laboratory conditions. Field test would mean many uncontrollable parameters that might influence the quality of test and render insufficient reproducibility. However, the test parameters should, within reasonable limits, reflect the environmental conditions and naturally occurring loads present in real applications. These aspects should be presented as recommendable test parameters and thus enabling different conditions to be used if desired or necessary.

The work of developing the methods has been focused on the most commonly used components in the Nordic countries. Efficiency tests, such as heat transfers of collectors, have been disregarded since too many aspects are involved when choosing components and influencing the efficiency for that kind of methods to be relevant.

During the work a well performing BHE has been defined by:

1. At least 100 years technical life (50 years for some components such as collectors);
2. No environmental impact concerning leakage of heat carrier fluid, contamination of fresh water aquifers due to infiltration of saline or polluted water and drainage or major disturbance of ground water aquifers.
3 Methods and standards

3.1 Adoptable methods and standards

As part of the project an investigation regarding adoptable methods that might be used to test components for these applications was performed. Suitable methods should be adoptable to the design, load and other characteristics defining the components conforming to the aim of the new method proposals as described in section 2 in order to be sufficient and adoptable.

Generally no official and suitable test methods or standards were found during the course of the project. An exception to this is collector pipes, i.e. plastics pipes, for which a number of usable standards exist. However, some standards could be used, partially or completely, to test or to evaluate parts of the components, such as sealants and materials, as specified in table 3.1.

Tests to determine resistance against hydrostatic pressure of well tops have been conducted in the past, but not according to any established method [26].

Table 3.1 Examples of partially or completely usable standards and methods to test materials and sealants.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Standard/Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aging characteristics of rubber sealants</td>
<td>ISO 6914:2004, “Rubber, vulcanized or thermoplastic - Determination of ageing characteristics by measurement of stress relaxation.”</td>
</tr>
<tr>
<td>Accelerated aging of rubber and thermoplastic</td>
<td>SS-ISO 188, “Rubber, vulcanized or thermoplastic – Accelerated ageing and heat resistance tests.”</td>
</tr>
<tr>
<td>Material requirements of rubber sealants</td>
<td>SS-ISO 4633, “Rubber seals - Joint rings for water supply, drainage and sewerage pipelines - Specification for materials”</td>
</tr>
<tr>
<td>Tensile strength of butt fused joints and spigot joints.</td>
<td>ISO 13953:2001 “Polyethylene (PE) pipes and fittings – Determination of the tensile strength and failure mode of test pieces from a butt fused joint.”</td>
</tr>
</tbody>
</table>
3.2 Nordtest-methods

Due to the vast variety of components and component design present a restriction of coverage of the new method proposals regarding output and components were defined. The tested parameters and components selected were:

1. Well tops – leakage resistance when subjected to hydrostatic pressure and resistance against lift (section 4 and appendix A).
2. Cast case sealing – leakage resistance when subjected to hydrostatic pressure (section 5 and appendix B).
3. Plug sealing and non-cast case sealing – leakage when subjected to hydrostatic pressure (section 6 and appendix C).
4 Performance test of well tops subjected to hydrostatic pressure and lift

4.1.1 Introduction

The significant stresses the well top may be exposed to are:

1. Hydrostatic pressure;
2. Mechanical lift due to coat of ice on the collector wall.

Besides these stresses biological and chemical breakdown have been investigated but established to be irrelevant in this application for any normal situation, considering materials presently used in well tops and the environment they are exposed to.

Possible effects due to low temperatures such as increased brittleness and reduced elasticity of material and the rubber sealing as well as differences in thermal expansion between the casing and the well top has been neglected due to the relatively small temperature span present (about -30°C to 30°C). Since well tops usually are made of steel, aluminium, plastics or other metals unrealistically low temperatures would be required for the brittleness to affect the stress strength to a degree of any importance. This also applies to polyethylene and rubber lids for which the brittle point is – 40°C and – 30 to - 60°C respectively, depending on type [22].

4.1.2 Scope and field of application

The scope of the method proposal is to describe a way of testing performance of well tops type A and B, according to section 1.2.3.1, regarding sealing capability and capability to resist lift due to build up of ice on the collector walls. Due to the existing variation regarding design of well tops the method is not always in all aspects relevant, necessary or applicable.

The proposal takes no consideration regarding effects due to extreme cold.

The method is applicable for well tops intended to act as sealing against fluids and that are firmly attached to the casing.

4.1.3 Evaluation of test parameters

4.1.3.1 Hydrostatic pressure

The well top might be exposed to hydrostatic pressure load from the interior of the BHE if it is constructed in conjunction with a flowing artesian ground water aquifer as illustrated in figure 4.1.
The magnitude of the pressure depends on the surrounding topography, the bedrock and the surrounding ground water levels and is therefore very hard to quantify [7]. Theoretically the hydrostatic pressure might be substantial in broken ground, where the ground water level follows the topography, which it more or less do in general. In Sweden pressures of up to 3 Bars has been observed [30] in artesian wells.

It is questionable, however, if the well top should withstand these considerable pressures since one must be certain that the well case sealing has the same or better performance for that kind of dimensioning to be meaningful. Even if that is the case, one can never prevent the water to exit through cracks and porosity in the bedrock instead, which means that the problem is not solved but only moved to another location of the BHE.

A high magnitude of pressure will also affect the collector system. In the Nordic countries the collector almost always consist of polyethylene pipes. Such pipes have a relatively low capability to resist external pressure loads compared to their ability to withstand internal pressures. A pipe that is designed to withstand 0,63 MPa internal load for 50 years can only take about 0,1 MPa if the pressure load acts externally on the pipe annulus, for the same period of time at the same temperature [11]. The latter value is based on the assumption that the pipe is perfectly round at start without any initial deformation, which never is the case in real applications, and that further lowers the resistance.

To secure both functionality and environmental safety in this manner is therefore not possible strictly speaking. Environmental impact in this respect consists of drainage of ground water reservoirs or water damage to property. A good compromise would be to test at 0,5 bars which should cover a great bunch of artesian waters as well as securing an expected life of more than 50 years for the collector system, with a safety factor of 2. Only 50 years are chosen here since that is the duration for which internal load resistance usually are guaranteed to within 97,5 % certainty according to EN ISO 9080:2003 [39].

Besides this the well top will always, at some point, be exposed to external hydrostatic pressure since it in most cases is located below ground level. However, the design of the well tops gives no indication regarding loss of sealing capability depending on which side the pressure is applied, why a single hydrostatic pressure load should be sufficient to evaluate the performance. The pressure level of 0,5 bars which equals 5 meter of water column should be enough in most applications and situations, including over flows.
4.1.3.2 Mechanical lift force

In colder climates, as in Sweden, freezing of the BHE is a phenomenon that is not very unusual. Temperatures well beyond the freezing point of water may occur in the heat carrier fluid circuit and the Swedish branch organisation Geotec has received reports of about 50 cases where complete freezing of the BHE has been observed [29].

The ice cover on the collector wall will induce lift which in turn may be transferred to the well top if the collector system is not anchored by fallen down material from the borehole walls.

Ice growth starts on the upper part of the collector, leading from the outlet of the evaporator. The layer than expands downwards, in the same direction as the flow of the heat carrier fluid, at the same time as the radial growth rate on the upper part decreases due to the thermal insulation caused by the ice layer.

Due to the geometry of the BHE and the collector, the radial expansion of the ice layer will be as illustrated in figure 4.2. Vertically, the thickness of the ice will decrease as depth increases, at least initially. Viewed in vertical segments the ice mass can be approximated by elliptic cones growing more and more circular with time. Far beyond this point, however, the ice in the upper parts would be in contact with the walls of the BHE, whereby the lift should be cancelled out due to frictional forces.

A reasonable assumption of a worst-case scenario would therefore be a weakly sloping cone throughout the entire length of the collector with $d_1 + d_2 < D$ as illustrated in figure 4.3.

Figure 4.2. Radial ice growth on collector system.

Figure 4.3 Simplified ice geometry during freezing of BHE’s.
The loss of volume using this simplified geometry should be outweighed by the fact that ice growth do not tend to appear along the total length of the collector but only on certain segments. This phenomenon has been discovered during dismantling of frozen BHE’s [28].

The volume of the ice ($V_{\text{ice}}$) may than be estimated as

$$V_{\text{ice}} = 2h_a \pi \left( \frac{1}{3} (r_1^3 + r_1 r_2 + r_2^3) - r_c^3 \right) \quad : (1)$$

where

$r_c$ = The outer radius of the collector pipe;
$r_1 = d_1/2$;
$r_2 = d_2/2$;
$h_a$ = The active depth of the BHE.

Assuming that the collector system is in mechanical equilibrium prior to the build up of ice, and the pilot weight barely having mass enough to weigh down the collector system, induced lift force ($F$) may be estimated incorporating Archimedes principle and (1) as

$$F = \left( \rho_w - \rho_{\text{ic}} \right) 2h_a \pi \left( \frac{1}{3} (r_1^3 + r_1 r_2 + r_2^3) - r_c^3 \right) g \quad : (2)$$

$\rho_w = \text{density of water (}\approx 1000 \text{ kg/m}^3\text{});$
$\rho_{\text{ic}} = \text{density of ice (}\approx 917 \text{ kg/m}^3\text{});$

$r_1$ and $r_2$ is restricted by $r_1 + r_2 < D/2$ and $d_1 = d_2 = 0.040 \text{ m}$. Another restriction is that $2(r_1 + r_2)$ must be less than the diameter of borehole at the transition between cased and uncased segments of the BHE.

The total depth of BHE’s seldom exceeds 200 m in the Nordic countries and active depths of more than 200 m are almost non-existent. Inserting $h_a = 200 \text{ m}$ in (2) and performing numerical analyses of the maximum value considering the restrictions specified above for the intervals of $r_1$ and $r_2$ accordingly, yields for the most commonly used casing dimensions the values specified in table 4.1 if the cased depth is less than 50 metres.

Fore comparison calculations of induced lift forces assuming ice cylinder with an outer diameter almost equalling the borehole diameter ($D_{bh}$) were conducted. This would be the absolute maximum ice volume that might occur, at least in theory due to reasons accounted previously if the diameter of the ice coat in the cased part of the BHE assumes to equal the ice coat in the rest of the BHE. The induced lift force may then be calculated using

$$F = \left( \rho_w - \rho_{\text{ic}} \right) h_a \left( \frac{\pi}{4} \left( D_{bh}^2 - (2r_c)^2 \right) \right) g \quad : (3)$$

Performing the calculations with input data as previously yields lift forces specified in table 4.1.
Table 4.1. Induced lift force when estimating ice coat as by equation (2) and (3) respectively.

<table>
<thead>
<tr>
<th>Outer diameter of casing [m]</th>
<th>Outer diameter of uncased borehole [m]</th>
<th>Induced lift force estimated as (2) [kN]</th>
<th>Induced lift force estimated as (3) [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.140</td>
<td>0.115</td>
<td>1.3</td>
<td>1.5</td>
</tr>
<tr>
<td>0.168</td>
<td>0.140</td>
<td>2.2</td>
<td>2.5</td>
</tr>
<tr>
<td>0.194</td>
<td>0.165</td>
<td>3.2</td>
<td>3.3</td>
</tr>
</tbody>
</table>

One should also bear in mind that the part of the collector being above the water table act as transmitter of the force, which might result in bending deformation before the lift reaches the magnitude of force specified above and thus causing the lift to cease. The risk of this to happen increase with increasing length of the transmitting elements, the duration of load, temperature and dimension of the collector etc.

Assuming the collector being of material quality MDPE 80 (SDR = 17), according to EN 12201-2 [38], the annual time of ice load 1000 h and the temperature 5 °C, yields a creep modulus of roughly 410 MPa derived from information given by [11] and [12]. Calculations indicate that deformation will occur within the annual time of load if the water table is below 1 m from the well top. A force of 3.3 kN requires a water table above 0.5-1 m which is not impossible, so the lift forces specified earlier still may be regarded as valid.

4.1.4 Sampling and preparation

The sampling procedure should follow agreement between the manufacturer/retailer of the test piece and the testing institute. Since some of the sealants tend to brake if reassembled the sample should preferably consist of at least two specimens to enable reassembling, or retesting, if necessary or at least comprise extra sealants.

Preparations of the test piece should not be necessary in general. In case preparations are necessary this should conform to recommendations from the manufacturer or retailer of the test piece.

It is also necessary to inspect the test piece before testing to reveal any injuries or other damage to prevent false results. If such injuries are detected a new test piece should be required.

4.1.5 Pre-conditioning

Since the method aims at testing specimens when assembled, prepared and pre-conditioned as intended in real applications, assuming this is the way they are used, any pre-conditioning should be in alignment with recommendations from the manufacturer or retailer of the test piece. However, this procedure should be recorded and specified in the test report or document containing the results.

If desired the test piece may be subjected to accelerated heat aging before test. In such cases should the temperature and time to use conform to at least 50 years of age. To calculate the temperature and exposure time an accelerating factor 2 per 0.2 °C elevated temperature may be used [32]. Of course the temperature should never be chosen such that melting or other damage of the test piece occurs.
4.1.6 Environment of test

The environment of test, i.e. surrounding air and pressurising fluid may not contain any pollution that might influence the results. Water should generally be regarded such a fluid.

Thermal influence on the results is regarded negligible in this context, as stated earlier, as long as the temperature span is reasonable. 10 – 30 °C may be regarded as reasonable. However, temperature fluctuations during test may not be of an extent that renders stability of pressure impossible to obtain.

4.1.7 Experimental work

4.1.7.1 Performed tests

Test of performance when subjected to a hydrostatic over pressure of 0,5 bars and a duration of one hour was performed on four specimens in order to evaluate the feasibility and applicability of the method. In an attempt to reveal the sensitivity of the results due to variations of mounting torque and surrounding temperature these parameters were altered during test of one specimen.

Test of resistance against lift force were performed on one specimen (type A according to section 1.2.3.1). The force were distributed evenly between the two pipes by means of equalizing the lengths between the attachment point to the tensometer, and the attachment points to the polyethylene pipes, as illustrated in figure 4.5. To investigate possible influence of uneven load distribution a test with lift distribution of 1:4 between the pipes was performed.

4.1.7.2 Test specimens

The tested specimens are presented in table 4.2. “Type” refers to specifications in section 1.2.3.1.

Table 4.2. Test specimens

<table>
<thead>
<tr>
<th>Denotation of specimen</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A:1</td>
<td>A (140 mm)</td>
</tr>
<tr>
<td>A:2</td>
<td>A (140 mm)</td>
</tr>
<tr>
<td>A:3</td>
<td>A (140 mm)</td>
</tr>
<tr>
<td>B:1</td>
<td>B (140 mm)</td>
</tr>
</tbody>
</table>
4.1.7.3 Equipment

4.1.7.3.1 Leakage performance when subjected to hydrostatic pressure

The test set-up is illustrated in figure 4.4.

![Experimental set-up when performing test of leakage resistance under hydrostatic pressure load.](image)

The pressure vessel consisted of a 600 mm piece of 5,0 x 197,3 mm steel casing with a steel sheet welded shut on the bottom. A frame made from metal profiles was attached to the bottom plate for connection of the assembly to the tensometer.

The polyethylene pipes used were 40 cm long 40 x 2,3 mm pipes (PN 6) with end caps in both ends and filled with water in order to minimise the pressure loss due to elastic compression.

The test pressure was measured with a Druck over-pressure gauge and an ordinary, manually handled pressurising pump was used to obtain the test pressure. The surrounding temperature and the temperature in centre of the pressure chamber was monitored using PT100 resistive temperature sensors.

The pressurising fluid was ordinary tap water and bolts, screws and hose clamps were fastened by usage of a calibrated dynamometric wrench.

The measured data were gathered and stored by a computerised data acquisitioning system.
4.1.7.3.2 Resistance against lift force

The casing and test piece where assembled to a tensometer as illustrated in figure 4.5.

![Figure 4.5. Experimental set-up during test of resistance against lift.](image)

The polyethylene pipes used were MDPE 80 40 x 3.0 mm (PN10) in order to resist the lift without much deformation. The end caps consisted of ordinary sleeve junctions equipped with taps for attachment to a connection device as illustrated in figure 4.6. The geometry around the connection to the hydraulic cylinder was generally kept symmetrical to ensure an even distribution of lift between the pipes.

![Figure 4.6. Connection between tensometer and polyethylene pipes. Observe; the unsymmetrical alignment of the equipment is due to no test being performed.](image)

4.1.7.4 Procedure

When assembling test pieces of type A the mounting screws where assembled with torques of 10 or 20 Nm. The torque was applied gradually in a shifting pattern between the screws in order for the well top to be aligned properly with the casing. Intervals of 5 Nm between each shift were used. Hose clamps of the type B specimen were tightened with a torque of 5 Nm (± 1 Nm) since higher torques caused damage to the hose clamps. If supporting screws were present these were tightened firmly against the case wall.
The pressurising fluid was tempered to the designated test temperature, i.e. the surrounding temperature, to within ± 3°C before testing to facilitate stability of pressure.

Specimen A:3 in table 4.2 where conditioned for a period of 24 h in water before testing in order for the sealant, consisting of Hydrotite rubber, to soak and swell. The specimen was assembled to the casing during the pre-conditioning.

The casing were freed of all oxidation at locations in contact with the test piece, and filled with water. All air present in the casing was evacuated. Thereby the test pressure was applied, smoothly and gradually in a period less than 30 seconds. The pressure was maintained for one hour or until leakage was observed.

4.1.7.5 Results

4.1.7.5.1 Leakage resistance test

The test results are summarized in table 4.3.

Table 4.3. Test results – leakage resistance

<table>
<thead>
<tr>
<th>Test</th>
<th>Specimen</th>
<th>Observation</th>
<th>Point of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A:1</td>
<td>Leakage</td>
<td>&lt; 5 kPa</td>
</tr>
<tr>
<td>B</td>
<td>A:2</td>
<td>Leakage</td>
<td>&lt; 10 kPa</td>
</tr>
<tr>
<td>C</td>
<td>A:3</td>
<td>Pressure loss</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>A:3</td>
<td>Pressure loss</td>
<td>-</td>
</tr>
<tr>
<td>E</td>
<td>B:1</td>
<td>Failure – separation from casing</td>
<td>40 kPa</td>
</tr>
</tbody>
</table>

Alarmingly enough only one of the tested specimens could withstand the hydrostatic pressure without apparent leakage, or failure, as specified in table 4.3. Specimen A:1 and A:2 started to leak at pressures as low as 10 and 5 kPa respectively, and one, the type B specimen, separated from the casing as a result of the pressure induced lift, at a test pressure of about 40 kPa. The failing specimens were reassembled with higher torque (if A-type: 20 Nm instead of 10 Nm) and the test repeated with no major effect on the results.

Specimen A:3 showed no visually detectable signs of leakage although a steadily decreasing test pressure showed otherwise. However, since no leakage could be detected even after an extension of the test period with over 13 hours the results were regarded as positive, even though the pressure continued to decrease until the test was finally terminated. One can never disregard the possibility of the pressure loss being caused by very small invisible leakage. No evidence that the leakage originated from the test piece could be discovered, which also was a contributing fact to regarding the test as positive. Test pressure and surrounding temperature during this test are plotted in figure 4.6. As can be seen in the figure the decline in pressure was about 6%. In test D the test piece was reassembled and the test repeated with almost identical result. However, the sealants at mounting screws had to be replaced before assembling.

Leaking specimens tends to show noticeable signs of leakage and rapid pressure loss, as can be viewed in figure 4.7 and 4.8, in short periods of time; in some cases almost instantly as the test pressure is applied.
As indicated in figure 4.6 the thermal mass of the pressure chamber shows to be sufficient to handle drastic changes in surrounding temperature without influencing the test pressure in any
major way, at least for shorter periods. It should thus be possible to test with relatively small deviations under normal conditions.

4.1.7.6 Resistance against lift

The results are presented in table 4.4. Gliding of the collector pipes occurred prior to any failure, i.e. separation between the test pieces and the casing. This also rendered investigations of sensitivity regarding load distribution fruitless.

Table 4.4. Test results – lift resistance

<table>
<thead>
<tr>
<th>Mounting torque [Nm]</th>
<th>Observation type</th>
<th>Point of observation [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Gliding</td>
<td>1,4</td>
</tr>
<tr>
<td>20</td>
<td>Gliding</td>
<td>1,6</td>
</tr>
</tbody>
</table>

4.1.7.7 Uncertainty of measured values

Estimated uncertainties of measured values are presented in table 4.5.

Table 4.5. Quality of results

<table>
<thead>
<tr>
<th>Measured value</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test pressure</td>
<td>± 0,009 bars</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>± 0,5 °C</td>
</tr>
<tr>
<td>Fluid temperature</td>
<td>± 0,3 °C</td>
</tr>
<tr>
<td>Torque</td>
<td>± 0,7 Nm</td>
</tr>
</tbody>
</table>

4.1.8 Conclusions

The method proposal (appendix A) is feasible to test performance of well tops when subjected to hydrostatic pressure and lift. Usually leakage appears in relatively short time after pressurisation why load duration can be kept short. Very small, invisible leakage may require detection by observing pressure loss instead. The importance of detecting these may however be argued, but they are unlikely to cause any environmental impact of importance and may thus be neglected.

The mounting torque did not seem to influence the results in any major way as long as the deviation where kept within reasonable limits. ± 1 Nm should thus be a sufficient accuracy.

After lift force test is terminated the assembly should be allowed to relax to enable some relaxation of the polyethylene pipes. If leakage occurs at this stage, originating from the through holes for the collector pipes, and no such observations have been done previously, the leakage should be disregarded since this might be an effect from gliding and contraction of the pipes.

To prevent separation of the test piece from the casing due to pressure-induced lift above those specified in table 4.1, the pressure used should be chosen so that conformity to these are obtained.
5 Cast case sealing

5.1 Introduction

The load of the case sealing is mainly hydrostatic pressure and thus the test parameters are quite obvious. The sealing should withstand a certain hydrostatic pressure load without leakage occurring. To imitate real applications the test piece should be assembled between a device imitating the borehole and a piece of casing conforming to national standards or regulations regarding casings in drilled wells. Deformations of the casing due to gravel load, differences in water table inside and outside the casing and fluctuations of temperature are neglected but to some extent incorporated indirectly in the proposal due to the pressure induced deformation during test.

The temperature is of particular importance during the cast process since it effects the hydration time of the sealing material. Low temperatures will generally slow down the hydration process and in some cases even stop it completely.

5.2 Scope and field of application

The scope of the test method proposal is to describe a way of testing sealing performance of cast case sealing in laboratory conditions by exertion of hydrostatic pressure in environmental conditions close to those found under ground. The test environment should be designed to be “a worst case” from the sealing point of view, based on real applications, within reasonable boundaries. A concrete block placed in an environmentally controlled surrounding act as fictional borehole. Due to practical reasons the sealing itself is shorter than it may be in real applications and effects resulting from that are neglected in the proposal. Certified and adequately educated personnel conduct the casting procedure in order to minimize influence on the result by this procedure itself.

The method proposal is focused on sealing where the grout is mechanically pressed out into the annulus of the casing but should also to some extent be feasible when using the principle of communicated vessels. The proposal does not require hydrating grouts to be feasible, why most types may be tested.

5.3 Evaluation of test parameters

5.3.1 Hydrostatic pressure

The main function of the case sealing is to act as water sealing between the interior of the BHE and the surface water and thus resulting in a hydrostatic load conforming to the difference in water level inside and outside the casing. The magnitude of the hydrostatic load is thus dependent on the depth of unconsolidated deposit, i.e. the length of the casing, static water level in the BHE and height of surface water column in the exterior.

In Sweden the depth of unconsolidated deposit may reach 200 metres at some locations but of course those are no places one would install a BHE. Economical considerations often restrict this depth, and BHE’s are seldom installed at locations with unconsolidated deposit depths of more than 30 metres. Considering that the static water level inside the BHE in most cases would comply with the water table present, which seldom is as deep as 30 metres, and assuming a surface water column conforming to the cased depth affecting the annulus of the casing and thus the case sealing, a test pressure of 3 bars should be sufficient for most situations. However,
since the water column pressure may be higher than that specified, and in most situations much lower, the test pressure may have to be altered in order to cover all possibilities and thus the specified pressure should only be regarded as a guideline value.

5.3.2 Environment

Ground temperatures are quite stable at some depth and in the Nordic countries, except Island, it normally lies within 3 – 15 °C at 100 m. At more shallow levels, where the case sealing normally is situated, the temperature will be influenced by the season, snow, solar heat flux etc. and is therefore harder to define. However, this effect is mainly focused to the top 6 metres of the soil below which the annual fluctuation amplitude is less than 1°C [18, pp 136] and should therefore be negligible in this application since casings shorter than 6 m should be very unusual as this is restricted by norms and standards regarding drilled wells [13, 17]. Neglecting this influence and assuming the thermal gradient to be about 1 – 1,7 °C/100 m in crystalline bedrock and 2 – 3 °C /100 m in sedimentary bedrock [18, pp 136] indicates that temperatures as low as 0 to 2 °C may be present.

As a worst-case scenario, considering the fact that most casings are longer than 6 m, a test temperature of 2 °C should be regarded as reasonable. And thus a thermally controlled environment will have to be used. As in the case with test pressure this may also be altered to fit specific applications and requirements.

The humidity in a BHE is likely to be substantial. Especially, of course, if the sealing is situated below the water table but also if not. Depending on the characteristics of the test piece the space in which the case sealing is cast should be water filled, or at least soaked with water, to mimic realistic conditions. If the test duration is kept relatively short no requirements of humidity of surrounding air should be necessary since influence from dehumidification should be negligible.

5.3.3 Preparations of test sample

To minimize influence on the test result due to human errors during the moulding of the test piece this should be done by sufficiently educated, competent and preferably certified personnel. The client who ordered the test should select these personnel to prevent dispute.

The preparation of the test piece, i.e. mix proportions, soaking, hydration time before test etc. should comply with recommendations from the manufacturer or retailer of the tested specimen.

5.3.4 Equipment

To test this component in laboratory environment obviously demands some kind of device simulating the borehole. Field-testing are possible but would mean to loose control over a large number of testing parameters that may render sufficient repeatability and comparability between tests impossible to obtain.

The device should be relatively cheap to construct and have qualities close to those found in real bedrock and thus concrete is a good substitute. However, the concrete will falsify the results somewhat than if natural rock is used due to difference in adhesion and material characteristics, but the feasibility and cost of test should requisite these restrictions.
Necessary equipment is illustrated in figure 5.1.

Concrete block
As described in section 5.3.4.1.

Casing
The casing should have the nominal dimension 139.7 x 5.0 mm and the length 1.5 metres. Any oxidation on the outer surface should be removed prior to test. The top end of the casing should be equipped with a flange to allow sealing of the inside. The cover flange should be equipped with an air release valve and connections for pressurisation and measuring device.

Pressure-measuring device
The pressure-measuring device should consist of a calibrated gauge capable of measuring over pressure or absolute pressure with accuracy better than ± 2 % of measured value. The measured value should be within the range of calibration.

Pressurisation equipment
The pressurisation equipment should be capable to exert the hydrostatic test pressure and to maintain it for the duration of the test. The accuracy of the device should be equal to, or better than the accuracy of the pressure-measuring device.

Thermal control system
A thermal control system is needed, consisting of a calorimetric chamber or equivalent, capable to induce and to maintain the test temperature for the duration of the test with accuracy equivalent to, or better than the accuracy of the temperature-measuring device. The chamber should be capable to receive the concrete block, test piece and any necessary equipment.

Temperature-measuring device
The temperature-measuring device should be capable to check conformity of test temperature with accuracy better than ± 1 °C. Sensors capable to measure surface temperature of the concrete block are also needed.
**Timer**
A timer to record the duration of test is needed. It should have accuracy better than $\pm 0.01 \text{ min}^{-1} 30 \text{ sec}^{-1}$.

**Data acquisition system**
Preferably the test data is collected by a data acquisition system capable to record the measured values. In such case should the sample time not exceed 60 seconds.

### 5.3.4.1 Concrete block

#### 5.3.4.1.1 Design and dimensions

A suitable design is illustrated figure 5.2.

![Concrete block design](image)

**Figure 5.2** design of concrete block.

#### 5.3.4.1.2 Dimensions

The length $h_1$ and width $d_2$ may affect the results of the test and should therefore be defined in the test method. Varying the casing diameter will not influence the result of the test, why the most usual dimension (139.7 mm) may be used at all times. Also smaller diameters of pipe may be used in order to lower the dimensions of the block, as long as they conform to national regulations, norms or standards regarding casing in drilled wells.

The gap between the casing and the bore is in practical applications between 0 – 10 mm depending on how worn the bore crown is [29]. From this point of view a small gap may have a negative influence on the performance of the sealing because of difficulties in getting a smooth and even distribution of the grout, why the gap should be made as small as possible. Also, this
simulates the possibility of the casing being off centre during the moulding process. A suitable
diameter of the centre hole should thus be 141 mm considering some thickness of grout is
necessary due to mechanical stress during test.

In real applications the amount of moulding material used is about 15 – 25 litres [29], which
gives theoretical lengths of the sealing far beyond practical values considering the gap being
smaller than 10 mm. The flow through a narrow crack is reciprocally proportional to the length
of the crack [1, pp 701] which indicates that leakage will occur no matter of length if there is a
crack present throughout the sealing and that this leakage will be noticeable as long as the test
pressure is sufficiently high. Furthermore, since only the lower part of the sealing that is
embedded in relatively homogeneous bedrock should be considered effective, using a short
length of the test sample should not falsify the test result strictly speaking, although the
possibility of such a crack to occur may be altered. In most cases the casing only stretches about
two meters into solid rock why a one-meter depth of the centre hole may be regarded as
relatively sufficient.

The casing will cancel out most of the pressure-induced stress. Assuming the block and the
casing being in contact, i.e. the test piece being completely rigid, and the deformation being
linear the hoop stress in the concrete, $\sigma$, is given by [34]:

$$\sigma = \frac{p(d_1 - 2t_c)}{(d_2 - d_1) + 2 \frac{E_{cb}}{E_c} t_c} \Rightarrow d_2 = d_1 + p(d_1 - 2t_c) - 2 \frac{E_{cb}}{E_c} t_c + \ldots$$

where

$p =$ test pressure ($\approx 3$ MPa);
$E_{cb} =$ the modulus of elasticity for the block ($\approx 30 000$ MPa);
$E_c =$ the modulus of elasticity for casing ($\approx 206 000$ MPa);
$t_c =$ thickness of the casing ($\approx 0.005$ m).

Assuming the concrete having a stress resistance of 1 MPa and using a safety factor 2 yields the
necessary block diameter $d_2 = 0.22$ m when solving (4). Because of possible strain during the
cast process itself the outer diameter of the block ($d_2$) is chosen somewhat larger, namely $0.3$ m.
The induced hoop stress is then $0.24$ MPa and the corresponding elongation $\varepsilon = 8.1 \times 10^{-6}$.

The axial stress being a result from the pressure induced end thrust should be cancelled out by
means of preventing elongation in this direction since this is not a naturally occurring load for
this component. The end thrust can be calculated using

$$F_x = p \frac{\pi(d_1 - 2t_c)^2}{4}$$

Performing the calculation yields $F_x \approx 4$ kN which will strain the test piece and thus will have to
be cancelled out. The device should be strong and rigid enough to withstand the thrust with
negligible elongation ($< 5 \%$ of critical elongation of the test piece material) in order to prevent
crack growth and unnatural strain.
5.3.4.1.3  Stress of test piece due to radial elongation of casing when subjected to internal pressure load

The test piece will experience stress during pressurisation that might induce crack growth and thus leakage in a non-natural manner.

A number of experiments and research projects have been conducted regarding effects of movements of casings on case sealants, among others by Goodwin and Crook [8] and Bosma et al. [4]. Among other things found was not surprisingly that low compressive strength cements (3 – 6 MPa) are more ductile and can better handle stress of this kind. This should obviously also comply with non-solid materials such as pure bentonite clay.

Assuming the test piece being a very brittle cement grout the modulus of elasticity may be estimated lower than 20 000 MPa [5, pp2] If the elastic elongation of the test piece equals the elongation of the casing and concrete block and this does not cause stresses that exceeds the tensile yield limit no major crack growth should occur. Inserting the elongation (ε) calculated in section 5.3.4.1 and modulus of elasticity $E = 20 000 \text{ MPa}$ assumed earlier in (6) yields the tensile strain $\sigma < 0.2 \text{ MPa}$ which should be far from enough to cause rupture for most materials. However, there is a possibility that ductile materials will benefit over brittle ones due to the nature of the method and should therefore be considered when performing test.

$$\sigma = E\varepsilon$$  \hspace{1cm} : (6)

5.3.4.1.4  Thermal stress in concrete block

The thermal stress during pre-conditioning and moulding procedure may be estimated [20] using

$$\sigma_r = \frac{\alpha E}{1 - \nu} \left[ 1 - \frac{d_2^2}{d_1^2 - d_2^2} \int \frac{rT(r)dr}{d_2^2 - d_2^2} - \int \frac{r'rT(r')dr'}{d_2^2} \right]$$

$$\sigma_\phi = \frac{\alpha E}{1 - \nu} \left[ 1 - \frac{d_2^2}{d_1^2 - d_2^2} \int \frac{rT(r)dr}{d_2^2} + \frac{1}{d_2} \int \frac{r'rT(r')dr'}{d_2} - T(r) \right] \hspace{1cm} : (7)$$

$$\sigma_z = -\frac{\alpha E}{1 - \nu} T(r)$$

$$T(r) = T(d_2) + \frac{T(d_2) - T(d_1)}{d_2 - d_1} (r - d_2)$$

where

$\sigma_r$ = Radial tension, MPa;
$\sigma_\phi$ = Hoop stress, MPa;
$\sigma_z$ = Axial stress, MPa;
\[ \alpha = \text{Thermal expansion coefficient (≈ 14*10^{-6} m/K)}; \]
\[ \nu = \text{Contraction coefficient, (≈ 0,2)}; \]
\[ T(r) = \text{temperature distribution as a function of radius, r}. \]

Assuming the temperature in centre of the block \( T(d_1) \) to be less than 40°C at all times and the distribution to be linear yields

\[ \sigma_r \approx r^{-2} - 5,983r + 1,867 \Rightarrow \sigma_{r,\text{max}} \approx 52\,\text{MPa} \]

\[ \sigma_\phi \approx r^{-2} + 6,054r - 8,117 \Rightarrow \sigma_{\phi,\text{max}} \approx 44\,\text{MPa} \]

\[ \sigma_z \approx 124,688r - 58,406 \Rightarrow \sigma_{z,\text{max}} \approx 21\,\text{MPa} \]

And thus the concrete should have a compressive strength yield limit higher than 52 MPa to prevent rupture. Since the yield limit normally takes long time effects in consideration, which is unnecessary here a stress resistance class of C50/60 according to SS-EN 206-1 [40] should be sufficient for this application.

5.3.4.1.5 Construction

The centre hole will have to be constructed during the cast process by usage of a casting mould consistent to the design of the centre hole. A guiding frame to ensure alignment of the hole and the centre axis of the block should be used during the construction of the block. To prevent the centrepiece and the concrete to stick, the centrepiece is rotated before complete solidification of the concrete sets in.

The block should be constructed at least 28 days prior to test in order for the concrete to obtain sufficient degree of stress strength. If storing the block is necessary the relative humidity should not exceed 85 % and the centre hole should be kept water filled to prevent dehydration.

5.3.4.1.6 Concrete quality

Based on the previous calculations the concrete should have the following characteristics.

- Modulus of elasticity: 30 000 Mpa or more.
- Compressive strength: 52 Mpa or more.
- Tensile strength: 1 Mpa or more.

To minimize the permeability of the concrete the water/cement ratio should not exceed 0,6 and the maximum nominal grain size of the bulk material should be kept sufficiently small, depending on capacity of pressurising equipment.

5.3.4.1.7 Pre-conditioning the block

The hydration rate of the test piece grout is normally, and partially, governed by the temperature present and thus this might influence the result. The block should therefore be pre-conditioned at test temperature before the test piece is cast.
The necessary pre-conditioning time to obtain test temperature throughout the block is determined by assuming the block to be a solid cylinder of radius \( r = 0.15 \) m, and thus neglecting heat transfer through the inner wall of the block. In reality the time \( \tau \) should be somewhat smaller than calculated due to this assumption.

The centre temperature \( T_0 \) may be approximated to within \( \pm 1 \% \) \[10\] by

\[
\frac{\theta}{\theta_i} = \frac{T_0 - T_\infty}{T_i - T_\infty} \approx C_{B,c} \exp \left( -A_{B,c}^2 \frac{\alpha \tau}{r_0^2} \right) C_{B,p} \exp \left( -A_{B,p}^2 \frac{\alpha \tau}{h_2^2} \right) \tag{8}
\]

where \( A_{B,c} \) and \( A_{B,p} \) are the solutions to

\[
A_{B,c} \frac{j_1(A_{B,c})}{j_0(A_{B,c})} = \frac{hr}{k} \tag{9}
\]

\[
A_{B,p} \tan A_{B,p} = \frac{hh_2}{2k}
\]

and \( C_{B,c} \) and \( C_{B,p} \) are defined as

\[
C_{B,c} = \frac{2}{A_{B,c}^2} \frac{J_1(A_{B,c})}{J_0(A_{B,c}) + J_1^2(A_{B,c})} \tag{10}
\]

\[
C_{B,p} = \frac{4 \sin(A_{B,p})}{2A_{B,p} + \sin(2A_{B,p})}
\]

\( T_i = \) Centre temperature at \( \tau = 0 \);
\( T_\infty = \) Surrounding temperature;
\( h = \) Thermal convection coefficient, W/m\(^2\)K;
\( k = \) Thermal conduction coefficient, \( \approx 2.1 \) W/m, K;
\( \alpha = \) Thermal diffusivity, \( \approx 9.5 \times 10^{-7} \) W/m, K;
\( J_0 \) and \( J_1 \) are Bessel functions of the first kind.

Since the block is not solid the temperature at \((r, h) = (0.08 \ m, 0.55 \ m)\) is calculated using

\[
\frac{\theta}{\theta_0} = \frac{T - T_\infty}{T_0 - T_\infty} = J_0 \left( \frac{2A_{B,c}r}{d_2} \right) \cos \left( \frac{2A_{B,p}h}{h_2} \right) \tag{11}
\]

The worst-case scenario is cooling only by natural convection. The convection coefficient, \( h \), may thus be estimated using \[9\]:

\[
h = 1.31(\Delta T)^{1/3} \tag{12}
\]
where $\Delta T$ is the average temperature difference between the surface and the surrounding air during the time $\tau$. Performing the calculation yields $h \approx 3.0 \text{ W/m}^2\text{ K}$.

Solving (8) and (9) yields $A_{B_c} = 0.635, A_{B_p} = 0.786$ and thus $C_{B_c} = 1.081, C_{B_p} = 1.100$. Inserting these constants in (8) and (11) and performing the calculation for varying times $\tau$ yields temperatures $T$ as accounted in table 5.1 assuming $T_i < 25 \, ^\circ C$.

Table 5.1 Temperature $T$ as function of pre-conditioning time $\tau$ at location $(r, h) = (0.08 \, \text{m}, 0.55 \, \text{m})$ from centre of the block.

<table>
<thead>
<tr>
<th>Time of pre-conditioning ($\tau$) [h]</th>
<th>$\theta_0/\theta_i$</th>
<th>$T_0$ [$^\circ C$]</th>
<th>$T$ [$^\circ C$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>12</td>
<td>0.52</td>
<td>14.0</td>
<td>10.2</td>
</tr>
<tr>
<td>24</td>
<td>0.23</td>
<td>7.3</td>
<td>5.6</td>
</tr>
<tr>
<td>36</td>
<td>0.10</td>
<td>4.3</td>
<td>3.6</td>
</tr>
<tr>
<td>48</td>
<td>0.05</td>
<td>3.0</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Due to the uncertainty when deciding the heat convection coefficient, the pre-conditioning time $\tau$ should be chosen somewhat longer, namely 60 h. Since the heat transfer in reality most likely consists of both free and forced convection a pre-conditioning period of 60 h should be sufficient to ensure test temperature throughout the concrete with some marginal.

5.3.4.1.8 Hydration heat

Since the hydration rate is influenced by temperature the produced heat during hydration of the test piece will have to be cooled off. The most unbeneficial situation for the test piece is a high heat transfer rate since this minimizes the temperature. In real applications the heat transfer is constituted by heat conduction to the surrounding bedrock and thus defined by the heat conduction coefficient of the bedrock. Typical heat conduction coefficients for various kinds of material are presented in table 5.2.

Table 5.2. Typical heat conductions for various kinds of material [7, pp18].

<table>
<thead>
<tr>
<th>Material</th>
<th>Heat conduction [W/m,K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>2.3-6.5</td>
</tr>
<tr>
<td>Limestone</td>
<td>1.5-3.3</td>
</tr>
<tr>
<td>Shale</td>
<td>1.5-3.5</td>
</tr>
<tr>
<td>Metamorphic rock</td>
<td>2.5-6.6</td>
</tr>
<tr>
<td>Concrete</td>
<td>1.7-2.4</td>
</tr>
</tbody>
</table>

The table indicates the thermal conductivity in general to be higher in rock than in concrete and thus the temperature might get unnaturally high. However, heat conduction in the concrete should be greater than 2.1 W/m, K due to it being relatively young and further; if the surface temperature of the block and the casing is kept constant as close as possible to test temperature during the heat release, any influence due to elevated temperatures is kept at a minimum. Especially since the amount of test piece material is much less than in real applications and since the temperature at the outer diameter of the concrete block when viewed in real applications should increase and thus decreasing the heat transfer.
If very small amount of grout, with low heat emitting, is used it might even be necessary to reduce the heat transfer in order to imitate realistic conditions. This is however neglected here.

5.4 Procedure

The test procedure should comprise the following steps:

1. Pre-conditioning of the concrete block to ensure test temperature throughout it as described previously. The surface of the centre hole should be prevented to dehydrate by means of keeping it water filled until the sample is cast.
2. Moulding of the test piece by competent personnel in accordance with recommendations from the manufacturer or retailer of the test piece. The block may have to be removed from the thermally controlled environment to enable this procedure. Hydration heat should be cooled off by means of keeping the surface temperature constant on the block and casing.
3. Exertion of test pressure. Air should not be present in the casing. The equipment and test piece should be monitored for any signs of leakage. If leakage occurs the test should be terminated.

5.4.1 Duration of test

The duration of the test should be sufficient to reveal visibly detectable leaks even from very narrow cracks (≈ 0.05 mm) in the test piece. The flow through a narrow gap with parallel and smooth walls may be expressed as:

\[ q = \frac{\Delta p l w^3}{12 \eta t} \]  \hspace{1cm} : (13)

where

- \( q \) = Flow rate, m³/s;
- \( \Delta p \) = Pressure, (0.3 MPa);
- \( \eta \) = Dynamic viscosity, (1.67*10⁻³Ns/m² @ 2°C);
- \( t \) = Depth of gap, m;
- \( l \) = Length of gap, m;
- \( w \) = Width of gap, m;

Since a crack in the test piece is not likely to be smooth only half the width \( w \) should be used [1, pp 701] when performing the calculation.

Assuming a crack in the test piece with a depth of 1 m, a width of 0.05 mm and length 1 mm yields a volume flow rate of 1.87*10⁻¹⁰ m³/s or 8.4*10⁻⁴ dm³/h. And thus test duration of 1 h renders a leakage volume of almost 1 centilitre that should be sufficient if the test piece is monitored regularly during test.

5.4.2 Rejection of results

The result should be rejected if leakage occurs with indefinite source, i.e. when uncertainty whether leakage originates from the test piece or from cracks in the concrete block close to the test piece exist.
5.5 Uncertainty and applicability

The applicability and accuracy of the method proposal to reflect real applications are hard to predict. Many factors would have to be investigated to obtain a meaningful definition regarding this, since many factors may influence. These might be errors during cast of the test piece, inadequate monitoring for leakage, usage by concrete as fictional borehole etc. that also might influence the repeatability of the test. This has thus not been investigated sufficiently here, although no apparent indications of this kind of influence have been discovered during the evaluation.

The uncertainty of test pressure, as well as temperature, is governed by the uncertainty of the device used and the stability of these parameters during test. If demands of stability and accuracy of pressure measuring device are met, according to the proposal in appendix B, and their contributions to the total uncertainty is regarded as normally distributed and independent from each other, the uncertainty may be estimated as

\[ U = k \sqrt{u_g^2 + u_s^2} \] : (14)

where

\[ U = \text{Total expanded uncertainty} \quad (k = 2); \]
\[ u_g = \text{Uncertainty contribution due to accuracy of gauge}; \]
\[ u_s = \text{Uncertainty contribution due to deviations of pressure during test, i.e. the standard deviation of individual values.} \]

Performing the calculation, with demands of stability and accuracy as stated earlier, the expanded uncertainty should be of less than ± 7 kPa and ± 1 °C.

5.6 Conclusions

Even though the method proposal (appendix B) has not been evaluated by experimental work it should be sufficient and feasible to test performance of cast case sealing as long as the restrictions set by the proposal can be accepted. There are however some unsolved issues:

1. If influence from using steel pipes instead of a concrete block is negligible pipes may be used whereby the time consumption of test may be shortened drastically.
2. A correlation to transfer test results to different types of rock with respect of differences of adhesion for different materials should be developed in order for the results of tests to be transferred to real applications.
3. Ability of the method to reflect real conditions should be evaluated.
4. Influence on test results of case gap width, test temperature, human competence when casting the test piece to evaluate repeatability.

Any future work may thus be focused on these parameters, which should require extensive investigations and experiments to get a satisfactory solution. The ability of the method to reflect real applications is as mentioned previously hard to predict since the human factor and many other aspects may render a vital influence on the performance. However, by stating the preparation procedure in conjunction with reporting test results and by using personnel with required competence this problem should be cancelled out to some extent.
6 Performance of non-cast case sealing and plug sealing

6.1 Introduction

The load of the non-cast case sealing and plug sealing is mainly hydrostatic pressure and thus the test parameters are quite obvious. The sealing should withstand a certain hydrostatic pressure load without leakage occurring. To imitate real applications the test piece should be assembled in a device imitating the borehole and/or a piece of casing conforming to national standards or regulations regarding casings in drilled wells.

Due to the similarities of function and to some extent design of plug sealing and non-cast case sealing the performance test of these are incorporated into the same method proposal and are presented in appendix C.

6.2 Scope and application

The scope of the test method proposal is to describe a way of testing sealing performance of plug sealing and non-cast case sealing when subjected to hydrostatic pressure. The principle of the test is to subject the test piece to hydrostatic pressure whilst monitoring it for any signs of leakage. During test the test piece is assembled conforming to it’s intended use. The thermal environment during test should be close to that found in real applications and controlled by a thermal control system. The borehole is simulated by usage of steel pipes or concrete block depending on type of test piece.

Since most sealing of this kind are similar in design the method proposal should be sufficient to test a majority of models present. The size of the test piece should thus be small enough to achieve feasibility of handling and performing the test.

6.3 Evaluation of test parameters

6.3.1 Hydrostatic pressure

The hydrostatic pressure for non-cast case sealing conforms to the load specified in section 5.3.1 since the function and thus the load is identical.

A plug sealing will endure hydrostatic pressure load consistent to the difference of pressure between the aquifer that is intended to be sealed off and the surrounding aquifers in conjunction to the BHE. As mentioned previously the possible magnitude of pressure in aquifers are hard to quantify, theoretically, since it depends on the surrounding topography, the bedrock and the surrounding ground water table.

If the collector is subjected to the hydrostatic pressure due to the design of test piece concerns regarding compressive collapse of the collector should be taken. And thus the test pressure should be less than 0.5-1 bar depending of collector type, i.e. resistance against external load. If the test piece design prevents the collector from being subjected to the load a pressure level of 3 bars, conforming to a hydraulic head of 30 m should be enough for most situations. These values should, however, be regarded as guideline values since the actual pressure in an aquifer may both be higher or lower than specified here. The actual test pressure to use may thus be
selected differently depending on design and intention of the test performed. If pressures higher than 3 bars are used it is important though that considerations concerning influence due to elastic deformation of the test equipment, as well as adjusting dimensions of the device are made to withstand the pressure.

6.3.2 Environment of test

The environment of test consists of the pressurising fluid and the equipment that simulates borehole, i.e. their temperature and chemical composition. Influence of biological composition may be regarded as negligible if a relatively short duration of test is emphasised.

The need to test at low temperature is dependent on the properties of the test piece, such as samples with swelling rubber sealants (Hydrotite) since the rate of swelling has showed to be influenced by temperature. Four pieces of Hydrotite, from the same batch of material, of which two were submerged in water at about 20°C and two in water at 2°C for about 30 hours. The pieces soaked in the colder water showed a lack in volume expansion consistent to 34 % in relation to the other pieces. Whenever influence of temperature may be suspected the value specified in section 5.3.2 should be emphasised as in the case with cast case sealing. The temperature of the pressurising fluid and any device in contact with the test piece during test should then conform to the designated temperature. Influence due to thermal expansion is on the other hand negligible because of the relatively low temperature span present.

Also the humidity of concrete in contact with the test piece may be of interest. Since the water content under ground is likely to be substantial as stated previously the concrete in the mentioned areas should be prevented to dehumidify before testing. This may preferably be done by keeping the centre hole water filled during the time between construction of the block and casting of the test piece. If the test piece is a cast plug sealing, the device in which it is intended to be mounted should be filled with water to mimic casting beneath the water table.

The pressurising fluid should be water. If the test piece is a plug sealing and the client who ordered the test do not advise otherwise, the water should have a salinity content of 3,5 % mixed as NaCl in water to simulate influence due to salinity when sealing off seawater aquifers. Hydrotite, as an example, looses drastically in expansion when exposed to saline water - about 85 % showed by experiments [6, pp27]. The saline water should also be used during any pre-conditioning. The specified saline concentration may appear in relatively saline oceans, such as the Atlantic [24], and is also the concentration denoted “standard sea water” although comprising a great number of components that are left out here for simplicity of the method since they are unlikely to influence the test results.

6.3.3 Sampling and preparation

The sample should consist of at least one of the specimen intended to be tested. The sample should be taken from the ordinary production line in agreement with the manufacturer/retailer and the testing institute. Preferably two randomly chosen samples should be taken to enable retesting if necessary.

The test piece should be prepared in accordance with specifications from the manufacturer or retailer of the specimen to be tested.

Preparation of test sample may consist of:

1. Soaking time of expanding sealants;
2. Hydration time of cast plug type sealing;
3. Mixing proportions of cast grout;
4. Other pre-test procedures necessary to obtain function of test piece.

The time lap between testing and preparation should be kept to a minimum when testing cast sealing to prevent influence of dehumidification. In case storing of prepared samples is necessary, precautions to prevent dehydration should be taken.

6.3.4 Pre-conditioning

6.3.4.1 Pre-conditioning of concrete block and steel pipes

The time to achieve test temperature throughout the concrete block \( \tau \) specified in section 5.3.4.1.7 is estimated sufficient also in this application.

Pre-conditioning of steel pipes may be estimated using lumped capacity method due to the relatively thin wall thickness. This yields the pre-conditioning time 1 hour if any fluid present is assumed to be pre-cooled to the designated temperature.

6.3.4.2 Pre-conditioning of test samples

Pre-conditioning of grout should conform to recommendations from the manufacturer. Directions regarding temperature of mixing water should comply with these recommendations. Due to the low test temperature casting grout may have to be pre-heated to obtain sufficient hydration. Since the pre-conditioning in this context may affect the results the actions taken should be recorded and stated in the test report.

For plastics test pieces pre-conditioning is not necessary unless the manufacturer advise otherwise. However, the test piece may be aged by means of accelerated aging in an oven or similar device before assembled if applicable, to evaluate long term performance. In such cases should the temperature and time to use conform to at least 50 years of ageing. To calculate the temperature and exposure time an accelerating factor 2 per every 0.2 °C elevated temperature may be used [33]. Of course the temperature should never be chosen such that melting or other damage of the test piece occurs.

Soaking of test pieces should be done using thermally regulated fluid at test temperature since this may affect the swelling, as stated previously. Further salinity or acidity defined in section 6.3.2 should be present in the fluid.

6.3.5 Equipment

Device simulating the borehole will be required when performing test. To facilitate the test the design of the device will have to be altered depending on type of test piece, i.e. cast plug sealing, case sealing and non-cast case sealing as specified in section 6.3.5.1.

Pressure-measuring device

To measure conformity of test pressure a gauge for measurement of over- or absolute pressure should be used. The gauge should be calibrated and the range of the gauge should be such that the measured value lies within the range of calibration. The accuracy should be better than ± 2 % of measured value.
**Pressurising equipment**

The pressurising equipment should be capable to induce the test pressure and to maintain it for the duration of the test to within \( \pm 2\% \) of set value. Since it may be difficult to achieve sufficient water tightness in concrete block the equipment used should have a relatively high capability of maintaining the pressure within the specified boundaries.

**Thermal control system**

A thermal control system consisting of a calorimetric chamber, or equivalent, capable to induce and to maintain the test temperature for the duration of the test with accuracy equivalent to, or better than the accuracy of the temperature-measuring device. The chamber should be capable to receive the test piece and necessary apparatus.

**Temperature measuring device**

Capable to check conformity of test temperature with accuracy better than \( \pm 1 \) °C. Sensors capable of measuring surface temperature on concrete block are needed.

**Timer**

A timer to record the duration of the test with accuracy better than \( \pm 30\) s.

**Data acquisition system**

Preferably the test data is collected by a data acquisition system capable to record the measured values. In such cases should the sample time not exceed 60 s.

**6.3.5.1 Cast plug sealing**

If the material of the test piece is cement or a cement mixture, such as cement/bentonite, cement/sand etc. a concrete block should be used similar to that described in section 5.3.4.1. This is due to the adhesion between rock/cement and concrete/cement being somewhat similar and thus yielding relatively realistic conditions. The set-up is illustrated in figure 6.1 and an alternative set-up may be viewed in figure 6.2.

![Figure 6.1. Set up of equipment when testing cast plug sealing. i.e. hardening, cast plug sealing.](image-url)
The choice of set-up is governed by the design of the test sample and of its intended use. If the sample consists of non-hydrating material such as pure bentonite a metal pipe may be used to reduce cost and time consumption of test.

6.3.5.1.1 Dimensions

The diameter of the centre hole is not likely to affect the results of the test. However it should be large enough to receive any components belonging to the test piece and the collectors. Assuming the concrete block being a thick cylinder with the inner diameter \( d \) and the outer diameter \( D \) the stress may be calculated as [19]:

\[
\sigma_r = \frac{p}{1 - \kappa^2} \left( 1 - \frac{D^2}{4r^2} \right)
\]

\[
\sigma_\varphi = \frac{p}{1 - \kappa^2} \left( 1 + \frac{D^2}{4r^2} \right)
\]

where

\( \sigma_\varphi \) = Hoop stress (MPa);

\( \sigma_r \) = Radial stress (MPa);

\( \kappa = \frac{d}{D} \);

\( p \) = Test pressure (MPa);

Inserting the most commonly used diameters of BHE’s as diameter of centre hole, i.e. 0.115, 0.140 and 0.165 m [25] and assuming \( \sigma_\varphi < 0.5 \) MPa; \( \sigma_r < 0.5 \) MPa yields outer diameters as specified in table 6.1.

Table 6.1. Outer diameter of concrete block

<table>
<thead>
<tr>
<th>Diameter of centre hole [m]</th>
<th>Outer diameter of concrete block [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.115</td>
<td>0.24</td>
</tr>
<tr>
<td>0.140</td>
<td>0.28</td>
</tr>
<tr>
<td>0.165</td>
<td>0.34</td>
</tr>
</tbody>
</table>
Since the collector system normally would cancel out part of the pressure-induced lift the polyethylene pipes should be supported to prevent vertical movement. The device used should cancel out any lift up to 2,1 kN, conforming to the long term allowable tensile stress in a collector system assuming polyethylene pipes: SDR = 17 and MRS = 4,8 MPa.

The length of the centre hole should be 1 meter.

6.3.5.2 Case sealing

In case of the test piece is a case sealing, the device may consist of metal pipes designed as illustrated in figure 6.3. The pipes should conform to standards specified in national norms or regulations, regarding casings of BHE’s. In Sweden this would mean material ST37 according to DIN 1626 [37]. If preferred the borehole sealing may be tested by usage of a concrete block. In that case the height of the block can be reduced.

![Figure 6.3. Set-up of equipment when testing case sealing.](image)

The dimension of the larger pipe, i.e. simulating the casing, should conform to the nominal diameter of casing for which the test piece is intended to be used. The inner diameter (d) of the pipe simulating uncased borehole, should be calculated as

\[ d = d_p + 0.010 \]  

where \( d_p \) is the nominal dimension of borehole conforming to the intended use of the test piece in metres. The length of the pipes is dependent on the length of the test piece but should be long enough to allow assembling of the test piece and connections to pressurising and measuring device as described in figure 6.3.
6.3.5.3 Non-cast plug-sealing

For non-cast plug sealing metal pipes may be used, as illustrated in figure 6.4. The dimensions and steel quality should conform to specifications in section 6.3.5.2.

![Diagram of equipment set up for testing double and single plug sealing](image_url)

Figure 6.4. Set up of equipment when testing double plug sealing (left) and single plug sealing (right).

6.4 Procedure

The procedure of test should consist of:

1. Pre-conditioning and preparation of equipment and samples according to section 6.3.4. If hydration heat is formed this should be evacuated as specified in section 5.3.4.1.8.
2. Removal of any redundant water that might render detection of leakage difficult.
3. Removal of any air in the pressurized spaces of the equipment.
4. Pressurisation for 1h. During this period the apparatus and test piece are monitored for any signs of leakage and pressure loss. Collector pipes should be supported so that any longitudinal force of magnitude specified in section 6.3.5 is cancelled out. If leakage is observed the test should be terminated.

6.4.1 Rejection of results

If separation occurs due to failure in supporting the device and test piece according to section 6.3.5, and this causes leakage that was not observed before separation, the result should be rejected.

6.5 Experimental work

Two tests were performed to evaluate the feasibility of the method proposal:

A. Leakage test of non-cast case sealing;
B. Leakage test of bentonite plug sealing;

To keep cost of the tests down they were not performed in a thermally controlled surrounding. This was however not crucial for the aim of the experiments.
6.5.1 Test pieces

The test pieces conformed to table 6.2.

Table 6.2 Test pieces.

<table>
<thead>
<tr>
<th>Test</th>
<th>Description of test pieces</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A non-cast case sealing made from polyethylene plastics of dimensions: casing: 0,196 m; borehole: 0,165 m with Hydrotite sealants..</td>
</tr>
<tr>
<td>B</td>
<td>A plastics plate fused to four pieces of polyethylene pipes. The outer diameter of the plate was 0,14 m. The grout consisted of bentonite pellets soaked in water. The length of the sealing was 0,21 m.</td>
</tr>
</tbody>
</table>

6.5.2 Experimental set-up

The experimental set-up for test A and B is illustrated in figure 6.5.

Figure 6.5. Experimental set-up. Test A to the left and test B to the right.

The equipment and sensors used are presented in table 6.3.

Table 6.3. Equipment and sensors.

<table>
<thead>
<tr>
<th>Measured value</th>
<th>Sensor</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surrounding temperature</td>
<td>PT100</td>
<td>± 0,5 °C</td>
</tr>
<tr>
<td>Temperature of fluid</td>
<td>PT100</td>
<td>± 0,3 °C</td>
</tr>
<tr>
<td>Test pressure</td>
<td>Druck, over pressure gauge</td>
<td>± 0,009 bars</td>
</tr>
</tbody>
</table>

The steel pipe consisted of pieces of casing welded shut at bottom in conformity to section 6.3.5.2 with diameters 0,140 (test B) and 0,194 (test A) metres respectively. The polyethylene pipes were sealed in both ends and filled with water in order to minimize influence from elastic deformation. Their dimension and strength was SDR 13,6 (PN 10) conforming to EN 12201-2 [38].

Data was gathered by a computerized acquisitioning system. The pressurising fluid as well as the fluid used during pre-conditioning was ordinary tap water.
6.5.3 Procedure of test

6.5.3.1 Test A

The test piece was assembled to the casing that was filled with water. The test piece was left to pre-condition for a period of 24 h. During this time precautions to keep the sealants completely soaked was taken. The arithmetic mean of the water temperature was 17 °C during the pre-conditioning.

Thereby all surplus water was removed from the visible parts of the test piece and steel casing. The polyethylene pipes were secured to the steel pipe by attaching a well top on their upper part, secured to the casing by usage of firmly tightened straps. The mounting torque applied on the screws were adjusted to cancelled out any lift up to 2,1 kN.

The designated test pressure was 3 bars above atmospheric.

6.5.3.2 Test B

The bentonite pellets and casing was submerged in a water tank for a period of 12 h until smooth clay was obtained. The arithmetic mean of the water temperature was 12 °C during this period.

To enhance the ability to detect leakage the test piece were left to dry somewhat until a crust was formed on the upper layer of bentonite. The polyethylene pipes were secured to the steel pipe by means of attaching a well top on their upper part, secured to the casing by usage of firmly tightened straps. The mounting torque applied on the screws were adjusted to cancelled out any lift up to 2,1 kN.

The designated test pressure was 3 bars above atmospheric.

6.5.4 Results

The results together with arithmetic means of measured data are summarized in table 6.4.

<table>
<thead>
<tr>
<th>Test</th>
<th>Surrounding Temperature [°C]</th>
<th>Temperature of fluid [°C]</th>
<th>Observation</th>
<th>Point of observation [bar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>16,8</td>
<td>17,8</td>
<td>Leakage</td>
<td>1,04</td>
</tr>
<tr>
<td>B</td>
<td>16,9</td>
<td>17,9</td>
<td>Leakage</td>
<td>0,07</td>
</tr>
</tbody>
</table>

As presented in table 6.4 both test pieces failed before the designated test pressures were obtained. For specimen A however, the leakage originated from the sealants against the collector pipes and not through the case sealing itself, why the results should be disregarded. This leakage made it impossible to obtain and maintain the designated test pressure. Thus the set-up of test equipment needs to be altered to avoid this kind of mishap in the test method proposal. A suitable set-up may be viewed in figure 6.3.

For specimen B, on the other hand, leakage occurred through almost any location possible at an over pressure of less than 0,07 bars. Perhaps, but not likely, should this specimen have benefited from usage of a longer bentonite plug.
6.5.5 Conclusions

Since failure occurred early in both tests the evaluation of the proposal may not be regarded as complete. However, leakage showed to be easily detected in both tests and nothing indicated that performing test according to the test method proposal (appendix C) should be insufficient in respect of determining sealing performance of these kind of components when subjected to hydrostatic pressure. Usage of a concrete block instead of steel pipes would render the test more difficult but not impossible.

If test pressures are adjusted to fit the test piece according to section 6.3.1 influence of elastic compression of test piece and expansion of the equipment should be neglectable. It is also important to prevent separation of the test piece from test equipment as stated earlier since this might cause leakage to occur.

The ability of the method to mimic real applications is considered to be relatively good, although some restrictions exist, such as material of test equipment. If influence from using steel pipes may be showed to be negligible, these may be used instead of a concrete block, whereby the time consumption of test may be shortened drastically.

A correlation to transfer test results to different types of rock with respect of differences of adhesion for different materials if cast test piece, may if necessary be developed in order for the results of tests to be transferred to real applications. Extensive investigations and experiments may be performed regarding influence on test results of test temperature, human competence when casting the test piece in order to evaluate the repeatability of the method proposal.
7 Collector pipes subjected to external hydrostatic pressure

7.1 Introduction

The capability of a plastics pipe to resist external hydrostatic load is much lower than if the load is exerted internally. A pipe that is designed to withstand 0.63 MPa (PN6.3) internal load for 50 years can only take approximately 0.1 MPa if the load acts externally for the same period of time at the same temperature [11, pp 150].

External over pressure may occur in BHE’s due to difference in density between the heat carrier fluid and the surrounding water, when high-pressure aquifers are sealed off and to some extent when grouting of other fluid material than water such as cement grout or bentonite, although this only can be compared to hydrostatic pressure before the solidification sets in.

The most common heat carrier fluid today is ethylene alcohol with a typical density of about 970 kg/m³. Assuming a 200 m deep well with a ground water level at 1 m matching a heat pump of about 12-13 kW heat, yields a net external pressure of about 0.5 bars at bottom of the well. L-E Janson [11] has derived an expression to calculate pressures of collapse due to external hydrostatic load, i.e. buckling pressure, as

\[ P_b = \frac{2E}{(1-\nu^2)SDR^2} \]  : (15)

where

E = Creep modulus of the pipe material;
\( \nu \) = Contraction coefficient (0.45 when PE);
SDR = Standard Dimension Ratio;

Performing the calculations for different standard dimension ratios (SDR’s) and loading times (\( \tau \)) yields results presented in table 7.1. The creep modulus are derived according to [16, pp 3.17] and [12].

Table 7.1. Buckling pressure at different load durations and pipe dimensions calculated according to (15).

<table>
<thead>
<tr>
<th>SDR</th>
<th>( P_b(\tau = 100 \text{ h}) ) [bar]</th>
<th>( P_b(\tau = 10000 \text{ h}) ) [bar]</th>
<th>( P_b(\tau = 50 \text{ years}) ) [bar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.6</td>
<td>1.4</td>
<td>1.2</td>
<td>1.06</td>
</tr>
<tr>
<td>21</td>
<td>1.3</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>26</td>
<td>0.44</td>
<td>0.37</td>
<td>0.3</td>
</tr>
</tbody>
</table>

The calculations indicate that the risk of buckling from density difference alone should be rather slim, given that most collector pipes used presently have a standard dimension ratio of about 17. The calculations, however, assume a perfectly round pipe without any initial deformation, which never is the case in real applications. Just one percent ovality will lower the stress resistance with almost 35 % [11, pp151] and thus buckling may be considered a real risk in some situations since 1 –1.3 % ovality is considered acceptable for a standard pipe according to EN 12201 – 2 [38].
If the BHE is equipped with some sort of sealing that seals off an artesian aquifer the risk of buckling obviously increases, since the induced pressure will have to be added to the effect from density difference.

The method proposal thus enables optimisation possibilities of collector pipes regarding heat transfer and durability.

7.2 **Scope and field of application**

The scope of the method proposal in appendix C is to describe a way to test the resistance of collector pipes against external hydrostatic pressure at constant temperature. The method should apply to collectors consisting of plastics pipes since this is the most common type used today. The main principle of the test method proposal is to exert hydrostatic pressure externally of the test piece(s) and determining buckling by:

- a) Sudden decrease of test pressure;
- b) Measurement of volume decrease of the test piece.

The method should be able to determine:

- a) Critical hoop stress at a given temperature and load duration;
- b) Time for collapse, i.e. buckling at a given temperature and load.

The method should also be usable to obtain input data for estimations of long-term load resistance.

7.3 **Evaluation of test parameters**

7.3.1 **Test pressure**

A designated compressive tension is to be applied during test. The conforming pressure \( p \) may be estimated using the ISO-equation [15, pp 15], i.e.

\[
p = 2\sigma_c \frac{s}{D_s - s} : (16)
\]

where

- \( \sigma_c \) = designated compressive tension or hoop stress of the material (MPa);
- \( s \) = minimum wall thickness of the pipe measured according to EN ISO 3126 [35], (mm);
- \( D_s \) = mean outer diameter of the pipe measured according to EN ISO 3126 [35], (mm);

7.3.2 **Sampling**

The samples should be taken from the ordinary production line in agreement with the manufacturer, retailer and the testing institute. A number of three or more samples should be tested to achieve a mean value of the results. A scatter of the results will always be obtained due to inhomogeneous material in the tested series, differing imperfections such as ovality in the test pieces and imperfect testing situations. A big scatter of individual values needs more samples to secure the quality of result.
The samples should all come from the same batch of material and the same extrusion run.

If the intention of test is to estimate long term stress resistance the sampling should conform to a number of specimens that enable estimations with 97.5% statistical confidence.

7.3.2.1 Test piece

The test specimen should consist of straight pipe with a mean outer diameter \( D_s \), wall thickness \( s \) and free length \( l \). Free length of the test piece is in this context defined as the length of the pipe exposed to the test pressure whilst unsupported by couplings or other device used for mounting of the test piece to the testing device. Coupling sleeves and similar components will influence the test result if \( l \) is too short.

Assuming the pipe is free to move lengthwise the buckling pressure of a pipe with a free length \( l \) (\( p_{bl} \)) may be expressed as [11, pp 151]:

\[
p_{bl} = \frac{2,2s\sqrt{E}}{l} \sqrt{p_b}
\]

\[
\frac{1,56s}{(s/D_m)^{1/2}} \geq l > 4\sqrt{\frac{sD_m}{2}}
\]

where

\( p_b = \) Buckling load for a long unsupported pipe (0.107 MPa);
\( E = \) Modulus of elasticity (230 MPa);
\( D_m = \) Mean diameter of pipe (37.6 mm);
\( s = \) Wall thickness of the pipe (2.4 mm).

Performing the calculation yields \( P_{bl} = 0.113 \) MPa and thus the influence is about 6%, which should be considered too high for this application. Plotting (17) as a function of \( l \) and performing regression analyses reviles that a free length of 7 times the outer diameter, in this case 280 mm should be sufficient since the influence would be close to 0% which further is supported by [20, pp6].

7.3.3 Pre-conditioning

The pre-conditioning periods specified in EN 921 [36] should be sufficient to use when performing the test according to the proposal.

7.3.4 Environment of test

The environment of test, i.e. the fluid in the tank and casing, is mainly defined by temperature and chemical composition. The temperature should not be specified in the method since this is a variable that is altered depending on the intention of the test. The deviations of temperature from set value however, should be kept to a minimum due to the results being strongly influenced by the temperature.
The environment may not contain any pollution that might influence the test result such as oil, fat, wax, strongly oxidising agents and organic chemicals. Water should generally be considered such an environment.

7.3.5 Equipment

Suitable equipment is presented in figure 7.1.

![Figure 7.1. Suitable test equipment.](image)

**Pressure-measuring device**
The pressure-measuring device should consist of a calibrated gauge capable to measure over- or absolute pressure with accuracy better than ± 2 % of measured value. The range of the gauge should be such that the measured value lies within the range of calibration.

**Pressurising equipment**
The device should be capable to exert the designated test pressure and to maintain it for the duration of the test with accuracy conforming to that of the pressure-measuring device. If buckling is determined by sudden decrease of test pressure the response time of the device should be long enough to emphasize this.

**Pressure vessel**
The pressure vessel should be capable to receive the test sample and to withstand the designated test pressure.

**Temperature-measuring device**
Calibrated temperature-measuring equipment capable to check conformity of test temperature with accuracy better than ± 0.5 °C. The device should be such that the measured value lies within the range of calibration

**Temperature control system**
The temperature control system should be capable to induce and maintain the designated test temperature with accuracy conforming to that of the temperature-measuring device.
Tank
The environment of test is water/fluid and thus a tank is needed, filled with water or other fluid and capable to receive the test sample and the pressure vessel. The fluid should be thermally controlled by the thermal control system.

Timer
Capable to record the duration of test.

The accuracy and simplicity of the test is enhanced if a computerised data acquisitioning system is used.

7.3.5.1 Evaluation of test data

The gathered test data may be evaluated differently depending on the intention of the test. The output of the test method should always however, include test temperature, test pressure, hoop stress of the pipe material and time for buckling. If more than one sample is tested with the same testing parameters, i.e. test pressure and temperature, an arithmetic mean of the results (X) together with standard deviations (S) should be presented and calculated as:

\[
X = \frac{1}{n} \sum_{i=1}^{n} x_i 
\]

\[
S = \frac{1}{n-1} \sum_{i=1}^{n} \sqrt{(x_i - X)^2}
\]

where

- \( n \) = Number of tests performed;
- \( x_i \) = Result of test nr \( i \).

7.3.6 Uncertainty of test

The uncertainty of the critical compressive hoop stress at certain temperature and load duration is mainly governed by:

a. Accuracy of measuring device;

b. Stability of test parameters during test;

c. Uncertainty when evaluating the time for collapse.

The critical compressive hoop stress may be expressed as

\[
\sigma_b = \frac{p_b D}{2s}
\]  

where

- \( \sigma_b \) = Critical compressive hoop stress;
- \( p_b \) = Critical pressure leading to collapse, i.e. test pressure;
- \( s \) = Wall thickness of the pipe;
- \( D \) = Outer diameter of the pipe.
Derivations of (19) with respect of pressure, temperature and time yields

\[
\Delta \sigma_b = \frac{D}{2s} \left( \frac{\partial \sigma_b}{\partial p} \Delta p + \frac{\partial \sigma_b}{\partial T} \Delta T + \frac{\partial \sigma_b}{\partial \tau} \Delta \tau \right)
\]  

:(20)

where

p = Test pressure;
T = Temperature;
\(\tau\) = Load duration;
\(\Delta p\) = Uncertainty of pressure;
\(\Delta T\) = Uncertainty of temperature;
\(\Delta \tau\) = Uncertainty of load duration.

Thus

\[
\frac{\Delta \sigma_b}{\sigma_b} = \frac{\partial \sigma_b}{\partial p} \frac{\Delta p}{p_b} + \frac{\partial \sigma_b}{\partial T} \frac{\Delta T}{p_b} + \frac{\partial \sigma_b}{\partial \tau} \frac{\Delta \tau}{p_b}
\]  

:(21)

For a certain pipe, with defined dimensions and material, the critical buckling pressure may be expressed as a function of the creep modulus (E):

\[ p_b = cE \]  

:(22)

where c is constant:

\[ c = \frac{2}{(1-\nu^2)SDR^3} \]

(21) and (22) yields

\[
\frac{\Delta \sigma_b}{\sigma_b} = \left( \frac{\partial E}{\partial p} \frac{\Delta p}{p_b} + \frac{\partial E}{\partial T} \frac{\Delta T}{p_b} + \frac{\partial E}{\partial \tau} \frac{\Delta \tau}{p_b} \right)
\]  

:(23)

The dependence of creep modulus due to load, temperature and load duration varies with type and quality of the material. Assuming common material used as collectors in BHE-applications, i.e. MDPE 80 (materials: Uponor ME2410, Borealis ME2418) reveals estimations of the derivatives in (23), when evaluating data received from [27, 31] and [12], as presented in table 7,2. The test piece is assumed as SDR = 17 and the Poison modulus \(\nu = 0,45 \) [11].
Table 7.2: Input data to (23).

<table>
<thead>
<tr>
<th>Factor</th>
<th>Estimated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\partial E}{\partial p}$</td>
<td>$&lt;-11$</td>
</tr>
<tr>
<td>$\frac{\partial E}{\partial T}$</td>
<td>$&lt;-9$</td>
</tr>
<tr>
<td>$\frac{\partial E}{\partial \tau}$</td>
<td>$&lt;-26/\tau$</td>
</tr>
<tr>
<td>$P_b$</td>
<td>$&gt;0.3 \text{ MPa}$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$&gt;0.5 \text{ h}$</td>
</tr>
<tr>
<td>$\Delta p$</td>
<td>$&lt;0.01 \text{ MPa}$</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>$&lt;0.6 \degree\text{C}$</td>
</tr>
<tr>
<td>$\Delta \tau$</td>
<td>$&lt;0.01 \text{ h}$</td>
</tr>
<tr>
<td>$c$</td>
<td>$5.1 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Assuming input data according to table 7.2 and the contributions to uncertainty being normally distributed and independent yields the expanded ($k = 2$), total uncertainty ($U$) as

$$U = k \sqrt{c^2 \left( \frac{\partial E}{\partial p} \Delta p \right)^2 + \left( \frac{\partial E}{\partial T} \Delta T \right)^2 + \left( \frac{\partial E}{\partial \tau} \Delta \tau \right)^2} \approx 0.02 = 2\%$$

One should consider however, that contributions to uncertainty due to determination of dimensions and installation effects are disregarded in the calculations above and $U$ should thus be somewhat higher, approximately 3 %.

The uncertainty of an arithmetic mean based on $n > 3$ test results should be evaluated using

$$\overline{U}_n = \frac{1}{n} \sum_{i=1}^{n} U_i$$  \hspace{1cm} (24)

### 7.4 Experimental work

#### 7.4.1 Performed tests

Three tests were performed at designated test pressures and temperatures specified below to evaluate the method proposal:

A. $p = 2.5 \text{ bars}, t = 20 \degree\text{C}$;
B. $p = 2.5 \text{ bars}, t = 20 \degree\text{C}$;
C. $p = 2.5 \text{ bars}, t = 15 \degree\text{C}$.

Actual arithmetic means of measured data are presented in table 7.3.

Table 7.3: Arithmetic mean values of measured data.

<table>
<thead>
<tr>
<th>Test</th>
<th>$p$ [bars]</th>
<th>$t_{i,\text{in}}$ [$\degree\text{C}$]</th>
<th>$t_{i,\text{out}}$ [$\degree\text{C}$]</th>
<th>$t_c$ [$\degree\text{C}$]</th>
<th>$t_{i,1}$ [$\degree\text{C}$]</th>
<th>$t_{i,2}$ [$\degree\text{C}$]</th>
<th>$t_{i,13}$ [$\degree\text{C}$]</th>
<th>$t_{i,14}$ [$\degree\text{C}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.44</td>
<td>20.1</td>
<td>20.1</td>
<td>20.1</td>
<td>20.1</td>
<td>20.1</td>
<td>19.7</td>
<td>20.0</td>
</tr>
<tr>
<td>B</td>
<td>2.51</td>
<td>20.1</td>
<td>20.1</td>
<td>20.1</td>
<td>20.1</td>
<td>20.1</td>
<td>19.7</td>
<td>20.1</td>
</tr>
<tr>
<td>C</td>
<td>2.56</td>
<td>14.9</td>
<td>15.0</td>
<td>15.0</td>
<td>14.7</td>
<td>15.0</td>
<td>14.7</td>
<td>15.0</td>
</tr>
</tbody>
</table>
7.4.2  Test pieces

The test pieces consisted of common collector pipe quality as specified below.

Manufacturer: Uponor Vårgårda AB  
Dimensions: 40 x 2.4 mm  
SDR: 17  
Nominal pressure: 6.3 bar  
Quality: MDPE 80  
Free length: 0.97 m

7.4.3  Experimental set up

The experimental set up is illustrated in figure 7.2.

![Figure 7.2 Experimental set-up.](image)

Due to initial deformation of the test piece the test pressure will decrease slowly if not maintained sufficiently. In the experiments conducted this problem was solved to some extent by usage of pressurized air as pressurising agent, described in figure 7.3.

![Figure 7.3 Pressurising equipment.](image)

This is however, not a recommendable solution due to difficulties in achieving the designated pressure, adequate accuracy and also due to problems with stability. The problem with stability should be especially difficult when performing long duration tests and thus a better device should be used.

To assure detection of buckling, the interior of the test piece were connected to a pressure gauge measuring induced pressure of the water column created by pressed out water during deformation as illustrated in figure 7.2. The pipes and container used were initially at atmospheric pressure.

The equipment and sensors used are presented in table 7.3.
Table 7.3 Measuring equipment and sensors.

<table>
<thead>
<tr>
<th>Measured quantity</th>
<th>Type of sensor/gauge</th>
<th>Estimated uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Druck, over pressure gauge</td>
<td>± 0,009 bar</td>
</tr>
<tr>
<td>p_{ind}</td>
<td>Fuji, differential pressure gauge</td>
<td>± 0,3 mbar</td>
</tr>
<tr>
<td>t_{in}</td>
<td>PT100</td>
<td>± 0,3 °C</td>
</tr>
<tr>
<td>t_{out}</td>
<td>PT100</td>
<td>± 0,3 °C</td>
</tr>
<tr>
<td>t_0</td>
<td>PT100</td>
<td>± 0,3 °C</td>
</tr>
<tr>
<td>t_{1,2}</td>
<td>thermoelement</td>
<td>± 1 °C</td>
</tr>
<tr>
<td>t_{3,4}</td>
<td>PT100</td>
<td>± 0,3 °C</td>
</tr>
<tr>
<td>t_{4}</td>
<td>thermoelement</td>
<td>± 1 °C</td>
</tr>
</tbody>
</table>

1. Referring to figure 7.2.

The data were gathered by usage of a computerized acquisition system and the pressurising fluid and the fluid in the tank were thermally regulated tap water.

### 7.4.4 Pre-conditioning

The pressure vessel and test piece were filled with pre-tempered water and conditioned in accordance with EN 921 [35].

### 7.4.5 Results

Deformation of plastics is basically governed by temperature, load and duration of load and thus need to be defined accordingly. These are the main variables that can be altered to influence the test result disregarding damaging the test piece. An elevated temperature will lower the resistance of the pipe and so will a long duration of strain. An elevated load on the other hand will, not surprisingly, decrease the strain resistance. So the critical buckling pressure for which collapse occurs need to be defined at a specific temperature and time of load to be unequivocal.

#### 7.4.5.1 Time to buckle

A criterion to define time to buckle is necessary since the collapse will occur gradually over a certain time due to the visco-elastic behaviour of plastics. A typical shape of test pressure and pressure induced by exiting water (water column pressure) from the interior of the test piece are presented in figure 7.4.
Compressive deformation sets in as soon as the test pressure is exerted. Unfortunately this is not indicated in the figure due to a design flaw of the container preventing the exiting water to reach the gauge initially. After about 60 minutes however, the amount of water is enough to overcome this flaw and the gauge starts to register. Even though the test piece gradually deforms throughout the test, final collapse seems to start first at 155 – 165 min of testing and then continue for the remainder of the test.

The initial decrease of test pressure occurring between 155 – 165 minutes of testing is not backed up by any increase of water column pressure which indicates that the exerted volume in this case is less than 4 centilitres conforming to 0.4 % of the entire volume of the test piece. This should not be regarded as initiated collapse but rather part of the ongoing gradual deformation. At 165 minutes a sharp decrease of test pressure may be detected, backed up by a sudden increase of water column pressure and thus indicating collapse. This pattern is repeated in test A and C and illustrated in figure 7.5. The unnatural behaviour of the water column pressure in the figures is due to leakage and the container being poorly ventilated preventing a smooth flow of exiting water.

Figure 7.4. Test pressure and water column pressure – test B.

Figure 7.5. Test pressure and water column pressure - test A.
In both these cases a similar increase of deformation lowers the test pressure prior to the final collapse, indicated by a sharp knee in test pressure and corresponding increase of water column pressure. The initial shape of test pressure in both figures is due to the poor capacity of the pressurising equipment to maintain stability as mentioned earlier. Plotting the test pressure curves for the three tests at time for collapse shows that the rate of deformation is dependent on temperature which is quite logic and thus such transparent collapses as in the figures may not appear when testing at lower temperatures. On the other hand, the initial deformation will also be slowed down, why the buckling should be relatively easy to detect. The collapse itself should be defined as the beginning of decline in test pressure leading to pressure loss of more than 2 %, i.e. the first observation of decline. The rate of decline, i.e. the derivative of test pressure, may not exceed zero at any point during this loss of pressure. Furthermore should the decline be preceded by a period in which the test pressure has been stable to within ± 2 % of the designated value. After termination of test the sample should be dismantled and the deformation verified. If no deformation is present the result should be rejected.

Following this definition the time to buckle ($\tau_b$) in test b should be as illustrated in figure 7.7.
The results of tests following the definition are presented in table 7.4.

Table 7.4 Time to buckle for test A, B and C when determined by test pressure and water column pressure.

<table>
<thead>
<tr>
<th>Test</th>
<th>Time to buckle when determined by test pressure [h]</th>
<th>Time to buckle when determined by water column [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3.38</td>
<td>3.38</td>
</tr>
<tr>
<td>B</td>
<td>2.82</td>
<td>2.83</td>
</tr>
<tr>
<td>C</td>
<td>14.36</td>
<td>14.37</td>
</tr>
</tbody>
</table>

The use of water column pressure or something similar, i.e. using a volume decrease approach, demands a similar kind of definition and a better set up than the one used in this project. Common between all three tests however, are a sudden peak or a sudden increase of pressure incline rate, almost vertical as can be seen in figures 7.4-6, giving a very transparent point of collapse. Using this indicator yields the resulting times for collapse presented in table 7.4 and thus differing less than 0.5 % from when determined by test pressure. The point chosen should be the first observation with change of indicator, i.e. water column pressure or exiting volume, leading to collapse. To prevent misjudgements the test should not be terminated at this point but go on until deformation causes a decrease in volume of the sample conforming to at least 50 % of the original inner volume.

The results show the necessity of keeping deviations of pressure and temperature to a minimum. Between test A and B a decrease of test pressure by less than 3 % resulted in an elongation of the buckling time by almost 20 % and a decrease in temperature by 5 °C by more than 500 % even though the test pressure in test C were 2 % higher than in test B.

### 7.4.6 Critical compressive hoop stress

Using arithmetic means of the test pressure yields when inserted in (19) the values of hoop stress specified in table 7.5. The deviation of pressure and the fact that dimensions of test pieces were not measured according to EN ISO 3126 [34] should at first glance render a higher uncertainty than specified in section 7.3.8. However, since the accuracy of the gauge used and the deviations of test temperature are much smaller than specified there the total uncertainty is estimated as roughly the same.

Table 7.5. Measured critical compressive hoop stress – test A, B and C.

<table>
<thead>
<tr>
<th>Test</th>
<th>Induced mean hoop stress [Bars]</th>
<th>Uncertainty according to section 7.3.8. [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>2.03</td>
<td>± 0.06</td>
</tr>
<tr>
<td>b</td>
<td>2.09</td>
<td>± 0.06</td>
</tr>
<tr>
<td>c</td>
<td>2.13</td>
<td>± 0.06</td>
</tr>
</tbody>
</table>
7.5 Conclusions

Determining buckling is feasible both by measurements of test pressure and by indirect measurements of volume decrease. To determine time to buckle by means of measuring the test pressure alone requires pressurising equipment with sufficiently long response time to enable detection of collapse. The latter detection method should be the most practical when performing long duration tests with many samples. In such cases the precision to determine time for collapse is not as vital and thus allowing simplifications of the set up and data gathering.

Precautions to minimize deviations of test temperature and pressure should always be taken.
8 References

8.1 Literature


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8.3 **Oral communication**

26. **Alexandersson, H.** Managing Director, PemTec AB. 0403-0411.

27. **Cedenblad, B.** Technical Director, Uponor Vårgårda. 041110.

28. **Hellman, O.** President at Avanti systems. 0404-0411.

29. **Nelson, A.** Managing Director, GEOTEC. 0402-0412.

30. **Risberg, G.** SGU – Sveriges Geologiska Undersökning. 0402-0412.


32. **Skarphagen, H.** Båsum Boring as, avdeling Oslo. 040427.

33. **Kero, A.** SP Swedish testing and research institute. 040427.

34. **Johansson, M.** SP Swedish testing and research institute. 041122.
8.4 Standards


37. DIN 1626. Steel pipes, welded, of unalloyed and low-alloy steels for piping, apparatus and containers; general specifications, lay-out and instructions for application.”

38. SS-EN 12201-2. Plastics piping systems for water supply – Polyethylene (PE).”


Appendix A. Method proposal: Well tops used on drilled wells – sealing capability when subjected to hydrostatic pressure and resistance against lift force

Key words: Well top, end cap, sealing, sealing performance, lift resistance, casing, vertical geothermal heat exchanger, test method, BHE, GHX.

Contents

1. Scope
2. Field of application
3. References
4. Definitions
5. Sampling
6. Method of test
7. Test report

1 Scope

This Nordtest method describes a way to test the sealing performance of well tops used as top sealants in vertical geothermal heat exchangers (GHX). Some parts of the method also apply to other applications as long as the function and design of the well top is similar. The method also comprises a way to test for resistance against lift due to build up of ice coat on the collector wall.

The principle of the method is to exert hydrostatic pressure on the well top. In this way, it’s capability to prevent surface water from infiltrate and ground water to exit is determined.

Build up of ice coat on the collector wall is simulated by exertion of evenly distributed and perpendicular mechanical lift on the appropriate locations of the well top, i.e. at through holes for collector pipes, if present.

The proposal takes no consideration regarding effects due to extreme cold.

Due to the vast variety of lid design, some parts of the method are not applicable and can therefore be omitted.

2 Field of application

The method is applicable for well tops with the following characteristics.

1. It should have an intended use to work as sealant between the well and it’s surrounding.
2. It should have a design that enables fixed attachment to the well casing.
3. In case of through holes for collector pipes present the dimension of the well top to be tested should be in compliance with installation on well casings with nominal outer diameter of 139.7 mm, 168.3 mm or 193,7 mm.
3 References


[2]: EN 12201-2:2003, “Plastics piping systems for water supply – Polyethylene (PE)”.

4 Definitions

For the purpose of this method, the following definitions apply.

Well top
A component intended to act as sealing between a drilled well and the surface.

Test pressure
Difference between the absolute pressure above and below the test piece expressed in bars. A positive value indicates a larger pressure below than above when the well top is assembled as intended.

Test temperature
The temperature, expressed in °C, of the test piece, its surrounding and the pressurising fluid.

5 Sampling

The sample shall consist of at least one specimen of the object to be tested. It should be taken from the ordinary line of production in accordance with agreement between the manufacturer or retailer and the testing institute.

Preferably should the sample consist of two specimens to enable retesting if required.

6 Method of test

6.1 Principle

The basic principle of the method is to exert hydrostatic pressure on the test sample mounted to a steel casing conforming to national standards or regulations regarding casings. Leakage will be detected visually.

Mechanical force is applied on the test piece in order to determine the resistance against lift force. The lift force simulates build up of ice on the collector wall and aims to test if the test piece will separate from the casing as a result from this.
6.2 Equipment

Suitable test equipment is illustrated in figure 1.

![Figure 1 Diagram of suitable equipment.](image)

**Pressure vessel**, capable to resist the test pressure and to receive the test piece as illustrated in figure 1. The vessel should be fabricated from a quality of steel case, conforming to national standards and regulations regarding casings used in drilled wells, and to the usage of the test piece. The radial dimension of the vessel is determined by the size of the test sample. The bottom of the pressure vessel should be attachable to the tensometer and device used should be strong enough to withstand the lift, as specified in clause 6.6.2.

**Pressure-measuring device**, calibrated and with accuracy better than \( \pm 2 \% \) of the measured value and capable to check conformity of the test pressure. The range of the device should be such that the measured value lies within the range of calibration.

**Pressurising equipment**, connectable to the pressure vessel and capable to exert the test pressure with accuracy equivalent to, or better than that of the pressure-measuring device and to maintain it for the duration of the test.

**Timer**, capable to record the duration of the test to within \( \pm \frac{1}{60} \text{sec} \).

**Polyethylene pipes** sealed in both ends by end caps or equivalent and filled with water. The pipes should conform to SDR 13.6, or lower, and PN 10 or higher according to EN 12201-2 [2]. The outer diameter is determined by the design of the test sample. The length of the pipes should be sufficient to allow gliding during test of lift without the end caps coming in contact with the test piece. The end cap at top of the pipes should be connectable to the tensometer and be capable to resist the test force specified in clause 6.6.

**Tensometer**, calibrated and capable to exert the longitudinal test force (see clause 6.6) and to maintain it for the duration of the test. The accuracy should be better than \( \pm 5 \% \) of measured value. The range of the tensometer should be such that the measured value lies within the range of calibration.

**Dynamometric wrench**, calibrated and capable to fasten hose clamps, bolts and screws present on the test piece, intended to be tested, with designated torque and with accuracy better than \( \pm 1 \)
Nm. The range of the dynamometric wrench should be such that the measured value lies within the range of calibration.

**Thermometers (or equivalent)**, capable of checking conformity of test temperature as specified in clause 6.4. The accuracy should be better than ± 1 °C.

### 6.3 Preparation

Before testing, it is recommended that a visual inspection of the sample be done to make sure that no visually detectable defects exist which might have adverse effects on the results.

Oxidation present at locations of the pressure vessel in contact with the test piece should be removed prior to assembling.

The test sample is mounted to the test equipment in accordance with recommendations from the manufacturer, retailer or client of the test. If the test piece is of type “A”, according to [1], the torque should be exerted gradually and evenly in a stringent pattern of shift between the bolts during mounting. The procedure used should be recorded and consist of at least 1 shift per 5 Nm applied torque. When the designated torque is achieved throughout the bolts, screws or hose clamps, conformity of torque should be checked by usage of the dynamometric wrench. The accuracy should be as specified in section 6.2.

### 6.4 Testing environment

The pressurising fluid may not contain any pollutions or components with adverse effects on the test sample.

The temperature of the ambient and of the fluid in the pressure vessel should be 20 °C ± 10 °C when test is performed. The ambient temperature in the lab-room where the test takes place may not deviate from the initial value to an extent that renders stability of test pressure impossible to obtain (see clause 6.6).

### 6.5 Pre-conditioning of test sample

No special pre-conditioning is necessary unless manufacturer advise otherwise. However, the time laps between production of the test piece and testing should not be less than 24 h.

However, the test piece may be aged by means of accelerated aging in an oven or similar device before assembled if applicable, to evaluate long term performance. In such cases should the temperature and time to use conform to at least 50 years of ageing. To calculate the temperature and exposure time an accelerating factor 2 per every 0,2 °C elevated temperature may be used.

Note: The temperature should never be chosen such that melting or other damage of the test piece occurs.
6.6 Procedure

The test sample is mounted to the equipment as described in clause 6.3.

6.6.1 Leakage resistance test

Bleed of all air in the pressure vessel. Pressurize until the desired test pressure of 0.5 bars is obtained to within ± 1 kPa. The pressure should be applied smoothly and gradually in shortest time practical.

Note: Necessary safety measures should be taken in case of failure of the test sample or some other component under pressure.

Note: The test pressure specified above should only be regarded as a guideline value. Other test pressures may be used if eligible or necessary. In such case should the allowable deviation of set value should conform to \[ ± \frac{2%}{1kPa} \]. To prevent separation of the test piece from the casing due to pressure-induced lift above those specified in Table 1, clause 6.6.2, the pressure used should be chosen so that conformity to these are obtained.

Stability of pressure shall be maintained to within specified allowable deviations of set value for the duration of the test. If leakage is detected during pressurisation the test sample should be reassembled or replaced and the procedure repeated. If leakage is observed after reassembling, the test is terminated and the observations recorded.

The test piece should endure the static pressure for at least 1 h \[ ± \frac{1min}{30sec} \]. During this period the apparatus should be monitored for any indication of loss in pressure and the test piece for any signs of leakage. If leakage is observed the test is terminated and the observations recorded.

6.6.2 Lift resistance test

The pressure vessel and test piece is mounted to the tensometer so that longitudinal force can be exerted perpendicular to the test piece as illustrated in figure 2.

Figure 2. Mounting of pressure vessel to the tensometer.

Record the position of the test piece and polyethylene pipes, to enable detection of separation of the test piece, or gliding of the pipes. The force is to be applied on the end caps of the polyethylene pipes and the bottom of the pressure vessel respectively, and should be evenly
distributed between the collector pipes. Apply the force gradually and evenly over a period of not less than 60 s and maintain it for 1 h $\pm 30$ min or until gliding of the polyethylene pipes occurs. If gliding of the polyethylene pipes is observed the test is terminated and the magnitude of lift at which gliding occurred recorded. The maximum magnitude of lift to apply is specified in table 6.1. Inspect the assembly and record any signs of separation between the test piece and the apparatus due to pull out. Also record any other signs of failure such as cracks and deformation of the test piece.

Note: The lift force test is only applicable for test pieces with through holes for collectors.

<table>
<thead>
<tr>
<th>Nominal outer diameter of casing conforming to the intended use of the test piece [mm]</th>
<th>Force [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>139,7</td>
<td>1,3</td>
</tr>
<tr>
<td>168,3</td>
<td>2,2</td>
</tr>
<tr>
<td>193,7</td>
<td>3,2</td>
</tr>
</tbody>
</table>

If no failure is observed, i.e. no separation of the test piece from the pressure vessel as well as cracks or deformation, the assembly is dismantled from the tensometer and left to relax for a period not less than 1 h. Then the leakage resistance test described in clause 6.6.1 is repeated and any signs of leakage recorded.

### 6.7 Applicability

In order for the method to have an acceptable repeatability, it is necessary that a great deal of effort be made to attach the test sample correctly and stringently to the pressure vessel as described in clause 6.3.

### 6.8 Rejection of results

If leakage occurs when repeating the test and the leakage originates from the through holes for the collector pipes, and no such observations have been done previously, the leakage should be disregarded.

### 7 Test report

The test report shall include the following information:

a. Name and address of the testing laboratory.
b. Name and address of the organization or person who ordered the test.
c. Reference to this method.
d. Name and address of manufacturer or supplier of the specimen.
e. Complete identification of the specimen tested.
f. Mounting procedure including torque applied on screws, bolts and hose clamps.
g. Identification of equipment and instruments used during test.
h. Any deviation from the test method.
i. Results including test pressure, test temperature and uncertainty of measured value.
j. Date and signature.
Appendix B. Method proposal: Performance test of cast case sealing used in drilled wells when subjected to hydrostatic pressure.

Key words: Case sealing, cast water caulking, sealing performance, vertical geothermal heat exchanger, bentonite sealing, cement sealing, BHE, GHX, test method

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1. Scope
2. Field of application
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1 Scope

This Nordtest method describes a way to test the sealing performance of cast case sealing used in drilled wells in laboratory conditions when subjected to hydrostatic pressure.

The method intends to help evaluate different grouts and sealing techniques in controlled environment. The environment is designed to be “worst-case” from the sealing point of view, based on real applications, within reasonable boundaries.

The principle of the method is to exert hydrostatic pressure on the sealing. In this way, the capability to prevent surface water from infiltrating the well and ground water to exit is determined.

2 Field of application

This method is intended for the determination of sealing performance of cast case sealing used as water caulking in drilled wells. To enhance feasibility of the method some deviations from real conditions are necessary:

1. The length of the test piece is shorter than can be expected in reality and affects from this are disregarded in the method;
2. Durable and flexible grouts may be benefited over rigid grouts due to the method;
3. Human flaws when moulding the test piece are not regarded.

The method is focused on sealing where the grout is mechanically pressed out into the annulus of the casing but should also to some extent be feasible when using the principle of communicated vessels. The proposal does not require hydrating grouts to be feasible, why most types may be tested.
3 References


4 Definitions

For the purpose of this method, the following definitions apply.

Cast case sealing
A component consisting of cement, bentonite or similar material used in drilled wells as water sealant preventing leakage through the annulus of the casing (i.e. the case gap).

Steel casing
Steel pipe used in the upper part of drilled wells conforming to national standards or regulations regarding casings in drilled wells such as DIN 1626 [2].

Case gap
Difference between the outside diameter of the case and the inside diameter of the hole in to which the casing is assembled.

Test pressure
Difference between the ambient pressure and the hydrostatic pressure for which the test piece is subjected expressed in bars. A positive value indicates a larger hydrostatic pressure than ambient pressure.

Test temperature
The temperature, expressed in °C, of the test piece, it’s surrounding and the pressurising fluid.

5 Sampling

The sample is taken from the ordinary production line in agreement between manufacturer or retailer of the test piece and the testing institute.

6 Method of Test

6.1 Principle

The principle of the test method is to subject the test piece to hydrostatic pressure in order to detect leakage. Leakage is detected visually by monitoring the test piece and concrete block during test.
6.2 Equipment

Suitable test equipment is illustrated in Fig. 1.

![Diagram of suitable equipment.](image)

**Concrete block**, as described in appendix A and [1].

**Straps**, or similar device that keeps the steel case fixed in its vertical position and thus preventing axial elongation of the casing. The device should be strong, and rigid enough to withstand the pressure-induced lift with negligible elongation (< 5 % of critical elongation of the test piece material).

**Pressure-measuring device** calibrated and with accuracy better than ± 2 % of the measured value and capable to check conformity of test pressure. The range of the devise should be such that the measured value lies within range of calibration.

**Pressurising equipment**, capable to exert the designated test pressure, with accuracy equivalent to, or better than, that of the pressure-measuring device and to maintain it for the duration of the test.

**Timer**, capable to record the duration of test to within ± $1\text{min} - 30\text{sec}$.

**Temperature-measuring device**, calibrated and capable to check conformity of test temperature with accuracy better than ± 1 °C. The range of the device should be such that the measured value lies within the range of calibration.

**Thermal control system**, consisting of a calorimetric chamber or equivalent, capable to induce and to maintain the test temperature for the duration of the test with accuracy equivalent to, or better than the accuracy of the temperature-measuring device. The chamber should be capable to receive the concrete block, test piece and any necessary equipment.

**Data acquisition system**, capable to record measured values with a sample time not exceeding 60 s.
6.3 Testing environment

The pressurising fluid may not contain any pollutions or components with adverse effects on the test sample. Water is generally considered such a fluid.

The ambient temperature shall be kept constant at 2 °C to within ± 1°C during the test.

Note: The temperature specified above should only be regarded as a guideline value. If desired another test temperature may be used. If so, the allowable deviation from set value should conform to ± 1°C and any effects on pre-conditioning time, thermal stress in the concrete block etc. should be considered.

6.4 Pre-conditioning and preparations

The concrete block should be conditioned, before casting of the test piece is conducted, at test temperature for a period of 60 h ±1 h or until conformity of test temperature throughout the block has been verified by other means. During this time and also when curing and eventual storing of the test piece is performed the centre hole of the block should be prevented to dehydrate, preferably by means of keeping it water filled.

The grout should have a temperature of 10 to 20 °C unless the manufacturer advises otherwise.

The test piece should be prepared in accordance with recommendations from the manufacturer. Directions regarding temperature of mixing water should comply with these recommendations from the manufacturer. Casting grout may have to be pre-heated to obtain sufficient hydration. Since the pre-conditioning in this context may affect the results the actions taken should be recorded and stated in the test report. During hydration and preferably also casting of the test piece, the concrete block should be kept in the thermally controlled surrounding. To facilitate the cast procedure the concrete block may be removed from the thermally controlled surrounding during this procedure for the shortest time practicable but not longer than 30 minutes.

The centre hole may be filled with water during casting of the test piece if desired.

Note: Casting of the test piece should be performed by educated personal certified by relevant organisations or administrations such as branch associations, municipal health and environment administrations etc. The person or organization that ordered the test makes selection of these personnel.

Hydration heat should be cooled of by means of keeping the surface temperature as close as possible at test temperature. The deviation may not exceed ±2°C. The surface temperature should be measured on at least five well-distributed and separated points on the block.
6.5 Test procedure and data processing

6.5.1 Procedure

Any oxidation on the outer wall of the case should be removed before testing. Visible parts of the test piece and its immediate surrounding should be wiped free of any surplus water to enable detection of leakage. The test piece may not extend above the case gap in such a way that detection of leakage renders difficult or impossible.

After conditioning and casting (including hydration) of the test piece, the metal flanges on top of the steel case are assembled and adequately sealed. Any air present in the pressurised spaces should be evacuated.

Precautions to prevent the steel case of separating from the assembly due to the pressure-induced force acting on the cover flange should be taken prior to the pressurisation, by usage of device that keeps the steel case fixed in its vertical position, thus preventing axial elongation of the casing.

Connect the pressurisation equipment to the casing. The pressurising fluid should be pre-cooled to the designated test temperature. Bleed of all air from the pressure chamber and pressurise until the desired test pressure of 3 bars is obtained to within ± 0.06 bars. Apply the pressure gradually in the shortest time practicable. Monitor the assembly and check for any indications of leakage.

Note: Adequate safety measures in case of failure of some component in the assembly under pressure should be taken during the test.

Note: The test pressure specified above should only be regarded as a guideline value. If desired or if necessary another test pressure may be used. In such case should the deviations from set value be within ± 0.06 bars and any possible effects regarding influence on test result and safety should be considered.

When the test pressure is obtained the test piece should endure the hydrostatic pressure for 1 h ± 1 min ± 30 sec. The pressure should be maintained within specified allowable deviations of set value for the duration of the test.

Inspect the case gap and the test piece regularly for any signs of leakage. If leakage is observed the test is terminated and the observations recorded. Note, if possible, the origin of leakage, i.e. between steel casing and test piece, through cracks in the test piece or between the concrete and the test piece.
7 Applicability and uncertainty

The applicability and accuracy of the method proposal to reflect real applications are hard to predict. Many factors would have to be investigated to obtain a meaningful definition regarding this, since many factors may influence. These might be errors during cast of the test piece, inadequate monitoring for leakage, usage by concrete as fictional borehole etc. that also might influence the repeatability of the methods.

Uncertainty of test pressure, as well as temperature, is dependent on the accuracy of the pressure measuring device and the stability of test pressure during testing. If demand of stability of test pressure and accuracy of the device is met as specified in this method the uncertainty of measured value should be better than ± 3 % and ± 1 °C calculated according to [4].

8 Test report

The test report shall include the following information:

a. Name and address of the testing laboratory.
b. Name and address of the organization or person who ordered the test.
c. Reference to this method.
d. Name and address of manufacturer or supplier of the specimen.

e. Name and address of organization or person who prepared the specimen.
f. Complete identification of the specimen tested including type and manufacturer’s code numbers.
g. Method of preparation and preconditioning periods of test sample(s) and concrete block.
h. Identification of equipment and instruments used during test.
i. Arithmetic mean values of measured temperature during pre-conditioning and testing including uncertainty and deviation of measured value.
j. Arithmetic mean values of measured test pressure during test including uncertainty and deviation of measured value.
k. Results, i.e. any observations of leakage or lack of such.
l. Any deviation from the test method.
m. Date and signature.
Annex A. Concrete block

[Image of a concrete block diagram]

Figure A:1. Concrete block.

Construction
The concrete block should be prepared at least 28 days prior to testing. The concrete should always be given sufficient time of curing before test is performed. Precautions to prevent plastic shrinkage and other crack growth mechanisms as well as processes that induce mechanical strength losses should be taken.

Precautions to prevent dehumidification of inner surface should be taken preferably by means of keeping the centre hole water filled during storing and pre-conditioning.

Example of a suitable casting procedure is given in [1].

Properties of concrete
The properties of the concrete used should comply with compressive stress resistance C50/60 conforming to EN 206-1:2000 [3] or with the list below.

a. Water/cement-ratio: < 0.6.
b. Tensile stress resistance: 1 MPa or more.
c. Compressive stress resistance: 52 MPa or more.
d. Modulus of elasticity: 30 GPa or more.

Dimensions
\[ d_1 = 141 \text{ mm} \pm 0.5_{mm} \]
\[ d_2 = 300 \text{ mm} \pm 1.0_{mm} \]
\[ h_1 = 1000 \text{ mm} \pm 5_{mm} \]

Casing
The casing should be made of steel with nominal outer diameter of 139.7 mm conforming to national standards or regulations regarding casings of drilled wells, such as DIN 1626. Any oxidation on the outer wall should be removed prior to test.
Appendix C. Method proposal: Performance of non-moulded case sealing and plug sealing when subjected to hydrostatic pressure.

Key words: Case sealing, plug sealing, water caulking, borehole, sealing performance, vertical geothermal heat exchanger, GHX, BHE, test method.

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1. Scope
2. Field of application
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1 Scope

The scope of the test method is to describe a way of testing sealing performance of plug sealing and non-cast case sealing when subjected to hydrostatic pressure. The principle of the test is to subject the test piece to hydrostatic pressure whilst monitoring it for any signs of leakage. In this way, the capability to prevent surface water from infiltrating the well, groundwater to exit and/or different layers of groundwater to mix is determined.

During test the test piece is assembled conforming to its intended use. The thermal environment during test should be close to that found in real applications and controlled by a thermal control system. The borehole is simulated by usage of steel pipes or concrete block depending on type of test piece.

2 Field of application

The method is applicable for testing sealing performance of components intended to act as sealing in drilled wells that belongs to one of the following categories:

1. Non-cast case sealing of plastics or other material with sealants against casing and borehole when assembled as intended and with length short enough to enable handling and performance of test;
2. Non-cast plug sealing of plastics or other material with one or two sealants connected by pipe or cylinder and short enough to enable handling;
3. Cast plug sealing or plug sealing of non-solid material, such as bentonite clay or similar. If the specimen is equipped with any component specifying a certain diameter of borehole to be used this should conform to 0.115, 0.140 or 0.165 meters.

Due to practical reasons the length of cast plug sealing to be tested according this method is restricted to one meter.
3 References


4 Definitions

For the purpose of this method, the following definitions apply.

Case sealing
A component used in drilled wells as water sealant preventing leakage through the annulus of the casing.

Steel casing
Steel pipe used in the upper part of drilled wells conforming to national standards, norms or regulations regarding casings in drilled wells.

Single plug sealing
A non-cast component used in drilled wells acting as sealing at one location of the well and used to prevent flow between two segments.

Double plug sealing
A non-cast component used in drilled wells acting as sealing at two locations connected together by a pipe or cylinder and used to prevent flow from a certain segment of the well.

Cast plug sealing
A cast component consisting of cement, bentonite, concrete or similar material used in drilled wells to prevent flow from a certain segment of the well.

Test pressure
Difference between the ambient pressure and the hydrostatic pressure for which the test piece is subjected expressed in bars. A positive value indicates a larger hydrostatic pressure than ambient pressure.

Test temperature
The temperature, expressed in °C, of the test piece, its surrounding and the pressurising fluid during test.

5 Sampling

The sample should be taken from an ordinary line of production in accordance with agreements between the manufacturer or retailer of the specimen to be tested and the testing institute. The sample should consist of at least one specimen of the object to be tested but preferably two randomly chosen samples should be taken to enable retesting if necessary.
6 Method of test

6.1 Principle

The principle of the method is to subject the test piece to hydrostatic pressure. Leakage will be detected visually as the test piece and equipment are monitored.

6.2 Preparations

The test sample should be prepared in accordance with recommendations from the manufacturer or the client who ordered the test.

Any soaking of test pieces or similar procedures should be done using pre-cooled fluids at test temperature.

Before testing, it is recommended that a visual inspection of the sample be done to make sure that no visually detectable defects exist that might have adverse affect on the test result. The device in which cast plug sealing are assembled should be filled with water unless specified otherwise by the manufacturer or retailer.

Time laps between preparations; moulding, soaking etc. and testing should be kept as short as possible to prevent dehydration of the test piece affecting the results.

6.3 Equipment

6.3.1 Case sealing

Suitable equipment is illustrated in Fig. 1.

![Diagram of suitable equipment](image)

Figure 1 Diagram of suitable equipment.

**Steel pipes** welded together and capable to resist the test pressure and to receive the test piece as illustrated in figure 1. The dimension and quality of the pipe receiving the section of test piece intended to be assembled in the casing should conform to national standards or regulations regarding casing of drilled wells. If no such standards or regulations are available they should
conform to [1] and material quality St 37 or equivalent. The inner diameter \( d \) of the pipe receiving the borehole sealant should be calculated as

\[
d = d_0 + 0.01
\]

where \( d_0 \) is the dimension of borehole in which the test piece is intended to be used in meters. The quality of pipe should conform to the quality of pipe hosing the case sealant, or equivalent.

**Pressure-measuring device** calibrated and capable to check conformity of test pressure with accuracy better than ± 2 % of measured value. The range of the gauge should be such that the measured value lies within range of calibration.

**Pressurisation equipment**, capable to exert the test pressure with accuracy equivalent to, or better than that of the pressure-measuring device and to maintain it for the duration of the test.

**Timer**, capable to record duration of the test to within \( \pm \frac{1}{30} \text{sec} \).

**Polyethylene pipes** (if necessary to enable intended function of test piece) sealed in both ends with end caps or equivalent and filled with water. The outer diameter and length of the pipes is determined by the design of the test sample. The pipes should conform to SDR 13.6 or lower and PN 10 or higher according to [2].

**Temperature-measuring device** calibrated and capable of checking conformity of test temperature with accuracy better than ± 1 °C. The range of the device should be such that the measured value lies within the range of calibration

**Thermal control system**, capable of inducing and maintaining test temperatures with accuracy equivalent to that of the thermal measuring device.

### 6.3.2 Single and double plug sealing

As specified in clause 6.2.1. The design of the steel pipe should however be as illustrated in figure 2a and 2b.

![Figure 2a. Suitable equipment when testing double plug sealing.](image-url)
Further a supporting device, such as straps, is needed, preventing separation of the test piece from the test equipment and cancelling out any pressure-induced thrust up to 2,1 kN.

6.3.3 Cast plug sealing

As specified in clause 6.2.1 except usage of a concrete block described in annex A instead of steel pipes. Suitable equipment and to alternative set-ups are illustrated in figure 3.

Further a supporting device, such as straps, is needed, preventing separation of the test piece from the test equipment and cancelling out any pressure-induced thrust up to 2,1 kN.

6.4 Environment of test

The test temperature should be kept constant at 2 °C to within ± 1°C during test.

Note: The temperature specified above should only be regarded as a guideline value. If desirable or necessary another test temperature may be used. In such cases should the allowable deviation from set value conform to ± 1°C and any possible affect on pre-conditioning periods or other parameter which might influence the results of the test be considered.

If desired the fluid may have a 3,5 % saline content measured by weight and mixed as Na+Cl- in water to ensure capability to seal off saline water layers. If sensitivity for acidity may be expected the fluid used should be of PH 5.5. The pressurising fluid may not contain any pollutions or components, other than saline, with adverse effects on the test piece. Water is normally considered such a fluid.
6.5 Pre-conditioning

The concrete block should be conditioned at test temperature for 60 h ± 1 h or until conformity of test temperature throughout the block has been verified and steel pipes for 2 h ± 6 min before the test piece is assembled or cast.

Any fluid used during test and preparations, except mixing fluid for grout, should be pre-cooled to test temperature to within ± 1°C before test is performed or the test piece is assembled to the test equipment.

Grout for cast plug sealing may be pre-heated in accordance with recommendations from the manufacturer. To enable moulding of test piece the concrete block may be removed from the environmentally controlled surrounding for the shortest time practicable but not exceeding 30 minutes.

The test piece should have a temperature as close as possible to the test temperature before testing, as specified in clause 6.4, but not lower than 0 °C or higher than 10 °C, if not advised otherwise by the manufacturer.

6.6 Test procedure

Bleed of all air from the pipes and/or concrete block. Wipe the interior of the steel case, the visible parts of the test piece or the concrete block dry, so that no surplus water is present prior to test to enable detection of leakage.

If the test piece is a single plug sealing or cast plug sealing, separation between the test equipment and the test piece must be prevented using a device that prevents separation to occur. The device should be strong enough to withstand the pressure-induced lift.

If the test piece is a single plug sealing or a cast plug sealing, separation between the test equipment and the test piece must be prevented using a device described in clause 6.2.2 and 6.2.3.

Pressurise until the desired test pressure of 3 bars is obtained to within ± 0,006 bars.

Note: Adequate safety measures in case of failure of some component in the assembly under pressure should always be taken.

Note: The pressure specified above should only be regarded as a guideline value. If desired or if necessary, another test pressure may be used. In such case should the deviations from set value be less than ±2% or ± 2 %, which ever is smallest. If the design of the test piece is such, that the collector will be subjected to the pressure, considerations to this should be taken when establishing suitable test pressure.

Apply the pressure smoothly and gradually in the shortest time practicable. Monitor the test piece for any signs of leakage. If leakage is observed the test is terminated and the observation recorded.

The test piece should endure the hydrostatic pressure for at least 1 h ± 1min 30sec.

The pressure should be maintained according to specifications of permissible deviations from the set value stated earlier for the duration of the test. Monitor the apparatus for any loss of...
pressure and the test piece for any signs of leakage. If any leakage is detected, the test is terminated and the observation recorded.

7 Applicability and uncertainty

The applicability and accuracy of the method proposal to reflect real applications are hard to predict. Many factors would have to be investigated to obtain a meaningful definition regarding this, since many factors may influence. These might be errors during cast of the test piece, inadequate monitoring for leakage, usage by concrete as fictional borehole etc. that also might influence the repeatability of the methods.

Uncertainty of test pressure is dependent on the accuracy of the pressure measuring device and the stability of test pressure during testing. If demand of stability and accuracy of the pressure gauge specified in this method is met the uncertainty of test pressure is better than ± 3 % calculated according to [3].

8 Test report

The test report shall include the following information:

a. Name and address of the testing laboratory.
b. Name and address of the organization or person who ordered the test.
c. Reference to this method.
d. Name and address of manufacturer or supplier of the specimen.
e. Complete identification of the specimen tested including type and manufacturer’s code numbers.
f. Method of preparation and preconditioning periods of test sample(s) and concrete block or steel pipe.
g. Identification of equipment and instruments used during test.
h. Arithmetic mean values of measured temperature during pre-conditioning and testing including uncertainty and deviation of measured value.
i. Arithmetic mean values of measured test pressure during test including uncertainty and deviation of measured value.
j. Results, i.e. any observations of leakage or lack of such.
k. Any deviation from the test method.
l. Date and signature.
Annex A. Concrete block

Figure A:1. Concrete block.

Construction
The concrete block should be prepared at least 28 days prior to testing. The concrete should always be given sufficient time of curing before test is performed. Precautions to prevent plastic shrinkage and other crack growth mechanisms as well as processes that induce mechanical strength losses should be taken.

The centre hole should be sufficiently large to receive the test piece.

Precautions to prevent dehumidification of inner surface should be taken preferably by means of keeping the center hole water filled during storing and pre-conditioning.

Example of a suitable casting procedure is given in [1].

Properties of concrete
The properties of the concrete used should comply with compressive stress resistance C50/60 conforming to EN 206-1:2000 [3] or with the list below.

- e. Water/cement-ratio: < 0,6.
- f. Tensile stress resistance: 1 MPa or more.
- g. Compressive stress resistance: 52 MPa or more.
- h. Modulus of elasticity: 30 GPa or more.
**Dimensions**

\[ h_1 = 1000 \text{ mm} \pm 10\text{mm} \]

<table>
<thead>
<tr>
<th>Diameter of centre hole [mm]</th>
<th>Outer diameter of block [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>115</td>
<td>240</td>
</tr>
<tr>
<td>140</td>
<td>280</td>
</tr>
<tr>
<td>165</td>
<td>340</td>
</tr>
</tbody>
</table>
Appendix D. Method proposal: Buckling resistance of plastics pipes when subjected to hydrostatic pressure

Key words: plastics pipes, collector, buckling, compressive collapse, BHE, GHX, external load, hydrostatic pressure, test method

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1. Scope
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1  Scope

This Nordtest method describes a way to determine the ability of plastics pipes to resist external load directed at right angles towards the pipe walls, as in case with hydrostatic pressure. The method focuses on pipes used as collectors in vertical geothermal heat exchangers but is also usable for other applications.

The principle of the test is to apply and measure hydrostatic pressure external to the pipe. Deformation of the sample is indicated either by sudden decreases of the measured pressure or by indirect measurement of the compressive deformation during collapse.

2  Field of application

The method is applicable for collectors consisting of plastics pipes of non-coaxial design, or any other type of plastics pipe intended to be used in such an application where an external load is directed constantly at right angles to the pipe walls, as in case with hydrostatic pressure. The method may be used to:

1. Determine critical hoop stress at a given temperature and load duration;
2. Determine time for collapse, i.e. buckling at a given temperature and load
3. Gather input for estimations of long term (50 years) stress resistance as well as to determine time to buckle at given stress and temperature.
3  References

[1]: ISO 3126, “Plastics piping systems – Plastics piping components – Measurement and determination of dimensions.”


4  Definitions

For the purpose of this standard the following definitions apply.

**Buckling**
Plastic collapse of a circular pipe due to external load resulting in an elliptically shaped cross section of the pipe.

**Test pressure (\(p\))**
Difference in absolute pressure between the inside and the outside of the sample expressed in bars. A positive value indicates an external absolute pressure that is larger than that present in the interior of the sample.

**Test temperature**
Temperature of the sample and of it’s surrounding during test expressed in °C.

**Test period**
Time between exertion of test pressure and collapse of the sample expressed in hours.

**Free length**
Length of the sample in metres, exposed to the test pressure whilst unsupported by couplings or other device used for mounting of the test piece to the testing device.

**Mean diameter (\(D_s\))**
Measured in accordance with [1].

**Minimum wall thickness (\(s\))**
Measured in accordance with [1].

**Hoop compressive stress (\(\sigma_c\))**
Circumferential compressive tension in the pipe material as a result of external over-pressure or internal under-pressure expressed in MPa.

5  Sampling and preparation

The number of samples is defined by the intention of test. If the test aims at gathering input for long time estimations of stress resistance, the number of specimens (i.e. observations) should conform to [2] or to a number enabling determination with 97.5 % statistical certainty.
In any other case should the sample consist of no less than three specimens. The sample should be taken from the ordinary production line in accordance to agreement between the manufacturer and the testing institute and belong to the same batch of material and the same extrusion run.

Before testing, an inspection of the sample(s) should be done to make sure no visually detectable defects exist which might have adverse effects on the test results. Any wax, oil or other residue should be removed from the sample before testing.

If storing of the sample is necessary before testing, it should be protected from contamination of substances, surroundings and other factors, which may have adverse effects on the test results.

The test specimens should be straight and have free lengths of at least 7 times the outer diameter.

6 Method of test

6.1 Principle

The principle of the method is to exert and measure hydrostatic pressure on the annulus of the test sample. As buckling occurs the surrounding pressure will decrease drastically whereby buckling is determined. If applicable, other means to detect buckling may be used, such as measurement of volume decrease, as long as the sensitivity and accuracy of the method used is equivalent to the method stated here.

6.2 Equipment

Suitable test equipment is illustrated in fig. 1.

![Diagram of suitable equipment](image)

Figure 1. Diagram of suitable equipment.

**Pressure vessel**, capable of resisting the test pressure and of receiving the sample. The dimension and design of the vessel should enable the sample to move freely lengthwise and be unbent during test.

**Pressure-measuring device** calibrated and with accuracy better than ± 2% of the measured value. The range of the gauge should be such that the measured value lies within the range of calibration.
**Pressurising equipment**, capable of inducing the test pressure gradually and evenly and then of keeping it constant to within ± 2 % for the duration of the test.

**Timer**, capable of recording the duration of the test up to, or beyond of, the point of failure of the test piece.

**Tank**, filled with water or other liquid, kept at test temperature and capable of receiving the pressure vessel.

**Temperature control equipment**, capable of obtaining and maintaining the specified test temperature of the surrounding liquid in the tank with an accuracy of at least ± 0,5 °C.

**Thermometers (or equivalent)**, calibrated and capable of checking conformity of test temperature. The accuracy should be better than or equal to the accuracy of the temperature control system.

**Data acquisition apparatus**, capable to record measured values with a sample time not exceeding 60 s.

### 6.3 Testing environment

During test, the test piece and pressure vessel is submerged in the thermally controlled tank. The tank should be filled with fluid.

Note: When fluids other than water are used, necessary precautions shall be taken concerning safety and any interaction between liquids and materials of the sample.

The test temperature, T, should be within ± 0,5 °C of the designated test temperature.

Note: The result of the test is strongly dependent on the temperature used why deviations from set values always should be kept as small as possible.

### 6.4 Calculation of test pressure

The test pressure (p) to use, based on designated compressive hoop stress may be calculated using

\[
p = 2\sigma_c \frac{s}{D_s - s}
\]

where

- \( s \) = minimum wall thickness of the sample measured according to [1];
- \( D_s \) = mean diameter of the sample measured according to [1];
- \( \sigma_c \) = designated compressive hoop stress in the pipe material.

### 6.5 Pre-conditioning of test samples

Conforming to EN 921, clause 8 [3].
6.6 Method of test

6.6.1 Test procedure

Mount the sample to the pressure vessel in such manner that it is free to move lengthwise and is unbent, and let it condition as specified in clause 6.5. Bleed off all air from the vessel. Apply the test pressure, gradually and smoothly in the shortest time practicable depending on the capacity of the pressurising equipment and size of pressure vessel.

Start the timer and the data acquisitioning when the test pressure is achieved to within ± 2 % of the designated value or within \( \pm 2\% \pm 0.01\text{bars} \) whichever is smallest.

Note: The result of the test is strongly influenced by the pressure why deviations should be kept as small as possible within the specified boundaries.

During the entire test, make sure that the assembly is submerged in the thermally controlled tank.

The test is terminated when:

a. Collapse is indicated by a sharp knee as illustrated in figure 2;

b. Or when deformation consistent to at least 50 % of initial volume of the sample is observed by other means.

The sample should then be dismantled and the deformation verified in sufficiently short time for such a verification to be feasible, after termination of the test.

![Figure 2. Typical shape of test pressure during test. The sharp knee to the right in the figure indicates buckling at time \( \tau_b \).](image)

6.6.2 Data processing

Time to collapse should be evaluated using one of the definitions specified below.
a. The first observation of decline in test pressure leading to at least 2 % loss of pressure as illustrated in figure 2. The rate of decline, i.e. the derivative of pressure curve, should be less than zero at any point during this decline. Points on the pressure curve where the derivative is indefinable, i.e. infinite, may be accepted.

b. The first observation of deformation increase leading to a loss of volume consistent to at least 50 % of the original volume of the specimen tested. The rate of deformation should be considerably higher than any foregoing elastic deformation.

If long-term stress resistance (50 years) is to be determined an adequate extrapolation method should be used resulting in a lower confidence limit of 97.5 % for the predicted long-term strength.

### 6.6.3 Expression of results

Deformation of plastics is governed by level of stress; duration of load and temperature and should thus be defined accordingly.

Test temperature and pressure should be expressed as arithmetic means of individual values up to the point of collapse calculated as

\[
p = \frac{1}{n} \sum_{j=1}^{n} p_j
\]

\[
T = \frac{1}{n} \sum_{j=1}^{n} T_j
\]

where

n = Number of observations;
T\(_j\) = Individually observed temperature, observation point j;
p\(_j\) = Individually observed pressure, observation point j;

Results should be expressed as arithmetic means of the results (X) together with standard deviations (S) calculated as:

\[
X = \frac{1}{n} \sum_{i=1}^{n} x_i
\]

\[
S = \frac{1}{n-1} \sum_{j=1}^{n} \sqrt{(x_i - X)^2}
\]

where

n = Number of tests performed;
x\(_i\) = Result of test nr i.
6.7 Uncertainty

Uncertainty of test is mainly governed by:

a. Uncertainty of measuring device;
b. Deviations of set values;
c. Uncertainty when evaluating time to collapse.

If the specifications of accuracy and permissible deviations stated in this method are met the uncertainty of critical stress, i.e. stress leading to collapse, at a specified temperature and load duration should be better than ± 3 %.

6.8 Test report

The test report shall include the following information:

a. Name and address of the testing laboratory.
b. Name and address of the organization or person who ordered the test.
c. Reference to this method.
d. Name and address of manufacturer or supplier of the specimen.
e. Complete identification of the specimen tested including type and manufacturer’s code numbers.
f. Identification of equipment and instruments used during test.
g. Any deviation from the test method.
h. Results including test temperature, hoop stress of pipe material, test pressure, time to collapse and uncertainty of results.
i. Date and signature.
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