Johannes Wischt

Master Thesis

Pressure Tests for Drillpipe Development

Mining University Leoben
Chair of Drilling and Completion Engineering
in cooperation with
Advanced Drilling Solutions GmbH

Advisor:
Univ.-Prof. Dipl.-Ing. Dr.mont. Gerhard Thonhauser

I declare in lieu of oath
that I did this master thesis

Pressure Tests for Drillpipe Development

by myself using only the literature
cited in the references.

Johannes Wischt, Leoben in September 2011

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Abstract

In order to meet future needs of the industry to drill more complex wells, with the necessity to place the well in the reservoir in the most optimum way, wired drillpipe, on the one hand and composite drillpipe on the other hand might be solutions meeting these demands. To further evaluate materials and verify constructive ideas, a pressure test, applicable to the different problems, was designed.

While composite drillpipe has the advantage to be rather lightweight it also has the flexibility and strength which can be well adjusted in the design process. For example allowing to drill shorter radii or enhanced reach wells. Wired drillpipe has the advantage that it provides a larger bandwidth for data communication with downhole tools, which is a big advantage when thinking of logging while drilling or geosteering.

Due to previous tests showing a leakage of composite pipe at a certain threshold pressure, the leakage behavior and breaking behavior of composite material, especially at increased temperatures, was examined in this work. While the leakage behavior could not be reproduced, the breaking behavior showed the interesting result that composite has a higher breaking pressure with increasing temperature. For examining these behaviors, a testing apparatus and testing procedure was designed.

Furthermore, solutions for applying an armored pipe, protecting wires in a drillpipe, were evaluated. Hereby solutions for leading and sealing the armoring pipe through the tool joint of the drillpipe were tested with simplified tests. The tested lead-through solutions involved cutting rings, which are commonly used for hydraulic applications. Due to the different loading, two ways of using these cutting rings were evaluated. While both test setups showed no leakage, further tests will be necessary to fully evaluate the cutting rings under combined loads.

Introduction

With the industry's demand to drill more complex wells with an optimized reservoir exposure and challenging trajectories, drillpipe that is applicable for these problems becomes necessary. The following thesis discusses different ideas and aspects of composite and wired drillpipe, with a special focus on a pressure test for performing tests on both subjects and the evaluation of the performed tests.

On the one hand a lighter or more flexible drillpipe is often required, for example for drilling shorter radii or for drilling extended reach wells. Composite drillpipe might be one solution for these challenges as it can be purpose designed. Depending on the application it can be designed e.g. for a high or low stiffness, or a higher torsional strength by adjusting the fiber structure in the composite matrix. While composite material seems to be well applicable for drillpipe, there are also several disadvantages. One is the leakage behavior, which has been previously encountered by Advanced Drilling Solutions GmbH when testing composite tubes with internal pressure, but is also reported in the literature. In order to generate more data on this behavior and find possible methods of mitigating this behavior several tests were conducted. Moreover burst tests were carried out at different temperatures to get a better understanding of the composite material for designing composite drillpipe at a later stage.

On the other hand optimizing reservoir exposure and also enhancing the drilling envelope requires downhole measurements. Having LWD (logging while drilling) data available in real-time, allows correcting the trajectory such that it is placed in the reservoir in the most optimum way. While having data from sensors monitoring the drilling process available at the surface may also allow optimizing the rate of penetration and the overall drilling process. However, for communicating data from downhole tools to the surface is necessary for any of these applications. While the communication is nowadays typically done with mud pulsing, allowing only a very small bandwidth, a wired drillpipe would accommodate the demand of a higher bandwidth. Although an electrical connection from the surface to the downhole tools is most favorable, several problems arise. Sealing and leading an armoring pipe, accommodating the wires, through the tool joints is still an unsolved problem. Therefore, finding and testing lead-through solutions were a further objective of this work.

Composite Drillpipe

Composite materials, made of carbon fibers or fiberglass and a resin, can be designed for several purposes in the oil industry. They are lightweight, but also can reach properties comparable to steel. This gives many advantages, as the weight of a drillstring results in torque and drag forces in inclined wells, which can be minimized that way. Therefore it might be a good option for special needs, like extended reach or ultra deep wells, where the weight of the drillstring and the torque and drag forces are critical. Also the combination of steel and composite drillpipe brings several drillstring design advantages, especially cost wise, since composite materials are rather expensive compared to steel drillpipes. E.g. a steel drillpipe can be used for vertical hole sections, while composite drillpipe is then used only in the lower, horizontal section of the drillstring, or the part of the drillstring that is e.g. exposed to the curved borehole section.[1]

Also, composites have a superior corrosion resistance compared to steel against media that might occur when producing a well. Therefore, depending on the fluids that are produced along with hydrocarbons, composite materials may be well applicable for tubing or casing tubulars.

On the other hand, also depending on the design of the drillpipe, composite materials can be very flexible, compared to other metal or steel drillpipes. Thus, composite drillpipe is flexible enough to pass through curved borehole sections with a rather short radius and can tolerate the high stresses that occur during e.g. short radius drilling. Also it shows a better fatigue life under these circumstances.[1]

Beside the mechanical advantages for special drilling operations, the production process allows the integration of electrical wires or fiber optic leads for high-speed data communication downhole. Besides communication, this is also an option for power transfer.

For similar reasons, like with other non-metal materials, the tool joints are made of steel. This allows the use of the standard pipe handling equipment at the rig. Beside that, the material itself limits its use for tool joints. Composites can be designed to work ideally in plane stress situations, according to the orientation of the carbon fibers, but its applicability for complex 3-D stress fields as the occur in a pin – box connection at the thread is very limited. Therefore, steel joints are mounted on the composite drillpipe. The composite to metal interface that needs to transmit torque and tension, is a big design challenge.[1]

A disadvantage of composite materials is their high physical wear, compared to metal drillpipes. Especially in highly abrasive formations, a high degree of wear can weaken or damage the drillpipe, since every scratch or abrasion on the composite surface results in fewer carbon fibers with integrity that can take loads. Solutions for the protection of the drillpipe can be either the coating and therefore strengthening the surface against wear, or avoiding wear, e.g. with centralizer, that reduce the contact with the borehole wall. Also the inner pipe surface is subject to wear due to the mud circulation and needs protection.

Another major disadvantage of composite drillpipe is the hydraulic behavior. To achieve efficient pipe properties (strength etc.), the wall thickness becomes relatively thick. Comparing steel and composite drillpipe with comparably strengths, the composite drillpipe would have almost twice the wall thickness of the steel drillpipe. This reduction of inside diameter results in increased pressure losses that need to be considered for when planning the drilling operation.[1]

Besides that, composite materials can be affected and weakened by the downhole conditions. One factor is the increased temperature and the wet environment, which can result in hydrolytic or hydro-thermal degradation. This can have a significant impact on the material properties. Also water in general affects the composite drillpipe, if e.g. it gets in contact with the composite material through scratches. Hereby water has two main effects. It causes swelling of the composite material as the water is absorbed, which results in uneven internal stresses, causing micro-fractures, delamination, and the bond between matrix and fibers may be weakened. On the other hand, water absorbed by the composite material can act as a plasticizer to the matrix material, as it attacks the matrix polymers and breaks their chemical bonds. Also other substances in the wellbore, e.g. salts can have effects on the composite material. Even though these are only minor effects[2], they need to be considered when designing the drillpipe for its application. Also a sufficient coating can be a sustainable option.[2]

Design and Manufacturing

Composite tubular products are typically built of a thermosetting plastic resin with continuous strands of fiber inlays for reinforcement. There are different options and combinations for the fiber and resin materials. While fiberglass has especially been used in the beginning, graphite / carbon fiber, is mainly used for tubular oilfield products. Another option is a fiberglass graphite fiber mixture. Typically polyester, vinyl ester, or epoxy thermosetting resins are used.

Production

While there are different processes available for the manufacturing of composite components in general, composite tubulars are typically manufactured by winding of fiber around a designed form. For tubular production, this is a cylindrical mandrel. The endless fiber strands, so-called filament, are wound in bands over the mandrel in several layers, forming the tube. For the further processing, the fiber is impregnated with a resin. When the winding process is finished, the tube is placed in an oven, where the polymer resin hardens due to cross-linking of polymer chains, which is triggered by heat. After the curing is finished, the tube has reached its full strength. Further on, there are options for hardening the surface with resins, to counteract wear, and steel tool joints are mounted, as described in the following chapters.

Design

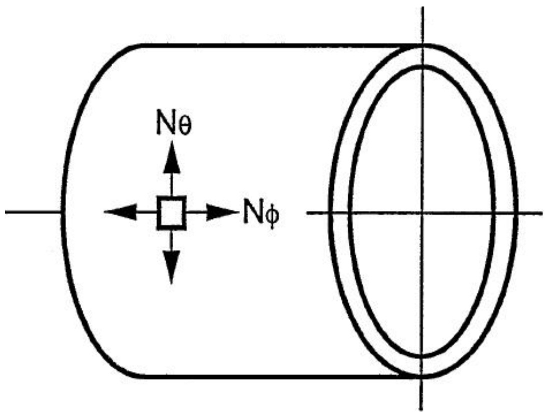


Figure 1: Orientation of loads in a composite cylinder [4]

The direction and structure of the fiber strands defines the loads that a composite can support. Therefore the design of the fiber layers and their angle is very important as it defines the properties of the product. Typically, for tubular structures, one part of the layers is wound perpendicular to the longitudinal axis of the tube. These, so-called hoop fibers, carry circumferential and pressure loads. If they are wound under tensions, they also squeeze out excessive resin from lower layers. The other layers that are wound

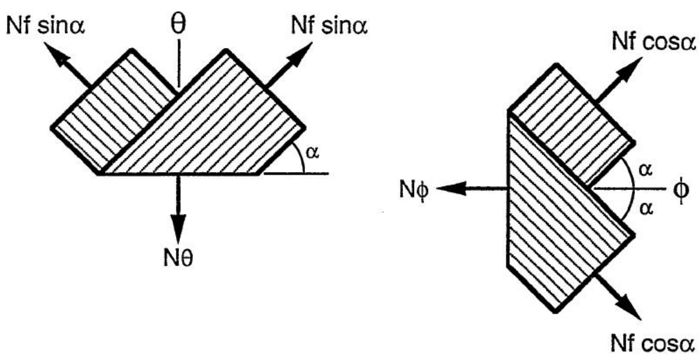


Figure 2: Loads acting on the fiber layers in θ and Φ direction [4]

under a certain angle are called helical layers, as they form a helical spiral in the cylinder. Depending on their angle, they define strength and stiffness of the product. Typically layers with low angles carry axial loads, while layers with high angles, close to the hoop layers, carry circumferential loads and layers at 45deg increase torsional strength. The different layers are usually alternated for better stress distribution.

While there are different software packages and finite element analysis available for composite design, the netting theory, which is based basic mechanics, still gives a good idea of the design. However, it uses several simplifications. For example there are no interactions between the different fiber layers and the resin does not carry any load. Also the tube wall does not carry any out-of plane stresses.

At any position of the tube, the composite wall is subject to the main membrane loads N_θ and N_Φ (see Figure 1). By definition, and as can be seen in Figure 2, one layer of fiber consist of two plies of fiber. This results in the following equations, to satisfy force equilibrium: [3]

$$N_\Theta = 2 * N_f * sin^2(\alpha) \quad \text{(Eq. 1)}^4$$

$$N_\Phi = 2 * N_f * cos^2(\alpha) \quad \text{(Eq. 2)}^4$$

Where:

N … membrane load [lb/in]

For further variables see Figure 2

This only describes the case where the entire load is supported by one helical layer of fiber. For a cylinder, thought, many layers at different angles need to be considered. Thus, the total supported force can be calculated by superposition. Hereby, the layers are assigned with different angles α_j and n_j describes the number of plies with the corresponding angle.[3]

$$N_\Theta = \sum_{j=1}^{i} 2 * n_j * N_{fj} * sin^2(\alpha_j) \quad \text{(Eq. 3)}^4$$

$$N_\Phi = \sum_{j=1}^{i} 2 * n_j * N_{fj} * cos^2(\alpha_j) \quad \text{(Eq. 4)}^4$$

The loads that have to be expected due to internal pressure, axial tensional load and bending can be determined as follows:

$N_{\theta P} = P * R$ (Eq. 5)[4] … internal pressure

$N_{\Phi P} = \frac{P*R}{2}$ (Eq. 6)[4] … internal pressure, when ends of tube are closed

$N_{\Phi T} = \frac{T}{2*\pi*R}$ (Eq. 7)[4] … axial tensile load

$N_{\Phi B} = \frac{M}{\pi*R^2}$ (Eq. 8)[4] … bending moment

Where: P … internal pressure [psi]
R … inside radius [in]
T … tensile load [lbf]
M … [in-lb]

The internal pressure results in two forces, one acting on the pipe wall, which results in a load in θ – direction, but the pressure also acts on any constriction in longitudinal direction (or when one or both ends of the pipe is closed) and therefore results in a tensile load on the pipe.[3]

Knowing the strength of one layer of fiber N_f and also knowing its thickness, allows calculating necessary layers and total wall thickness to achieve the desired total strength. For thickness calculations the resin in the matrix needs to be considered. Thus, the calculated thickness needs to be divided by 0.6 to account for the resin in the matrix. The value of 0.6 is an approximation for the volume of fiber in the matrix, it can reach up to 0.7, if the fibers are in one direction only, or be as less as 0.5 for composites using fibers in cloth form.[4]

For the design, knowing the actual fiber strength is essential. On the one hand this is a material parameter, but moreover, it is also dependent on several influencing factors. E.g. cyclic loading, long term static loading, thermal effects, chemical degradation, ultraviolet degradation, fabrication process variation, stress concentrations and unconformities in the product, and structural geometry reduce the virgin composite fiber strength.

Calculating the actual strength is done with probabilities, which results in the following equations:

$$\sigma_\alpha = \sigma_\nu * P_c * P_s * P_t * P_{ch} * P_u * P_p * P_{sc} \quad \text{(Eq. 9)}^4$$

$$\sigma_\alpha = \frac{2 * N_f}{t_\alpha} \quad \text{(Eq. 10)}^4$$

Where: σ_α … allowable fiber design strength / stress [psi]
σ_v … virgin fiber strength of the strand [psi]
P … one minus the reduction of the fiber strength [1]; the subscripts represent the influencing factors: cyclic load, long term loading, thermal degradation, chemical degradation, ultraviolet degradation, process variation, stress concentration factor (in the same order)
N_f … membrane load [lb/in]
t_α … fiber thickness of all layers in direction α [in]

The different modifiers can be understood as a strength reduction for a certain expected life of the product. E.g. if a product is designed for 10 years or a certain amount of cycles, the strength of the fibers weakens over time, resulting in an ultimate strength of the material after this time. This is expressed as a factor for each weakening process, which is then multiplied to obtain the reduced material strength. The factors can be determined from empirical charts, knowing the influencing parameters, similar to an S-N diagram for metals. Besides the strength reducing factors, temperature is both, reducing strength, but also giving a general maximum operating environment of about 300 to 350°F depending on the used resin.[5]

Introducing the strand strength in the design is done with the stress at angle α, which is the material strength on the one hand, but also the load in α – direction divided by the thickness of all layers in this direction. Further on, the necessary thickness can be determined for a certain load scenario.[4]

Tool Joints

Since composite materials do not suit for complex 3D stresses like they would appear in a pin – box connection, the tool joint has to be manufactured of another material and then be mounted on the composite pipe. A metal tool joint with standard API thread pattern is used, allowing mixed composite steel drillstrings. These tool joints also bring the positive side effect, that the pipe handling, e.g. iron roughnecks that are designed for steel drillpipe, can be used with composite drillpipes as well.

One of the major design problems of composite drillpipes is the steel – composite interface at the tool joint, which has to withstand torsional and tensile load.

One solution (see Figure 3) is a drilled-and-pinned system, joining the steel tool joint to the composite pipe. Therefore two rows of radial holes are drilled through the steel – composite interface. Steel dowel pins are then press fit into the radial holes, to transfer the stress from one material to the other.[7] The steel pins are exposed to shear stress and bearing pressure, which is also applied to the composite and the steel. The number of pins and their diameter are calculated from the stresses that need to be transferred and the material properties (e.g. how much contact pressure by unit area they can support without damage).

A steel sleeve is weld to the tool joint. It holds the pins in position and provides the surface for applying tongs or iron roughnecks etc. The resulting composite – steel interface is adhesively bond together. For a 5½in composite drillpipe with metal (steel or titanium) tool joints ultimate tensile strengths of up to 200,000lbm have been reported.[7]

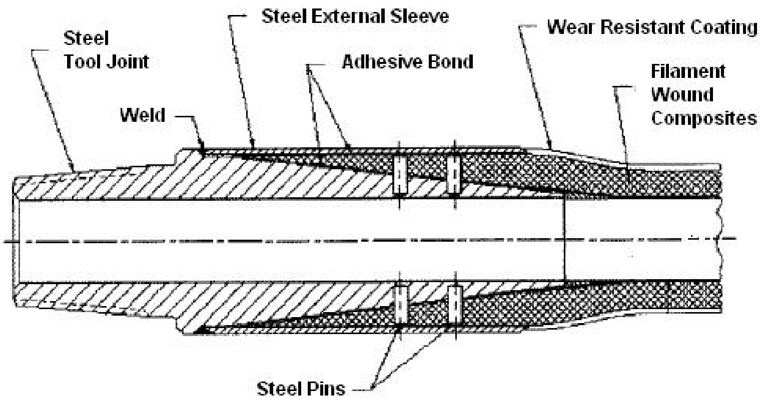


Figure 3: Cross-sectional view of a steel - composite interface of a tool joint[7]

Using the same technology, the female tool joint is mounted on the other end of the drillpipe. Additionally so-called wear knots or centralizers are placed along the drillpipe, to protect the pipe body from excessive wear. These sleeves are typically built with fiberglass cloth to the required diameter and a steel sleeve is attached to decrease wear. The steel sleeve therefore is mounted with the same drilled-and-pinned system as the tool joints.[6 7]

For weight reduction other materials than steel for the tool joints and centralizers can be applied. E.g. titanium gives a certain weight reduction, while the material properties for the tool joints are comparable.

Young's Modulus

Composite materials generally show different Young's modules for different directions. Since a composite material typically consists of layers at different angles and every layer has different properties in different directions, determining a Young's modulus for the entire compound can be rather complicated.

Generally a fiber ply has a main direction, in which it can take a very high load. Perpendicular to that direction, the ply is the weakest. The Young's modules of single layers can be calculated from the fiber and resin properties of the used components.

Since a composite tube would consist of layers with different angles, the total Young's modulus is also a result of the single layers, their direction and the direction for which the Young's modulus is calculated. E.g. for bending, hoop layers will only have a minor influence, as for them only the transversal Young's modulus can be considered. For layers parallel to the pipe's axis, the longitudinal Young's modulus would be considered, and for the other layers, with a certain angle, both the longitudinal and transversal Young's modulus has to be considered in combination with the angle of the layer. The thicknesses of the layers would weight the Young's modules for the layers with the rule of mixture.

This shows again, that the Young's modulus can be designed for the different purposes of a drillpipe. Depending on the tension a drillpipe needs to support, layers with a low angle need to be applied, a low angle on the other hand means stiffness against bending, while layers with an angle of approximately 45deg create a good torque resistance, but result in little stiffness against bending.

The Resin and its Temperature Dependency

An epoxy resin is typically used as the matrix material in composites.

Generally an epoxy resin is a thermosetting polymer that is formed from an epoxy resin and a polyamine hardener, resulting in an amorphous structure (see Figure 4). Adding a hardener results in curing a narrow meshed structure, a so-called duroplast, which is an irreversible process.[8]

Due to the short distances between the molecules and the well meshed structure, micro movement of the molecules is not possible, which makes duroplasts very stiff at room temperatures. At elevated temperatures, however, some movements of molecules become possible, which can lead to a softening of the material. A melting, like with thermoplasts, of set duroplasts is however not possible.[8]

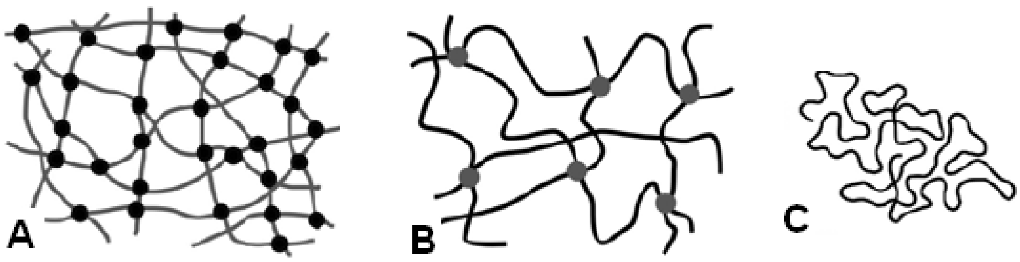


Figure 4: Narrow meshed, amorphous structure of a duroplast (A), compared to elastomer (B) and thermoplastic (C)[8]

The temperature where the duroplasts or plastics in general become soft is referred to as glass transition temperature.

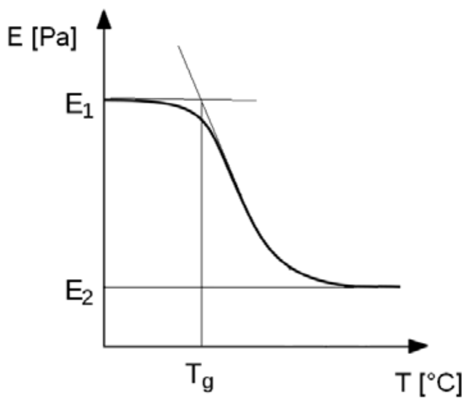


Figure 5: Glass transition temperature

Figure 5 shows the schematic behavior of the Young's modulus with increasing temperature. The glass transition temperature Tg hereby indicates the temperature where the initial Young's modulus E1 starts changing to E2, which is evaluated after the tangent method (DIN 65583).[9] The glass transition temperature should not be considered as an absolute value, it gives rather an idea of temperature where the behavior of a plastic changes.

Increasing the temperature has little effect for duroplasts. For thermoplasts, which do not form knots, but are essentially chain molecules forming a meshwork, the curve has a plateau with E2 and then the Young's modulus further decreases as the melting temperature is approached and the material melts.[8]

This material behavior is an essential property of the composite product that it is used for and the epoxy resin and hardener need to be carefully chosen for the desired properties of the end product. Generally the glass transition temperature can be as low as ca. 70°C, but as already mentioned highly depending on the used materials.[10]

The carbon fibers in the composite however generally do not need further attention as they are very resistant to temperatures below 600°C.[10]

Problems and Possible Solutions

Besides all the advantages that composites have for oilfield applications, the material also has weaknesses, that limit its use. As already mentioned, one is the high degree of abrasion in abrasive formations and the resulting limited lifetime of e.g. composite drillpipe. On the other hand, there are several limits that need to be considered. One of the most important ones is the temperature. Especially when using composite drillpipe for weight reduction of the drillstring, for very deep applications, this might become a problem. As any other synthetic material the resin and fiber materials used have a rather low glass transition temperature, compared to metals. If however the temperature where the synthetic material starts to change from a hard, brittle state, to a soft, rubber-like state is rather low, this essentially gives the limit for applying the material for higher temperatures. Selecting the right material is can however solve or oppose these problems. Other problems, like leakage at increased internal pressures or abrasion need to be addressed differently.

Leakage

The problem further investigated in the following is the leakage of composite materials under high pressure applications in general and the specific problem of leaking composite tubulars tested by Advanced Drilling Solutions GmbH. As previous tests have shown, when applying an increased inside pressure to a composite pipe, it starts to leak at a certain threshold pressure. When releasing the pressure to a lower level, the leakage stops and the pipe seems to be tight again, until increasing the pressure again. The general failure mode, of a sudden appearing leakage can be seen in Figure 6 where the test was carried out with E-glass fiber pipe specimen (ID=38.1mm, OD=40.7mm, length=90mm). The end tabs were mounted by adhesive bond, to ensure a good sealing and the test was carried out with a hydraulic oil (viscosity $\mu_{oil}=6.56*10^{-2}$Pa/s). Interestingly, the test also found that the pressure loading rate as a not negligible influence on the leakage behavior. The test was carried out with loading rates of 0.46, 4.63 and 46.3kPa/s.

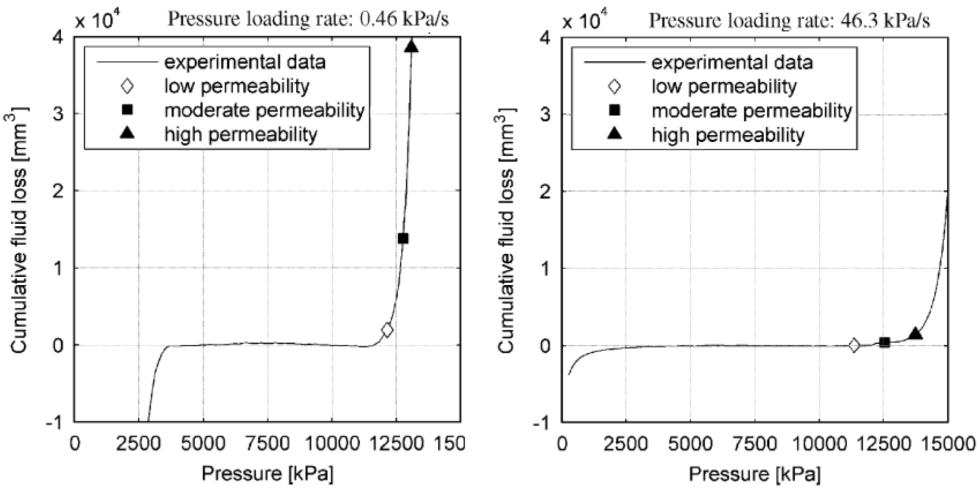


Figure 6: Fluid loss vs. pressure at different pressure loading rates[11]

As Figure 6 shows, the pressure loading rate has a relatively high impact on the leakage threshold pressure and seems also to influence the severity of the formed fractures. While this test was carried out with three loading rates, resulting in corresponding results, Figure 6 only shows the lowest and highest loading rate.[11]

This damage mode results from fractures that generate from cracks in the polymer matrix, which occur in all layers and if they happen to intersect, a flow path through the entire structure can be generated.[12] Besides these transverse cracks, running parallel to the fibers, there are generally many other defects that can cause leakage or generally influence the leakage behavior. This can for example be debonding between fiber and matrix, voids or other defects introduced to the matrix during production.[13] Hatta et.al. found that the main leakage routs are transverse fractures that intersect as can be seen in Figure 7.

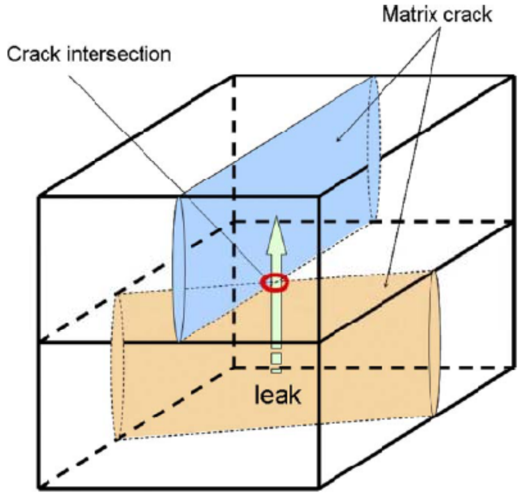


Figure 7: Leakage induced by multilayer matrix cracks[12]

Besides all the negative impacts that leakage of composite pipe may have, one further problem is gas invading into the composite structure. Especially when applying composite material for drillpipe or tubing, which can be recovered from the wellbore. While the tubular is in the borehole, fluids, especially compressible fluids like gas, can enter the composite matrix under a high pressure. When recovering the tubular from the well, and consequently reducing the pressure, the compressible fluid that is entrapped in the composite matrix, would expand and may damage the composite matrix.

Figure 8 shows a magnification of composite cross-sections. Especially the transversal cracks can be very well seen in the 2D-C/C cross-section. Further defects like delamination and matrix pockets can be seen in the 3D-C/C cross-section. Another defect found are elongated voids, which are fiber scale voids in the composite matrix that extend along fibers over rather long distances.[13]

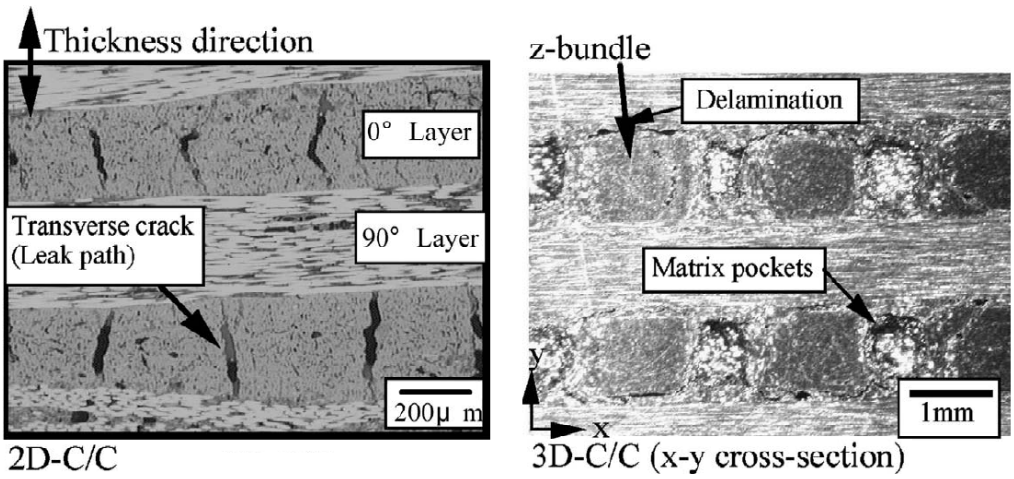


Figure 8: Cross-sections of a cross-ply laminate (2D-C/C) and a 3D reinforced laminate (3D-C/C)[13]

Possible reasons for the transversal cracks and the delamination are especially the anisotropic shrinkage of the matrix in the carbonization process and also due to differences in thermal expansion.[13]

Another variable influencing the leakage behavior are forces acting on the composite material. Tests with uniaxial loading applied to composite coupons showed, that the leakage rate resulting from a constant applied pressure, highly depends on the uniaxial tension applied. The actual values highly depend on the direction of the applied tension relative to the fiber structure. Figure 9 shows the leakage rate in relation to an applied uniaxial tensional stress. The test has been carried out with gas and a relatively low pressure of 1bar, still showing a clear dependency on the tensional stress applied.[12]

Since the forces acting on a drillpipe are rather complex and also the design of the composite structure would be so, it is rather hard to evaluate the impact of a single stress state on the leakage behavior of a more complex structure and it becomes even harder when the stress state is not constant.

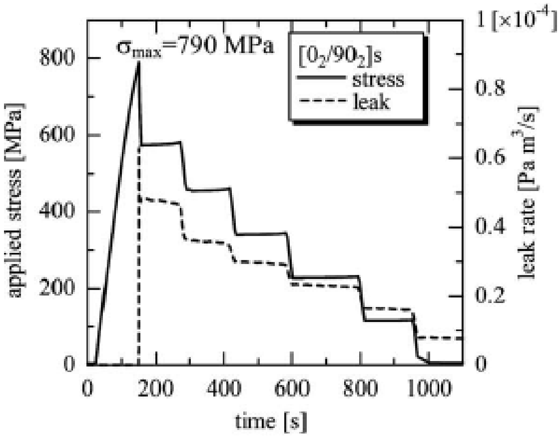


Figure 9: Leakage rate in relation to tension[12]

Cyclic load or stress reversals are very common when thinking of a drilling process. Rotating drillpipe in a deviated wellbore, varying tensional loadings and vibrations etc. would be the most common forces acting on drillpipe. While these forces may cause fatigue and can shorten the lifetime of a drillpipe, also the integrity of the structure is highly influenced and consequently the leakage behavior is influenced as the forces are introducing small cracks that contribute to the fracture network of the composite.[12]

Leakage of Composite – Previous Tests

Previous tests, carried out by Advanced Drilling Solutions GmbH, which examined composite tubulars amongst others for internal pressure, showed that the specimen started leaking at a certain threshold pressure. The used specimen had the following specifications.[14] The results presented in Figure 10 present the leakage pressure of the given pipes.

Fiber	TOHO Tenax® HTS 40
Resin	Huntsman Araldite® LY 556
Outside Diameter	33mm
Wall thickness	1.3, 2.25, 3mm
Fiber volume fraction	ca. 60%
Fiber structure	± 45deg

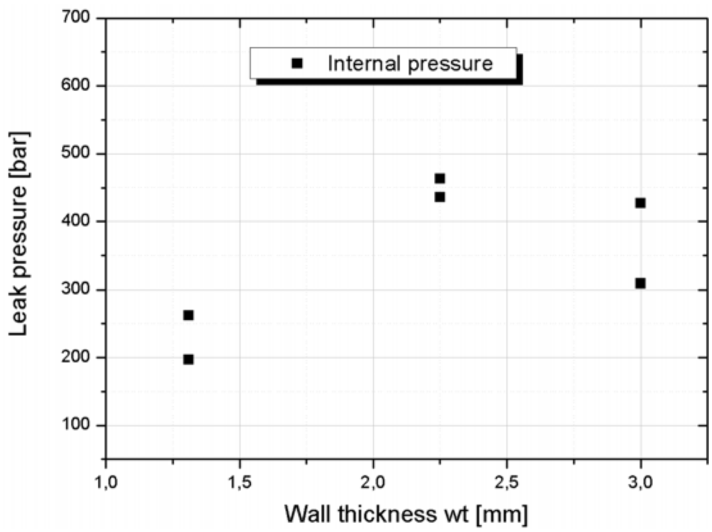


Figure 10: Leak pressure vs. Wall thickness of previous tests[14]

Possible Solutions

There are many possible solutions for improving the leakage behavior of composite material. Mainly by introducing some sort of coating or in general a sealing layer on the surface of the composite. There are also several possibilities to improve the structure or introduce sealing layers within the structure. The main difference is if the sealing layer is applied on the surface or within the structure. The latter one has the main disadvantage that it represents a discontinuity in the composite and therefore weakens the entire structure.

Plastic liner

One way of introducing a fluid tight pressure barrier in a composite pipe is a plastic liner. This has several advantages. Beside the sealing effect of a liner, a plastic liner may also easily allow the implementation of electrical wires for downhole communication of power supply. Furthermore, depending on the material, the density of the plastic liner may not be too high and divergent compared to the composite, which saves weight. Also the Young's modulus of plastics is rather low compared to metals, which leaves the overall stiffness of the drillpipe rather unaffected (compare values from table below with e.g. Young's Modulus for steel: 29000ksi).

On the downside, a rather large reduction of the inside diameter may result from the necessity of a rather thick plastic liner. Besides that, the applicability of specific plastics according to the expected temperatures and media need to be closely considered. The following table gives a overview and ideas over possible materials and their essential properties:[15]

Material	Media				Max. Temp.	Density	Young's Modulus
	Aromatics	Aliphatics	H_2O	Acid	[°F]	[g/cc]	[ksi]
PE	--	-	++	+	160	0.95	130
PP	--	+	++	+	180	0.91	200
PA11	+	++	-	--	212	1.04	180
PK	+	++	-	-	220	1.24	230
PVDF	++	++	++	++	500	2.15	70
TFE	-	+	++	+	250	1.78	213
FEP	+	++	++	+	400	2.15	80
ETFE	+	++	++	+	350	1.70	200
ECTFE	+	+	++	+	275	1.68	240

Table taken from Reference 15.

Where:

Polyethylen	PE	Polytetrafluorothylene	TFE
Polypropylene	PP	Fluorinated Ethylene Propylene copolymer	FEP
Polyamide 11	PA11	Ethylene-tetrafluoroethylene copolymer	ETFE
Polyketone	PK	Chlorotrifluoroethylene – ethylene copolymer	ECTFE
Polyvinylidene Fluoride	PVDF		

Beside the presented materials, others may exist and be also well applicable. However, when considering a plastic liner, also the adhesive bond between pipe and liner and the different thermal expansions of the liner and pipe body need to be considered.

Metal liner

Beside a plastic liner, also a metal liner is a possible option to seal and protect the composite pipe body. Especially erosion corrosion resistance and comparably thin wall thicknesses are advantages of metal liners. However thermal expansion relative to the used composite, adhesive bond and the comparably high stiffness of metals might be problems to consider. Due to the conductivity of metals, metal liners might also provide an electrical connection e.g. for communication or power supply of tools in the drillstring.

Improved fiber structure

There are several variables that can be adjusted when designing a composite towards a good leakage behavior. The first thing is a decrease of layer thickness. The winding of pipes is usually done with roving or tapes and the maximum stress applicable results from orientation of the plies and the thickness of the plies. The thickness however can be broken down into the so-called roving tex or tape thickness. Since the crack deformation for unidirectional plies in multi-directional composites is known to increase with ply thickness, a smaller ply thickness is desirable as it consequently has a direct effect on the leakage pressure.[16] Figure 11 clearly indicates the dependency of the rowing tex on the leakage pressure of a test that has been carried out with fiber glass/epoxy (ED-20) pipes with an internal diameter of 111mm, a wall thickness of 4mm and water was used as a testing fluid.[16]

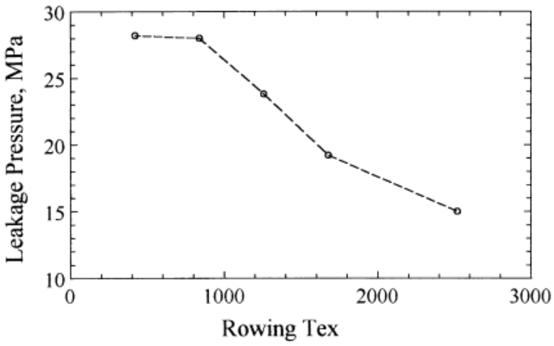


Figure 11: Dependency of leakage pressure on rowing tex[16]

As described in chapter "Design and Manufacturing", the orientations of layers have a high impact on the later properties of the pipe. Generally speaking, introducing ±55deg layers has shown to have a high impact on the reinforcement of pipe that is internally pressurized and can therefore also improve the leakage behavior.[16]

Ductile sealing layers in the matrix

While the fiber structure and especially the application of the said 55deg layers can improve the leakage behavior, a further step in matrix design is the implementation of barrier layers. These barrier layers generally consist of a significantly higher resin to fiber ratio, can e.g. consist of up to 90-95wt%. Due to the high resin content, these layers have a very low content of pores, matrix cracks and violations of fiber-matrix bonds and as a consequence of that have a high resistance of liquid penetration through them.[16] These barrier layers act very similar to unreinforced polymer. Although these layers can be generally described as rather ductile layers, they can change to a brittle structure under the effects of e.g. aggressive environments or shocks.[16]

For further improving the structure of such layers, dividing layers can be introduced between sealing layers, to avoid possible propagation of cracks from the actual composite structure into the sealing layers in an early stage of loading.[16]

While these layers seem to be a good way of improving the general leakage behavior, there are also downsides, that make them not that well applicable. On the one hand, sealing layers are generally speaking only improving the leakage behavior and not eliminating leakage problems, as the problem of bad fiber resin bonding, cracks in the matrix or matrix defects caused during production can still cause bad leakage behavior. On the other hand, introducing a layer with different properties in a composite structure is not desirable, as it is an obstacle and stress a riser and may make it necessary to increase the wall thickness.

Coating

Coating generally is a production technique for surfaces. It essentially means the application of an adhesive layer of an amorphous material on the surface of a substrate. Depending on the technology, the applied coating layer has different properties, like thickness, hardness etc. but it can also consist of multiple layers. Generally it is differentiated between chemical, mechanical, thermal and thermo-mechanical processes. Also the material used for coating can have any state from vapor to solid.[17]

PVD (Physical Vapor Deposition) is a vacuum deposition of a thin film on a target surface. The vaporized material is bombarded at the target, where depending on the time of the bombardment a thin film develops, atom by atom.

The widely used techniques for coating are magnetron sputtering, pulsed laser ablation and arc evaporation. For the deposited coatings, typically are very hard, thin ceramic coatings. Carbides, nitrides, borides and silicides of the 4th, 5th and 6th groups of the periodic table are typically used. The most common ceramic coatings are TiN, CrN, TiCN and TiAIN.[17]

Magnetron sputtering is one of the most common and an extremely flexible coating method. It can be used on basically any material and is therefore well applicable for coating composite materials.

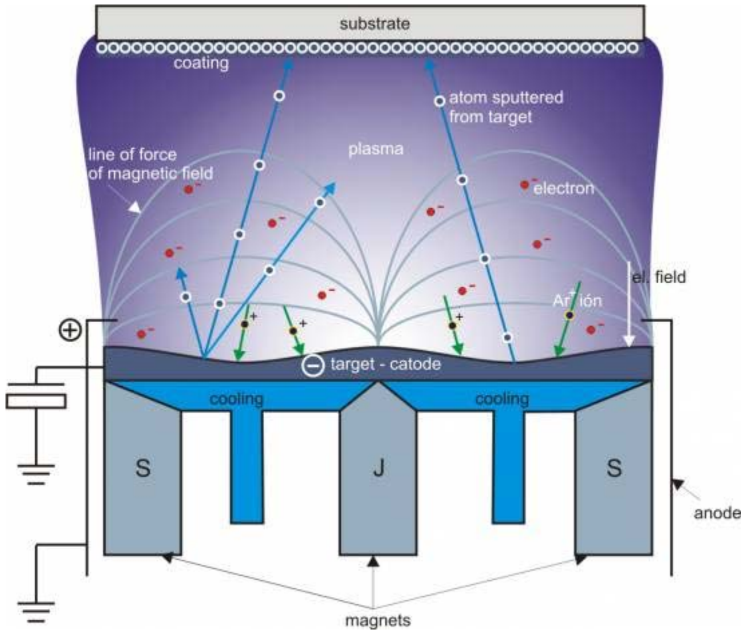


Figure 12: Magnetron sputtering - schematic[17]

Prior to the sputtering process a vacuum of less than one ten millionth of atmospheric pressure must be achieved. Once this pressure is established, an inert gas flow is introduced. A negative potential of typically -300V or more is applied on the target, the cathode that should be deposited on the substrate. The negative potential attracts the positive ions and causes an acceleration of the ions towards the target. Bombarding the target with inert gas ions, typically argon, knocks atoms out of the target surface. These so-called sputtered atoms are neutrally charged and not affected by the magnetic field and can therefore move towards the substrate where they condensate and form a thin film of the sputtered material. The very low pressure is essential, so that the sputtered atoms can reach the substrate and do not get lost by colliding with gas atoms. The magnets are used o trap secondary electrons close to the target, which accelerates the process.[17]

The other said coating techniques work on a similar principle. They all have a way of dissolving atoms from the target, which are then condensed on the substrate.

Besides the small thickness of the coating, which is advantageous in many cases, the coating also has a high hardness is resistant to wear and abrasion and due to its small thickness also adds only very little weight to the pipe body. Also, the coatings are conductive which can be e.g. used for downhole communication. On the downside, the strain of the substrate or drillpipe generally must not exceed 2%, to ensure the integrity of the coating and also the application of the coating on the inside of a pipe needs to be further investigated.

Abrasion

The physical wear or abrasion on the exterior is a known disadvantage of composite drillpipe compared to standard steel pipe. The degree of wear highly depends on the abrasiveness of the formation that is drilled, on the deviation and build radius, and on the pipe geometry itself. Since wear can severely damage the composite structure and weaken the drillpipe, protective measures become necessary.[19]

On the one hand, wear resistant coatings can be used improve the wear resistance. These coatings, e.g. urethane or epoxy based materials, are applied on the composite surface and provide a harder, more wear resistant surface than the blank composite body.[19]

An other option are so-called wear knots, which are simple centralizers, that are positioned on the pipe in well designed distances, so that these wear knots and the metal tool joints have contact with the borehole wall rather than the composite pipe body. The wear knots are essentially either short steel tube section that are mounted on the composite pipe body, possibly even partly in the fiber structure (see Figure 13). Also high durometer elastomeric centralizers as they are used for protecting steel pipe can be used. A positive side effect of using wear knots is reduced torque and drag on the drillpipe and the possible protection of the casing.[19 20]

Internal wear however is not a serious problem and can be addressed with similar measures that are used for steel drillpipes, where rather thin thermoplastic coatings or liners are typically used.[19]

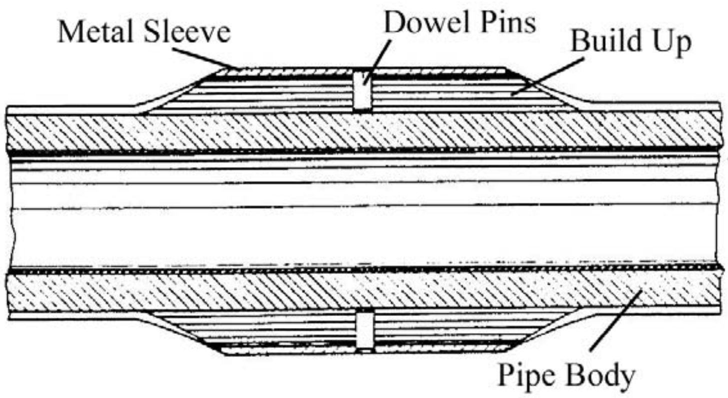


Figure 13: Sketch of mounted wear knot[20]

Conclusion

Composite materials clearly have several advantages for the use as composite drillpipe. The ability to design the materials properties in the manufacturing process allows the development of purpose fit drillpipe that has the desired stiffness or flexibility, which is especially useful e.g. for short radius drilling. Besides that the composite material is rather lightweight and therefore, in inclined wells, where torque and drag can be a problem, composite drillpipe may be the solution. However, there are still issues, like the leakage of composite materials that need to be considered. While previous tests showed that composite materials are subject to leakage, the tests described in the following should verify this behavior and gather more information on this subject. Also the hydraulic loading capacity in relation to the different temperatures was further investigated.

Lead-Through Solutions for Wired Drillpipe

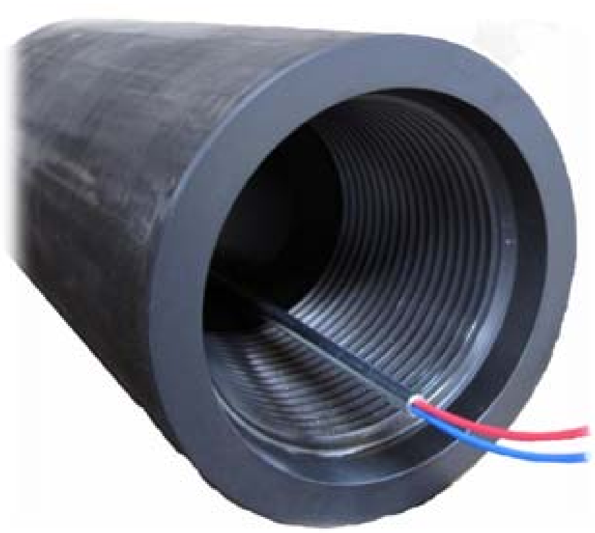


Figure 14: Symbolic wired drillpipe

Wired Drillpipe

With the demand for drilling more complex wells with an optimized reservoir exposure to improve the recovery from the reservoir, new technologies like LWD (logging while drilling) or geosteering play a big role. For a long time, mud pulsing was a common method for downhole communication. While this might be sufficient for technologies like MWD (measurement while drilling), where comparably little data needs to be communicated, it is not for tools generating more data. Also the use of tools that store the recorded data, which can be recovered once the tool has been tripped out of the well is not an option for more advanced technologies. The bandwidth plays an important role hereby, if it allows to communicate e.g. logging data in real-time, it allows to evaluate the drilled formation right away and furthermore allows adjustments to the trajectory to place a well in the most optimum way. Still the data generated by measurements like gamma ray, multiple resistivity, density, neutron logs, formation imaging and others may lead to tremendous data volume. Therefore, selecting the most important data at a sufficient resolution for communicating to the surface and making decisions, is necessary. The excessive and more detailed data can be stored in the tool and e.g. downloaded when reaming or circulating.[21] This obviously requires a two way communication so that settings at the downhole tools can be adjusted. This for example allows drilling along thin reservoir layers, ensures the optimum placement of the wellbore in the reservoir and the measurement of drilling parameters like weight on bit, torque and vibrations which may help to improve the overall drilling performance. Having all this data available also allows monitoring the drilling process from remote operation centers, from where critical decisions can be made, having a better knowledge of what is happening.[21]

What is necessary for a sufficient downhole communication is essentially a conductive path through the entire drillstring. While this might sound rather simple, it still holds many challenges. First of all, the inside diameter should be rather unaffected by the introduced wire, so that e.g. balls can still be dropped for the activation of certain tool and it should also be possible to run tools into the drillstring. Besides that the connection is also a big challenge, since a continuous wire in the drillpipe would not allow to add or remove stands of drillpipe to or from the drillstring, which is necessary for drilling and also for tripping the drillstring in or out of the hole. Furthermore, the wire needs to be somehow permanently attached to the inner wall of the drillpipe, since a freely moving wire, which might block a part of the caliper is not desired. Besides all that, the introduction of a wire into a drillpipe should not affect the strength of the pipe itself.

For one major issue, the electrical connection between two drillpipes over the tool joints, there are essentially two main solutions. Firstly, a method that is for example used by NOV for its IntelliServ® drillpipe, are inductive coils at the pin and the box, which are parallel when the connection is made up and allow an inductive, contactless communication between the drillpipes. Figure 15 shows a tool joint (pin) with an inductive coil, the box screwed to this pin would have the coil placed such that the coils directly face each other when the connection is made up. The wire inside the drillpipe is an armored coaxial cable. This setup allows the transmission of 57,000 bits per second, compared to 24 bits per second for mud pulsing under ideal conditions.[22]

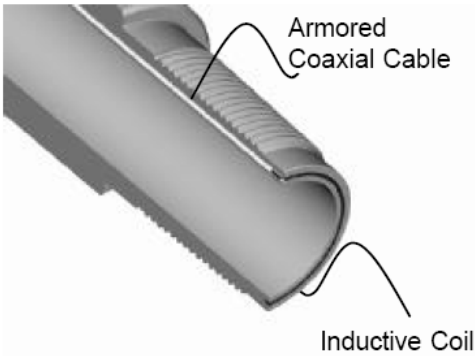


Figure 15: Tool joint with inductive coil[21]

Contrary to that, Advanced Drilling Solutions is developing a wired drillpipe with an actual electrical connection from surface to the downhole tools, meaning that an electrical connection needs to be securely established every time a connection is made up. This solution has the advantage, that besides having the connection for data communication, the wiring can be dimensioned such that a power supply of downhole tools becomes possible. This can be for example used to supply measurement tools with power or open and close simple valves and in a later step may also supply e.g. downhole motors.

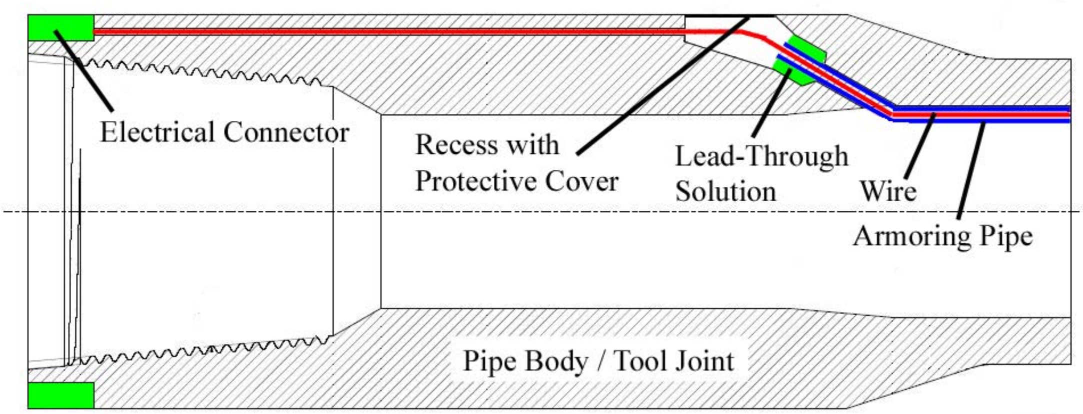


Figure 16: Schematic tool joint with electrical connection

Due to the design of this solution, which can be seen in Figure 16, the cable must be lead from the high pressure side inside the drillpipe to the low pressure side where it is connected to the electrical connector. While there may be different solutions for implementing the electrical connection along the drillpipe, by an armored cable, a copper foil or a conductive coating, there is always the challenge of leading al electrical connection or armoring pipe through the tool joint wall. The electrical connector consists of two parts, one on the box and one on the pin of the drillpipe, where a mechanical mechanism establishes an electrical connection over two pins that are punched from the male into the female tool joint when screwing the drillpipes together.

Though depending on the final setup of the wiring a downhole supply of 200W over a length of 20km may be possible. The signals for data communication are modulated onto the same wires but with a higher frequency. This is done with so-called power line communication (PLC) on the “C” or narrow band, a distance of 20km and a rate of 1 mega bit per second might be possible.

Challenges and Requirements

Since Advanced Drilling Solutions decided to develop a drillpipe with the described electrical connection from surface to the downhole tools, the following will only describe this design idea.

For maybe one of the biggest challenges, the establishment of the electrical connection between the tool joints, a solution was already found and tested. This rather complex mechanical system allows the rotation of a sleeve until a certain distance between pin and box is met, where two conducting pins are forced from the pin into the box and an electrical connection is established in a safe and ex zone compatible way.

As already mentioned, for the conductor along the inside of the pipe, there are different solutions possible. One are copper foils which are isolated against the drillpipe wall and against each other. This essentially means that only a thin wire or contact needs to be led through the tool joint wall.

On the other hand there is the option of running cables along the drillpipe. However, running cables requires an armoring pipe to protect the cables against pressure, chemicals and mechanical impact. Also the cables need to have a insulating coating that is resistant against higher temperatures as they are encountered with increasing depth. To protect the wires over the entire length it is necessary that the pipe is led into the tool joint, as can be seen in Figure 16. This means that if the pipe can be sealed on both ends against the tool joint, the cable will be fully protected. Running a pipe inside the drillpipe also brings along some difficulties.

First of all, a pipe accommodating two wires with a sufficient diameter consequently results in pipe with a certain diameter. While the pipe diameter should be kept as small as possible in order not to affect the caliper of the drillpipe, the idea of using the cables for power supply calls for cables with a larger diameter for a sufficient power transfer, hence is requiring a larger armoring pipe. One option to work around this is to flatten the pipe over most of its length. This however complicates leading the pipe into the tool joint body, as sealing a round pipe is always by far easier than sealing a pipe of any other form. This leaves having the ends of the pipe round while flattening the rest of the pipe as one option.

Furthermore it needs to be considered how the sealing is established, as high pressures have to be expected, but also increased temperatures and a sour environment. Also, the sealing needs to keep the pipe in place as tension or compression have to be expected. The sealing also has to be durable and must not loose its properties over time.

The pipe has to have a sufficient wall thickness, as it must not contract once hydraulic pressure is applied on its exterior, which could cause a collapse of the pipe or a failure of the sealing due to a reduction in diameter.

An important question is also how the armoring pipe is placed inside the drillpipe. Two options are possible for this. Either the pipe is mount under tension inside the drillpipe. Hereby the tension has to be sufficiently high that under any bending the drillpipe might experience during drilling, the armoring pipe is still under tension, keeping it straight and fixed in position.[21] Another option is to place the armoring pipe helically inside the drillpipe, which keeps the armoring pipe close to the wall of the drillpipe but also flexible for any bending. The downside of this is an enormous increase in wire length, when considering an entire drillstring. For protecting and also for fixating the armoring pipe, the drillpipe can be coated with a plastic coating on the inside, which is often applied to drillpipe.

Possible Lead-Through Solutions

As already described there are two possible ways of leading a conductor through the wall of a tool joint. One is to only lead a contact through the tool joint, which is then connected to e.g. a copper foil. The other way to go is that an armoring pipe is led through the tool joint, containing two or more wires.

Lead-through for Armored Wires

This solution is already described in Figure 16, showing the armoring pipe that is led through the tool joint from the outer side, where the lower pressure is to be expected, to the inner side of the tool joint and drillpipe where generally a higher pressure can be expected.

Sealing round pipes is a problem that is relatively often encountered. However, this application requires the resistance against high pressures in different environments and at elevated temperatures. High pressures are also common for hydraulic applications, where pipes are often used to transfer pressure using hydraulic oil. For attaching and sealing these pipes to some advice or adapter, typically cutting rings are used. These cutting rings are put over the end of the pipe and when screwing the connection together and fastening it, the cutting ring cuts into the pipe material and generates a seal. All other surface getting in contact and requiring a sealing are matched conical surfaces, creating a good seal when screwed together with force.

Progressive Stop Ring

One of the simpler cutting rings, that is commonly used is the so-called progressive stop ring (PSR), from Parker's EO-Plus series.[23]

Generally, the PSR cutting ring on an adequate pipe produces a high pressure, leak free connection.

Figure 17: Progressive Stop Ring[23]

Figure 18 shows a PSR on a pipe, before and after it is tightened. When only applying little torque to pre-fasten the function nut, the front cutting edge already starts cutting into the pipe body (A), Once the first cutting edge has really started to cut, then also the

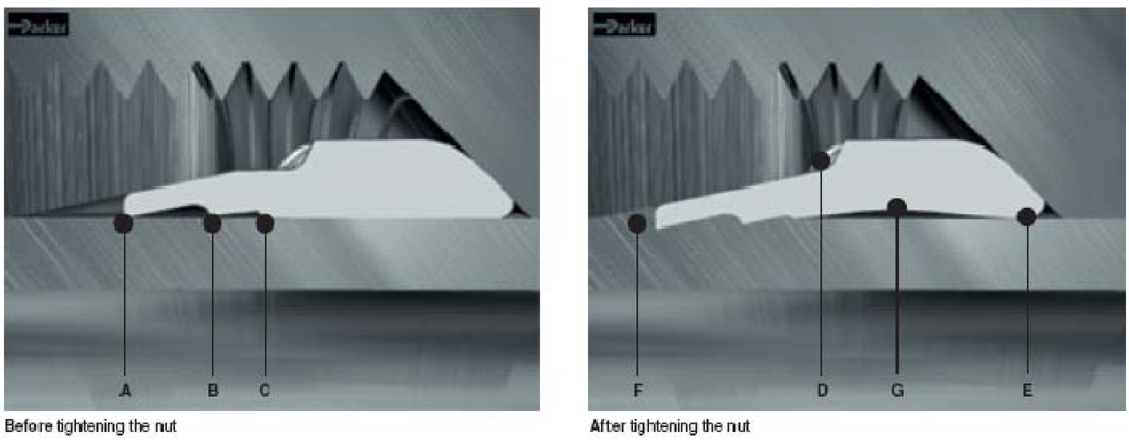


Figure 18: PSR before and after mounting[23]

second cutting edge (B) starts to cut and is eventually stalled by the so-called stop shape (C) and the over tightening protection (D). Once the cutting edges are stalled, the forces start to distribute evenly, increasing safety with the internal collar (E). After tightening, a visible collar (F) of cut tube material completely fills the space in front of the first cutting edge. A slight bending of the cutting ring (G) is desirable, as it acts like a spring that provides permanent compensation against flexural vibration and settling effects in the thread of the function nuts. (A, B, C etc refer to Figure 18)

Figure 19 shows the three effects of the progressive stop ring:

The tube bite (1) ensures a leak free sealing and ensures the necessary holding power for high operating pressures.

The tube clamping section (2) in the rear of the progressive stop ring is designed to clamp the pipe firmly. This ensures that vibrations from the pipe due to operations are not present at the tube bite area.

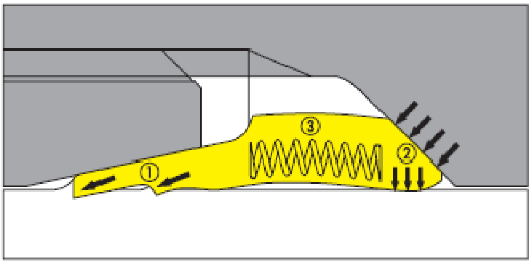


Figure 19: Three effects of the PSR[23]

The spring effect (3) compensates subsidences of tube bite and threads and therefore ensures a long term performance without leakage, while retightening is not necessary. This spring effect is achieved due to the design and material of the progressive stop ring.[23]

For the application of such a progressive stop ring for a lead-through solution all these effects are of great advantage, compared to cutting rings of older designs, not having these features. The tube bite effect for ensuring a good seal, while biting into the pipe and therefore allowing tension on the pipe are obvious features that are necessary for using a cutting ring. On the other hand, the spring effect for a good long term sealing effect without the necessity of retightening the connection is also very good to have, since retightening the connection would cause more inspections on the pipe over time, which is not desired. Furthermore, the tube clamping is a good side effect of this cutting ring, as vibrations are most likely on an armoring pipe that is mounted in a drillpipe.

Thinking of the application of such a cutting ring for a lead-through solution, there are several effects to take into account. First of all the pressure, which is on the one hand requires an adequate sealing but on the other hand compresses the pipe, as the pressure is outside the pipe, while the wires to be protected run inside the pipe. Furthermore, the armoring pipe will most likely be put under tension, which requires a good clamping or biting of the armoring pipe.

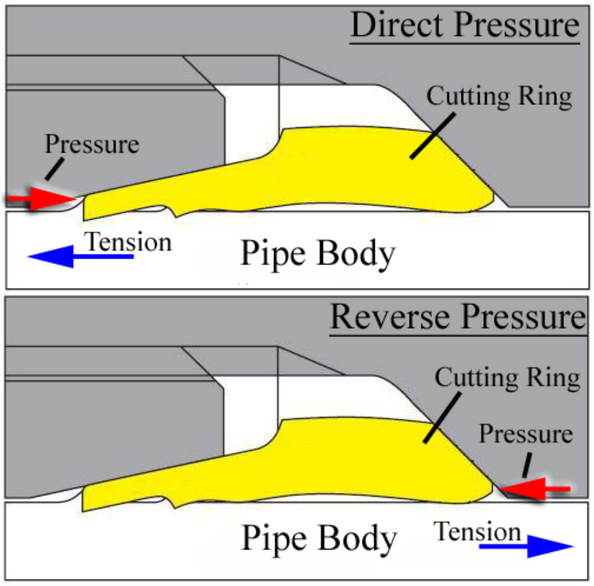


Figure 20: Direct vs. reverse pressure (from Reference 23, modified)

This results in two ways of using the cutting ring, as can be seen in Figure 20. In the “Direct Pressure” application pressure is applied like it would be applied on the cutting ring in any hydraulic application, while tension is applied in the opposite direction. For the “Reverse Pressure” application this is exactly vice versa. In addition, however, the pipe is in both cases contracted due to external pressure, which is not the case for hydraulic applications where high pressure is inside the pipe. This needs to be kept in mind as it may weaken the sealing capacity and the tension that can be applied on the pipe.

Therefore, the applicability of cutting rings needs to be further investigated.

Generally the PSR cutting rings are available for pipe in various sizes; the most interesting ones for the lead-through application are probably sizes for 6 to 16mm OD pipe, available in 2mm steps. Parker certifies them for the hydraulic fitting application for a maximum pressure of

800bar (up to 10mm pipe OD) and for 630bar (up to 16mm pipe OD), though, deductions need to be made to account for the use at elevated temperatures.[23]

Detailed drawings of the cutting ring and their possible assemblies can be found in Appendix D.

EO2-Plus fitting

Like the progressive stop ring, also the EO2-Plus fitting is a product by Parker. Generally it works very similar to the progressive stop ring, though it has some advantages. As Figure 21 shows, it consists of a cutting edge, biting into the tube material, but also a sealing ring, consisting of an elastomeric material, which provides and additional sealing capacity. Due to the design, the sealing ring is further compressed, which causes an even better sealing capacity once hydraulic pressure is applied. This is indicated with "P" in Figure 21.

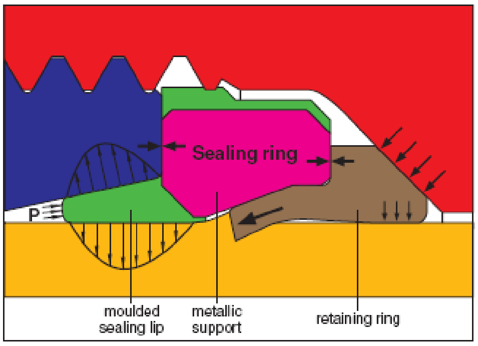


Figure 21: EO2-Plus fitting[23]

The big advantage of this sealing ring is its large cross-section, which can better compensate for manufacturing tolerances of the tube and the fitting.

At least for direct pressure application this solution seems promising, as the seal may provide a better seal, compared to the progressive stop ring only cutting into the tube material. For reverse pressure application the progressive stop ring is probably more favorable, this needs further investigation though.

The EO2-Plus system is available in the same sizes and ratings as the progressive stop ring. The elastomeric sealing ring is available in ratings of up to 150 or 200°C.[23]

Alternative Options

As already mentioned, there might also be other possibilities of wiring a drillpipe. One would for example be to implement two, against each other and the drillpipe isolated, copper foils as conductors. Since these copper foils would not need to be armored, leading an electrical contact through the tool joint wall also becomes simpler. For leading electrical contacts through metal, while isolating the electrical contact and sealing against pressure, many solutions are available, mainly for rather low pressures though.

Figure 22 shows such a contact that is weld into a comparably small (6mm) hole and provides an electrical contact while sealing pressures of up to 241bar and temperatures of up to 450°C.[24] While this specific example might not be perfectly applicable due to its rather low pressure rating, but it still shows that there are alternative solutions possible.

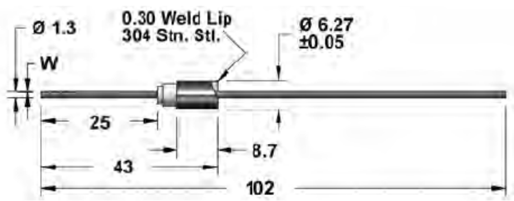


Figure 22: Electrical feed-through[24], measurements in mm

Another option, for composite drillpipe, might be the implementation of electrical conductors in the composite structure. This has the advance that the internal cross-section of the pipe remains unaffected, while the electrical contact between the pipe and the tool joint may then be possible inside the pipe, so that no lead-through solutions may be necessary.

Conclusion

Having a data communication with downhole tools available has many advantages. However, the bandwidth is also an important issue. Considering the different options, like mud pulsing, the communication with coils over the tool joints or an electrical connection from the surface to the downhole tools; the latter is the most desirable, as it provides the largest bandwidth and does not require battery powered repeaters. Establishing an electrical connection every time drillpipe is screwed together is rather complicated. Besides that also running cable inside the drillpipe and leading it from the inside of the drillpipe to the outside, as described in the previous chapters, is still subject to investigation. The main problem hereby is the possible pressure inside the drillpipe. On the one hand, any wire that is run inside the drillpipe needs to be protected, e.g. with a steel pipe. On the other hand, the steel pipe with the cable inside needs to be lead from the inside of the drillpipe to the outside. For the further development of the wired drillpipe, different lead-through solutions were investigated and evaluated for their applicability with different pressure tests as described in the following chapters.

Testing Apparatus

For testing leakage and breaking behavior of composites it was necessary to find a method which allows running multiple tests in an easy and not too cost intensive way. Therefore a testing principle and all apparatuses needed to be defined.

Idea

The main idea was to apply hydraulic pressure on a composite coupon to test whether it can withstand the pressure, how the sample behaves while breaking, how the sample reacts when re-pressurizing the sample after it has already shown leakage and how possible coating influence the behavior.

Previous tests with composite pipe showed that if a certain threshold pressure in a pipe is reached, the pipe fails and fluid leaks through the tubing wall.

Testing pipe is rather complicated. Besides the price of the sample, there are problems with sufficiently sealing the ends of the pipe. To work around this it was found sufficient to make first tests with composite plates, to easily verify applicable coatings and later on test them applied on a real size and shape specimen.

For testing composite plates, an apparatus needed to be designed that can hold composite samples or coupons and allows pressurizing them to 250bar, to verify their sealing capacity. Due to the lack of offset data, for leakage pressure of the composite and the composite in combination with the sealing layers, it was decided to design the testing apparatus such, that it would allow the application of a hydraulic pressure of up to 500bar. This e.g. would allow testing the coupons, even if the composite would withstand more than 250bar, and also, if possible applied sealing layers would improve the leakage behavior, it can be better tested how well e.g. the leakage behavior can be improved.

Essentially a sample holder, which allows the application of the said pressure on one side of the coupon, against atmospheric pressure on the other side needed to be designed. In the first stage, the applied fluid would be hydraulic oil; still the apparatus should allow the use of any other fluid for testing. Furthermore it needed to be kept in mind that the surface of the coupon should not be damaged or influenced, to get valid test results.

The measurement itself should a visual/manual one, but also automated. For the visual/manual measurement, the coupons should be visually inspected in a safe way, while having an analogue pressure gauge, allowing to visually inspect the coupon for leakage and reading the leakage pressure from the pressure gauge. For the later one, the automated measurement, a pressure sensor was implemented in the design. Linking this pressure sensor to a programmable logic controller (PLC) would allow recoding the pressure at a high frequency. Having the pressure data recoded at a high frequency, allows the later evaluation of the pressure curve. The main idea behind that was to get precise information about the leakage pressure in general, but also about the events that may occur before the coupon starts to leak.

For generating the pressure, a hydraulic hand pump should be used. Besides its easy application and low cost intensity, this would allow the easy variation of the pressure build up rate.

Design

The general design of the testing equipment can be seen in Figure 23. The hydraulic hand pump generates the pressure and is connected to the testing apparatus via a hydraulic hose (red line) or via a hydraulic pipe for high temperature applications. The testing apparatus itself consists of two steel plates which can be screwed together to clamp and hydraulically seal the coupon. This results in the application of the generated pressure on the coupon on one side, while atmospheric pressure is on the other side. The pressure is monitored by the measurement components, which are connected to a computer for reading out the recorded data. The applied pressure can also be observed on an analogue pressure gauge.

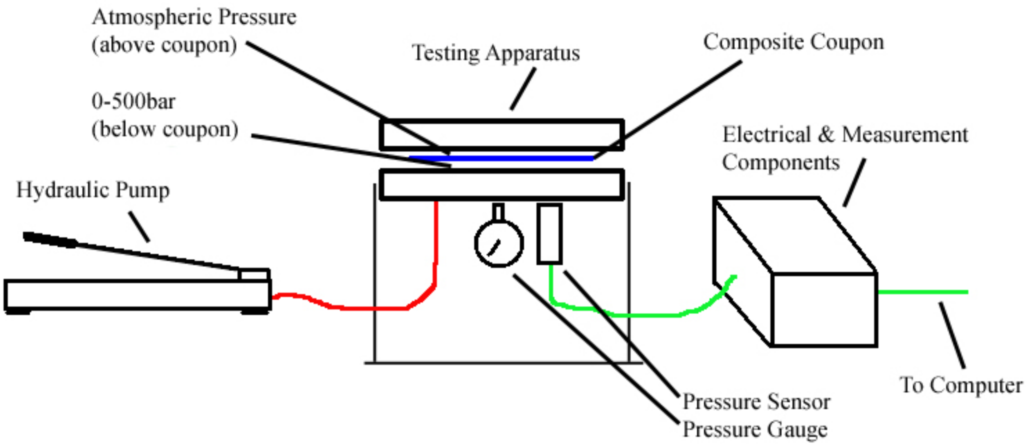


Figure 23: General layout of testing equipment

Essential Properties

Maximum testing pressure	500bar
Coupon size	150x150mm Coupons of varying thickness can be used
Test surface	Diameter 61mm (2930mm^2)
Alternative test surface	Diameter 61mm, with 37 5mm holes (with adapter)
Fluid used	Hydraulic oil
Manual pressure gauge	0-600bar
Pressure sensor	0-600bar ±1.5bar accuracy 4-20mA signal output
Alternative pressure sensor	0-400bar ±1bar accuracy 4-20mA signal output
Quality of measurement	±0.07bar resolution (with 600bar sensor) ±0.049bar resolution (with 400bar sensor) 100Hz sampling frequency
Hydraulic hand pump	700bar max. pressure output
Visual inspection	Visual inspection of the test surface, through a safety shield

Mechanical and Hydraulic Design

Criteria

The main criteria for the mechanical and hydraulic design is the maximum allowable pressure of 500bar including a sufficient safety margin that can be exposed to any part in the construction. Furthermore, the plates (top and bottom plate in the following chapters) holding the coupon need to be stiff enough, so that the application of the said pressure and resulting forces does not result in a bending of the plates that could influence the test results.

The apparatus also should be well applicable for testing numerous coupons. Hence, changing the coupons should be easy and not time consuming.

To ensure the integrity of the coupons, the coupons are clamped symmetrically between two rubber seals. While the rubber seals should help applying the sealing force in a non-damaging way on the coupons, the symmetric clamping of the coupons should avoid any unnecessary and influencing shear forces on the coupons.

Due to the high pressures applied on the equipment, sufficient safety factors are necessary to the design of the testing apparatus. Besides that, a safety shield is necessary to allow a close visual inspection of the tested coupon, but also of the apparatus and working close to the pressurized equipment.

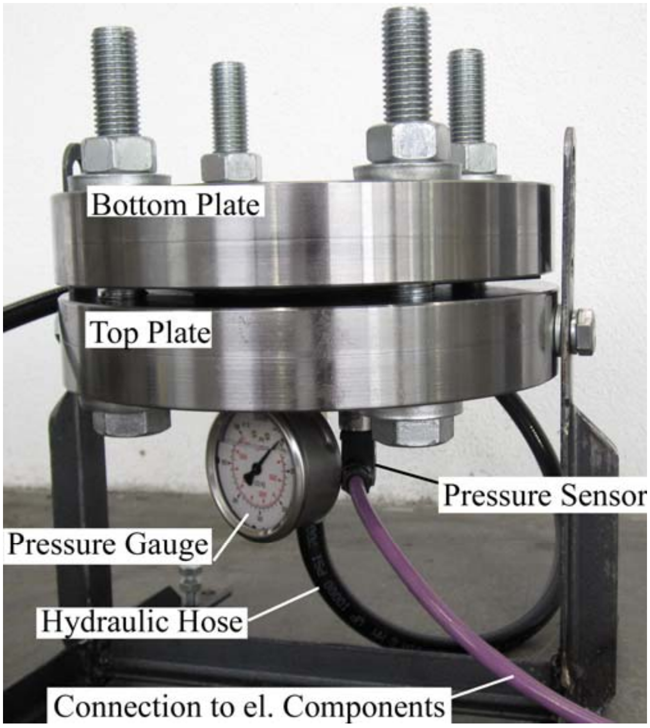


Figure 24: Mechanical components

Components

As Figure 24 shows, the mechanical part of the testing apparatus essentially consists of two metal plates, between which a coupon can be sealed and pressure can be applied on one side, while having atmospheric pressure on the other side. The plates are therefore screwed together with four screws and the entire construction is mounted on a simple pedestal. Since the coupon can be seen through a hole in the "bottom plate", the apparatus was mounted upside down, for easier visual inspection. For evaluating the measurements, an analogue pressure gauge and a pressure sensor were implemented.

The design and calculations are presented in the following chapters. Detailed blueprints of the apparatus can be found in Appendix B.

For safety reasons, a protective shield, which is not shown in this figure, needs to cover all pressurized components.

Figure 25: Hydraulic hand pump[25]

Strength of Material Calculations

Top Plate

The applied pressure results in a bending of the top and bottom plate. Since the bending should be a minimum, the theoretical maximum bending under pressures of 250 and 500bar was calculated for the top plate:[26]

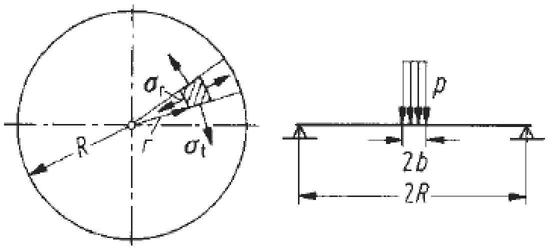


Figure 26: Sketch of round plate[26]

$$\sigma_r = \sigma_t = 1.95 * \left(\frac{b}{R}\right)^2 * \left[0.77 - 0.135 * \left(\frac{b}{R}\right)^2 - \ln\left(\frac{b}{R}\right)\right] * \frac{p * R^2}{h^2} \quad \text{(Eq. 11)}^{26}$$

$$f = 0.682 * \left(\frac{b}{R}\right)^2 \left[2.54 - \left(\frac{b}{R}\right)^2 * \left(0.75 - \ln\left(\frac{b}{R}\right)\right)\right] * \frac{p * R^4}{E * h^3} \quad \text{(Eq. 12)}^{26}$$

Where:

σ_r ... Max. Tension in radial direction [N/mm^2]

σ_t … Max. Tension in tangential direction [N/mm^2]

f … Max. bending [mm]

b … Radius of area where force is applied [mm]

R … Radius of total plate [mm]

p … Applied pressure [N/mm^2]

h … Thickness of plate [mm]

E … Young's modulus [N/mm^2]

With:

$b = 30.5mm$

$R = 115mm$

$h = 40mm$

$E = 205000N/mm^2$

$p = 500bar = 50N/mm^2 \ or \ p = 250bar = 25N/mm^2$

This results in:

- $p = 250bar$: $\sigma_r = \sigma_t \cong 60N/mm^2$ and $f = 0.11mm$
- $p = 500bar$: $\sigma_r = \sigma_t \cong 120N/mm^2$ and $f = 0.22mm$

Bottom Plate

Due to the more complicated design of the bottom plate, the disc spring equation is applied to calculate the maximum bending and tension:

$$F = \frac{4*E}{1-\mu^2} * \frac{t^4}{K_1*D_e^2} * K_4^2 * \frac{s}{t} * \left[K_4^2 * \left(\frac{h_o}{t} - \frac{s}{t}\right) * \left(\frac{h_o}{t} - \frac{s}{2*t}\right) + 1\right] \quad \text{(Eq. 13)}^{27}$$

Where:

F …Applied force [N]

s … Bending [mm]

μ … Poisson's ratio [1]

E … Young's modulus [N/mm2]

t … Thickness of the plate [mm]

D_e … Outside diameter [mm]

K_1 … Statistical value from table

K_4 … Statistical value from table

h_0 … Spring deflection [mm]

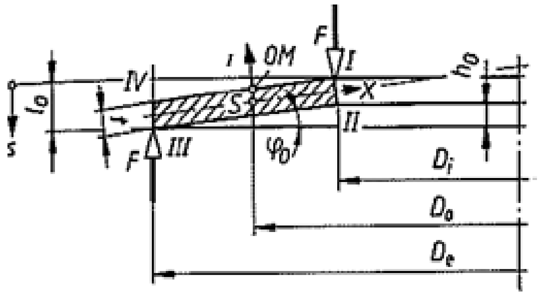


Figure 27: Sketch of a disc spring[27]

Setting h_0 to zero, and solving for s with:

$F = 50N/mm^2 * 612mm^2 * \pi / 4 = 146100N$

$\mu = 0.3$

$E = 205000N/mm^2$

$t = 40mm$

$D_e = 230mm$

$K_1 = 0.795$ [28]

$K_4 = 1$ [28]

$h_0 = 0mm$

results in a maximum bending of $s = 0.11mm$ with a maximum stress of $\sigma_{max} = 199N/mm^2$.

Screws

The plates are screwed together with four M20 screws, which need to apply the sealing force on the composite coupon and need to hold the plates together when a pressure of 500bar is applied.

The applied force is:

$$F = A_p * p = 146100N \quad \text{(Eq. 14)}$$

Where:

F … Force applied on screws due to pressure [N]

A_p … Area where pressure is applied [mm^2]

p … Pressure [N/mm^2]

With:

$$A_p = b^2 * \pi = 2922mm^2$$

$$p = 500bar = 50N/mm^2$$

This results in a force of 146.1kN.

Applying a factor two for the sealing force necessary and a safety, this results in 292.2kN.

Therefore, each screw needs to hold 73.05kN.

M20 screws have a cross-sectional area of 225mm^2 and a yield strength of 640N/mm^2.[29]

The applied force results in a stress of: $\sigma = 73050mm/225mm^2 = 325N/mm^2$, which is well below the material limit of 640N/mm^2. Therefore, M20 screws with a quality of 8.8 are sufficient for this application.

Material Verification for Bores/Threads in the Top Plate

The bores in the top plate, fitting the pressure gauge, pressure sensor and hydraulic hose are all G¼" bores. Due to the high pressure, a rather high fastening torque is necessary, to ensure good sealing between the top plate and the screwed in components. A high fastening torque consequently results in a higher force and therefore stress acting on the thread, which must not exceed the material's limits.

Assuming a fastening torque of 40Nm and applying:

$$F_{ft} = \frac{M_f}{0.5*d_2*\left[\mu_{tot}*\left(1+\frac{d_a+D_B}{2*d_2}\right)+\tan\varphi\right]} \quad \text{(Eq. 15)}^{30}$$

Where:

F_{ft} … Force acting on the thread due to the fastening torque [N]

M_f … Fastening torque [Nm]

d_2 … Effective diameter [mm]

d_a … Inside diameter of sealing ring [mm]

D_B … Outside diameter of sealing ring [mm]

μ_{tot} … Total friction [1]

φ … Angle of the thread [deg]

With:

$M_f = 40Nm$

$d_2 = 12.4mm$ [31]

$d_a = 13mm$ [31]

$D_B = 14mm$ [31]

$\mu_{tot} = 0.14$ [30]

$\varphi = 1.96deg$ [31]

$$F_{ft} = 19745N$$

Additionally to this force a force due to the applied pressure of max. 500bar acts on the thread, calculating as follows:

$$F_p = p * A_{screw} = 7700N \quad \text{(Eq. 16)}$$

Where:

F_p … Force due to the applied pressure [N]

p … Applied pressure [N/mm^2]

A_{screw} … Cross-sectional area of the screw [mm^2]

With:

$p = 500bar = 50N/mm^2$

$Ascrew = 154mm^2$

This results in a total force of:

$$F_{tot} = F_{ft} + F_p = 27445N \quad \text{(Eq. 17)}$$

Assuming a minimum length of the thread of 6mm and a slope of the thread of 1.337mm results 4.5 revolutions possible.[31]
Having a minimum male thread diameter including tolerance of 12.907mm and a maximum female thread diameter, also including tolerance, of 11.890mm results in a contact area per revolution of: A_{min}=19.8mm^2 and consequently in a total contact area of A_{tot}=89mm^2 that needs to hold the applied force.[31]

The calculated force acting on the said minimum total contact area results in a stress applied on the material of:

$$\sigma_{max} = \frac{F_{tot}}{A_{tot}} = 308N/mm^2 \quad \text{(Eq. 18)}$$

Considering a yield strength of 500N/mm^2 of the C45 steel, the maximum applied stress of 308N/mm^2 is well within the range.[28]

Electrical and Measurement Design

The electrical pressure measurement is mainly to verify the manually measured leakage threshold pressures. Though, the sampling rate and resolution may allow to measure events of leakage generation, propagation and the visual evaluation of the recorded pressure curve. Besides that, an analog pressure gauge is required for a visual measurement, which also should give an orientation of the current pressure when pumping with the hydraulic hand pump.

Criteria

Again, the most important criteria is that the used sensors, which are the only electrical or measurement equipment that experience the applied pressure, can withstand the pressure including a safety.

For recording the pressure data a PLC is used, which should have an analog I/O port available, which allows connecting the pressure sensor. The pressure sensor itself can evaluated pressures from 0 to 600bar and gives an output of 4 to 20mA, which can be sampled with up to 100Hz. For further evaluating the recorded data, it should be possible to read out the data on a computer via an TCP/IP connection. Light emitting diodes (LEDs) should indicate the proper working order of the PLC and indicate when a measurement is in progress. This is necessary as the PLC should not be continuously recording, but detect if a measurement is in progress by a given threshold pressure. While measuring a 5bar threshold pressure was found to be well applicable, as it does not trigger a measurement when assembling and especially screwing together the mechanical components.

Components

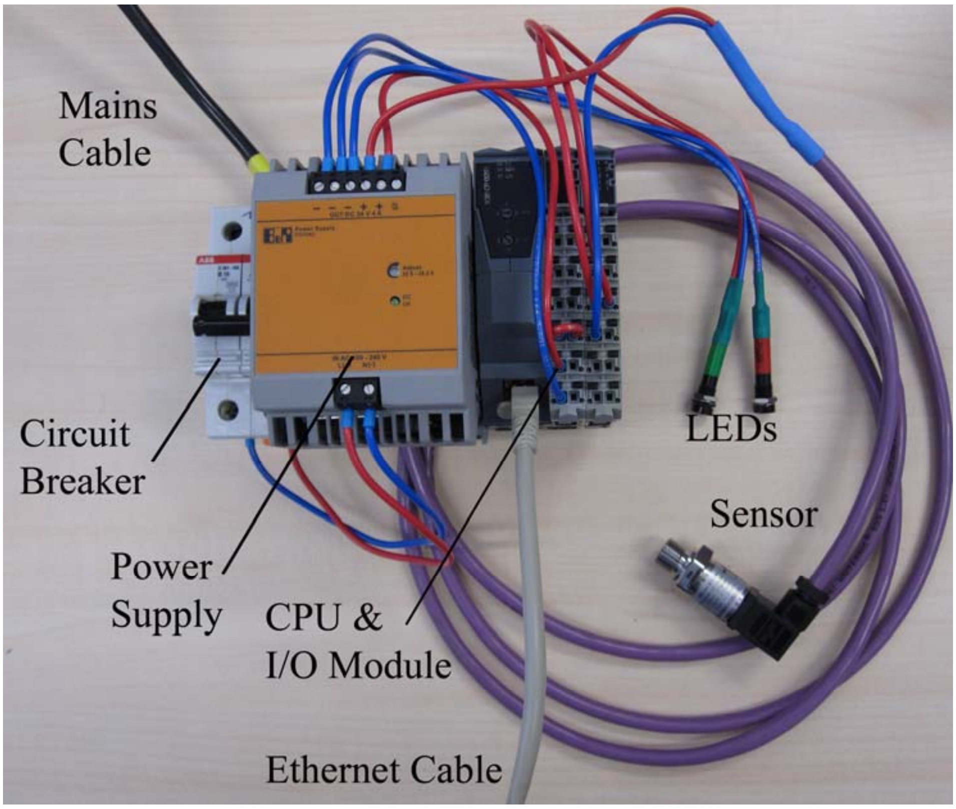


Figure 28: Electrical components

Figure 28 shows the electrical components used for recording the pressure data. The essential component is the PLC (here indicated as CPU & I/O module) which records the data, establishes the TCP/IP connection and controls the LEDs. For security reasons, the mains cable is connected to the system via a circuit breaker. The following table shows the major components and their exact specifications:

CPU	B&R – Automation	X20 Fieldbus CPU (Model Number: X20XC0292)
I/O Module	B&R – Automation	X20 universal mixed module (Model Number: X20CM8281)
Power supply	B&R – Automation	B&R Power supply module (Model Number: 0PS1040.0) 24VDC, 2A
Pressure sensor	Gems Sensors	0-600bar, 4-20mA, 10-35VDC power supply (Model Number: 3100B0600S01B000)
Circuit breaker	ABB	16A current rating

Figure 29: Assembled measurement unit

Figure 29 shows the assembled measurement unit, with the connection cable to the sensor, the Ethernet cable for the TCP/IP connection and also the power supply. The red LED indicates that the PLC is working and running the sequentially repeated program, while the green LED indicates if a measurement is in progress.

Properties of Measurement

The chosen components result in a sampling frequency and a resolution resulting from the PLC, the I/O module and the pressure sensor as follows:

Sampling frequency	10, 20 or 100Hz
Resolution	±0.07bar resolution (with 600bar sensor) ±0.049bar resolution (with 400bar sensor)

The sampling frequency is essentially a function of the CPU. Since it is a real time system, it allows assigning programs or routines at certain time intervals, which means essentially that the pressure value is captured at given time intervals. These time intervals range from 10 to 100ms with the given CPU, resulting in the said sampling frequencies. However, the CPU can be programmed for a higher sampling frequency, which was not necessary for testing, though.

The resolution of the measurement is governed by the resolution of the I/O module and the pressure range of the used sensor. The used I/O module gives a 12 bit resolution on the analog input ports, which is for this project assigned to 4 to 20mA. The range of 4 to 20mA however represents 0 to 600bar or 0 to 400bar, depending on the used sensor. Therefore the resolution depends on both, the I/O module and the used sensor. The intention behind the two sensor solution is that measurements that with a very high certainty stay below 400bar can be recorded with a higher resolution and making small pressure changes e.g. from a leakage or breaking behavior visible, while still having the full pressure range when using the 600bar sensor.

A 5bar threshold was chosen to start and end the recording of a measurement. Due to compression when assembling the mechanical equipment when inserting a new coupon, small pressure peaks can occur, which should not trigger a measurement.

Measurement Automation

The measurement data acquisition is automated with the PLC. It has a program running that is executed at fixed time intervals, acquiring data from the pressure sensor and further processing the data. The time intervals can easily be changed from 100ms to 50ms or 10ms, resulting in a sampling frequency of 10 to 100Hz.

The programming of the B&R PLC routines is done with B&R Automation Studio, which is a visual computer interface for setup and programming of B&R components. The programming is done with the programming language C.

The running program essentially captures the current value from an analog 4 to 20mA I/O port (Input/Output port), that is connected to the pressure sensor. Having the raw data representing the pressure in a value range of 32768 values needs conversion to pressure values in bar, which is a simple multiplication.

The next step in the program routine is the check if a trigger value is reached, which should essentially ensure that the acquired and calculated data is only sent if the pressure has reached a certain trigger value, or in other words the measurement has started.

Sending the data is done via a TCP/IP connection to the computer, where the data is received in a simple communication program like "HyperTerminal" or "Tera Term", which records the data and allows saving the data in text files and the further importing in Microsoft Excel, where it can be evaluated and e.g. displayed in graphs. Establishing the TCP/IP data connection is done with available libraries in the software package of the PLC. Figure 30 shows such a connection and recording of data via a TCP/IP connection with "Tera Term", where the left row are time stamps (here in 50ms intervals) and the right row gives the corresponding measured pressure value (units are seconds and bar).

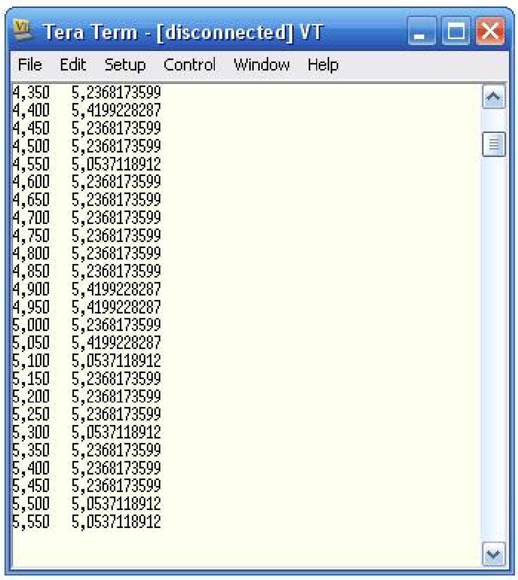


Figure 30: Recording a measurement with "Tera Term"

Before sending the data, it is processed and put together in predefined data sets, consisting of a calculated time stamp (starting with the trigger) and the pressure data in bar. To ensure a proper TCP/IP sending and that the sending of one data packet is finished before the next packet is sent, the data sets are collected and only sent after ten values have been recorded.

For visualization, the two LEDs, show if the cyclic program is running and if the trigger value for the pressure value is exceeded and collecting and sending the pressure data is in progress.

The code for establishing the TCP/IP connection and also the cyclic program can be found in Appendix C.

Additionally, to the data recording on the connected computer with the said TCP/IP connection, the data is recorded in B&R Automation Studio where it can be displayed as a graph for a first evaluation of the test immediately (see Figure 31).

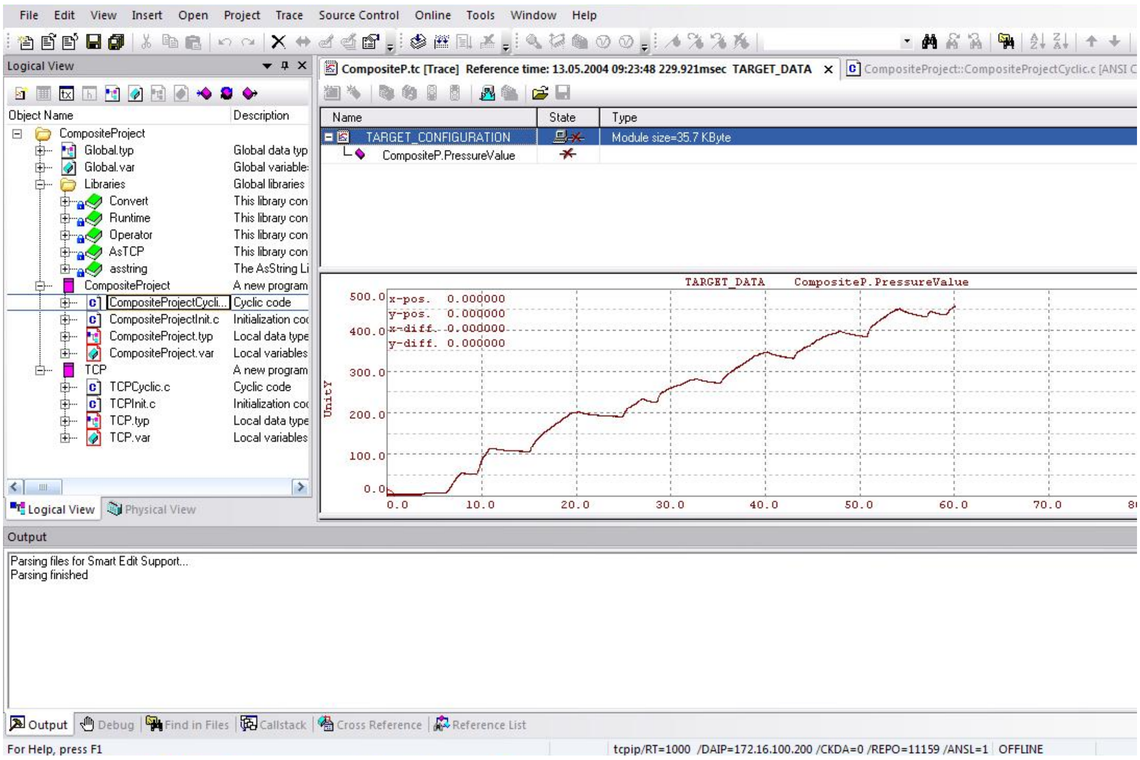


Figure 31: Recording data with B&R Automation Studio

Testing Procedure

Working Steps before First Measurement

- ✓ Connect all hydraulic and electric lines to the testing apparatus; if they were previously connected, ensure a proper connection
- ✓ Connect PLC to the power socket and the computer via the Ethernet cable and wait for the red LED to turn on
- ✓ Start “Terra Term” or “Hyperterminal” and connect to the PLC with the given IP Address and Port (for the program shown in Appendix C, IP Address: 172.16.100.200 Port: 50000)
- ✓ Wait for the connection to be established

Repeated Steps for Multiple Measurements

- ✓ Ensure the release valve at the hydraulic pump is open and that there is no testing fluid in the cavity of the top plate
- ✓ Insert a new seal in the top plate (which is upside down)
- ✓ Close the release valve at the hydraulic pump and slowly pump to fill the cavity in the top plate and inside hole of the seal with testing fluid
- ✓ Put the coupon to be tested on top and press it against the seal
- ✓ Open the release valve at the hydraulic pump again, the coupon should now be slightly sucked down
- ✓ Put the bottom plate and with a second seal on top and insert the four screws
- ✓ Tighten the screws crosswise and measure the gap between the top and bottom plate, which should be evenly wide
- ✓ When the plates are tightly screwed together, put the protective shield above the apparatus
- ✓ Increase the pressure by pumping with the hydraulic hand pump (the measurement starts at 5bar with the program shown in Appendix C)
- ✓ Further increase the pressure as desired while observing the pressure on the pressure gauge and visually inspecting the coupon through the hole in the bottom plate
- ✓ When the measurement is finished, open the release valve of the hydraulic pump
- ✓ Ensure that the pressure is released by checking the pressure gauge
- ✓ Disassemble the apparatus
- ✓ Copy the recorded data from “Terra Term” to e.g. “Texteditor” or “Microsoft Excel”, safe it there and clear the “Terra Term” recording screen for the next measurement

Applicability

Although the apparatus was designed for testing the behavior of composite plates under a hydraulic pressure from one side, it may also be well applicable for many other measurements and testing of components.

The testing of leakage behavior and the breaking pressure of composite coupons was intention behind the design. The components were designed such that the composite coupons are not damaged by edges when assembling and tightening the apparatus, while allowing a maximum pressure of 500bar on the pressurized side of the coupon and a recording of the pressure as described in the previous chapters. The initial design of the components intended a working temperature below 50°C.

Adaption for Measurements at Increased Temperatures

For testing at increased temperatures, which became necessary, it is required to make some minor modifications, as the pressure sensor, pressure gauge and especially the hydraulic hose can not withstand increased temperatures. Therefore, two of the bores for the hydraulic inlets at the top plate need to be sealed and the third one is used to connect a hydraulic tube which provides the hydraulic connection in the area of increased temperature (e.g. inside the oven). Outside of the area of increased temperature, the hydraulic hose leading to the hydraulic pump and the pressure sensor and pressure gauge can be connected to the tube.

Figure 32: Measurement setup for increased temperatures

As can be seen in Figure 32 the entire testing apparatus was placed in an oven. It also shows the hydraulic tube which replaced the hydraulic hose and the pressure sensor and pressure gauge that are placed outside the oven. At the cross connector connecting the measurement components, also the hydraulic hose leading to the hydraulic hand pump is attached, which can not be seen in this figure.

Temperature Measurement

The temperature was measured with a simple Pt1000 resistance thermometer, which was calibrated with a Type K thermocouple. A Pt1000 resistance thermometer has 1kΩ at 25°C and a negative, non linear slope with increasing temperature. The equation describing this curve is rather complex and can be described with measurements. Further on, the resistance of the sensor is measured which allows a simple calculation of the temperature. For the measurements this was rather simple, as a fixed measurement temperature was given which could be converted in a resistance value and the heating of the sample could then be done according to this value. Figure 33 shows the negative temperature dependency of the used resistor. In order to get more accurate results, the resistor curve was recalculated with measurements made with a simple thermocouple temperature sensor available as a multimeter enhancement.

Pt1000 Resistor	AVX N4080
Tolerance	5%*
Multimeter Thermocouple	Agilent U1186A
Tolerance	±1.1°C

*to manufacturer provided values.

To get a better temperature connection and consequently a more stable and reliable measurement, the temperature was measured in hydraulic oil in the cavity of the bottom plate as can be seen in Figure 34. Having oil rather than e.g. air made the measurement much easier, as convection is far less in oil and the temperature is more stable and easier to control.

Therefore, it was decided to place the sensor in oil to get a good connection to the composite plate. Basically, any fluid could be used for this, however hydraulic oil is already the only fluid in the system and as it is often sucked into the pump when e.g. a coupon is broken and the pressure is released, hydraulic oil is obviously the best option as it does not affect the hydraulic pump. The oil was filled in cold (room temperature, ca. 20°C) and then heated to the desired temperature where it was kept for 20min in order to ensure a constant temperature of the composite coupon. It also needs to be mentioned that prior to testing the entire testing apparatus needs to be heated to approximately the measurement temperature as it is very hard to keep the desired temperature otherwise and also the heating process takes rather long compared to the "usual" testing procedure, which might distort the measurement.

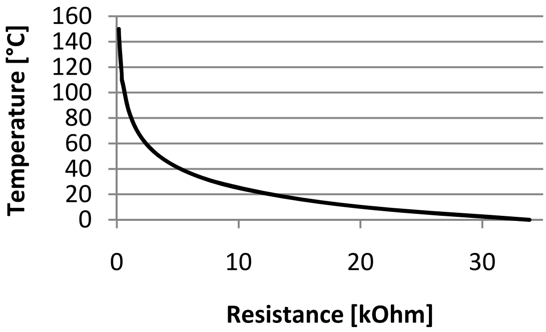


Figure 33: Temperature dependency of "AVX N4080" (recalculated curve)

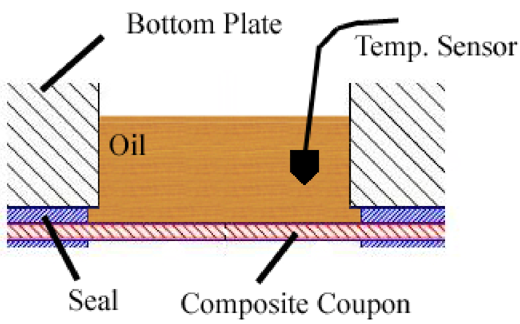


Figure 34: Temperature measurement

Problems

First tests showed that due to the applied temperatures of up to 85°C, the seals lost some strength and got softer, resulting in breaking seals when pressure was applied. This problem could be solved by re-tightening the four screws holding the top and bottom plate together shortly before the measurement is made. This was successful to temperatures up to 85°C, however some measurements had to be repeated due to failing seals. For higher temperatures another material for the seals might be necessary.

Another problem with this test setup was the cross connector. For the initial test setup the highest point in the hydraulic system was the cavity in the top plate, therefore it could be ensured that there is almost no air in the hydraulic system when assembling the testing apparatus. For the test setup for increased temperatures however, the cross connector and the attached pressure gauge was the highest point of the hydraulic system as can be seen in Figure 32. Due to that, the setup did not allow to entirely vent the hydraulic system, which could be a reason for the unstable pressure curves (see Appendices F to I).

Extended Testing Procedure

The basic testing procedure is much like the normal testing procedure for tests at room temperature. However, there are certain factors that need to be kept in mind in order to get good results:

- ❖ Additional Working Steps before First Measurement
  - ✓ Attach the temperature proof components, so that the sensible parts are not exposed to an increased temperature
  - ✓ Place the entire testing apparatus (incl. the screws) in the oven and heat it approximately the desired testing temperature
- ❖ Additional Repeated Steps for Multiple Measurements
  - ✓ Assemble the testing apparatus like usual
  - ✓ Fill the cavity in the bottom plate with cold hydraulic oil and place the temperature sensor in the oil

- ✓ Put the testing apparatus in the oven and wait for the oil to reach the desired testing temperature
- ✓ Keep this temperature for 20min
- ✓ Remove the temperature sensor and cover the cavity with a steel plate
- ✓ Take the testing apparatus out of the oven and quickly re-tighten the four screws holding top and bottom plate together
- ✓ Place the testing apparatus in the oven again and close the oven (the oven acts now as the protective shield!)
- ✓ Carry out the measurement like usual

Note: The testing apparatus is hot and can only be handled with protective gloves!

Lead-Through Testing Adapter for Direct Pressure

For testing the lead-through solutions a simple solution needed to be found that allows an efficient testing on the one hand and is cost effective and allows the use of parts of the initial testing apparatus. As already described, there are two setups for this test, depending on the direction of pressure application, where this adapter is designed to apply the pressure on the usual high pressure side of the cutting ring.

Essential Properties

Maximum Pressure	500bar
Specimen Size	Testing Pipe: - OD 10mm - Length ca. 40 mm
All further properties can be taken from the initial testing apparatus	

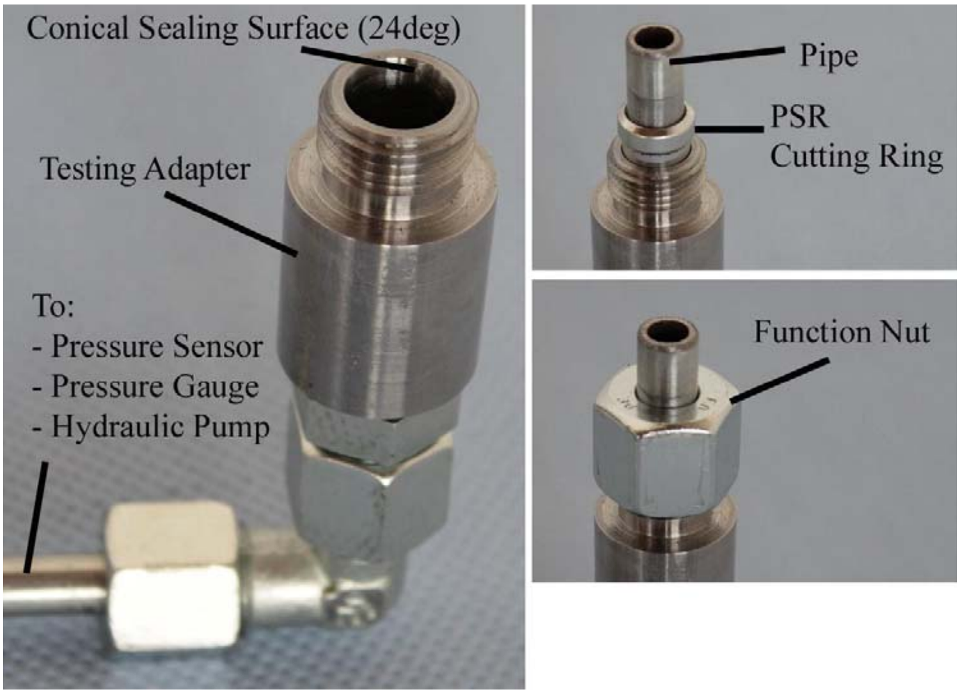


Figure 35: Lead-through test setup

Design

For the simple test, where the pressure is applied on the usual side high pressure side of the cutting ring, a simple adapter was designed, which can be seen in Figure 35.

The testing adapter for these tests is rather simple. It is essentially a steel tube, with sufficient dimensions to withstand 500bar and has a thread for attaching the hydraulic pump, the pressure sensor and the pressure gauge over a tube on the one end. On the other end of the adapter, an especially made adapter construction was manufactured. Due to the design of the cutting rings and the necessary dimensions of the armoring pipe that they should seal (OD 10mm pipe) a M18 thread was necessary to fit the function nut and a 10.1mm bore was necessary to fit the test pipe and the cutting ring, which also needs a conical sealing surface with 24deg. For testing, the lower end of the testing pipe, which can not be seen in the picture, needs to be closed to allow the application of pressure.

The evaluation of the sealing capacity is mainly a visual one. Thought the pressure is again recorded with 20Hz sampling rate. Since the apparatus is pressurized with up to 500bar and requires close visual inspection, a protective shield is again essential for testing. It is very important that the safety shield covers also the top of the test setup, as the pipe may become loose and be propelled upwards due to the applied pressure. Detailed blueprints of the testing apparatus and the cutting ring assembly can be found in Appendix D.

Problems

There are some problems concerning the pressure. If for example a pressure of 500bar is applied on the sample and then the apparatus only monitored, without applying further pressure, the pressure will still slightly drop (approx. 2bar over 1min with a starting pressure of 500bar). This is due to the hydraulic hand pump not maintaining the pressure. However, the testing adapter is planned such that if any fluid should leak through the cutting ring, it would show between the function nut and the testing pipe. A visual inspection of the testing setup through a safety shield is therefore indispensable.

Testing Procedure

First of all, the initial working steps have to be carried out like described for the initial testing apparatus. This mainly involves the starting of the automated measurement.

This is followed by the repeated working steps for each test:

- ✓ Clamp the testing adapter in a bench vise for assembling
- ✓ Place the cutting ring in the conical sealing surface
- ✓ Put some tape on the open end of the testing pipe, so that it can not slip through the orifice of the function nut (3 to 5mm are sufficient)
- ✓ Place the function nut in position & insert the testing pipe
- ✓ Tighten testing pipe, 5 to 6 Nm are a sufficient fastening torque and remove the tape
- ✓ Place the protective cover over the testing adapter
- ✓ Increase the pressure by pumping with the hydraulic hand pump, again the measurement will start at a 5bar threshold pressure
- ✓ Further increase the pressure as desired while observing the pressure on the pressure gauge and visually inspecting the testing adapter and specimen for any signs of leakage
- ✓ When the measurement is finished, open the release valve of the hydraulic pump
- ✓ Ensure that the pressure is released by checking the pressure gauge
- ✓ Disassemble the apparatus
- ✓ Store the recorded data as described for the testing apparatus

Lead-Through Testing Adapter for Reverse Pressure

Furthermore, the cutting ring lead-through solution needed to be tested for a reverse pressure application, meaning that the pressure needs to be applied on the side of the cutting ring that under regular use does not experience any hydraulic pressure.

Essential Properties

Maximum Pressure	500bar, over approx. 2min*
Specimen Size	Testing Pipe: - OD 10mm - Length ca. 25 mm
All further properties can be taken from the initial testing apparatus * resulted from the sealing capacity	

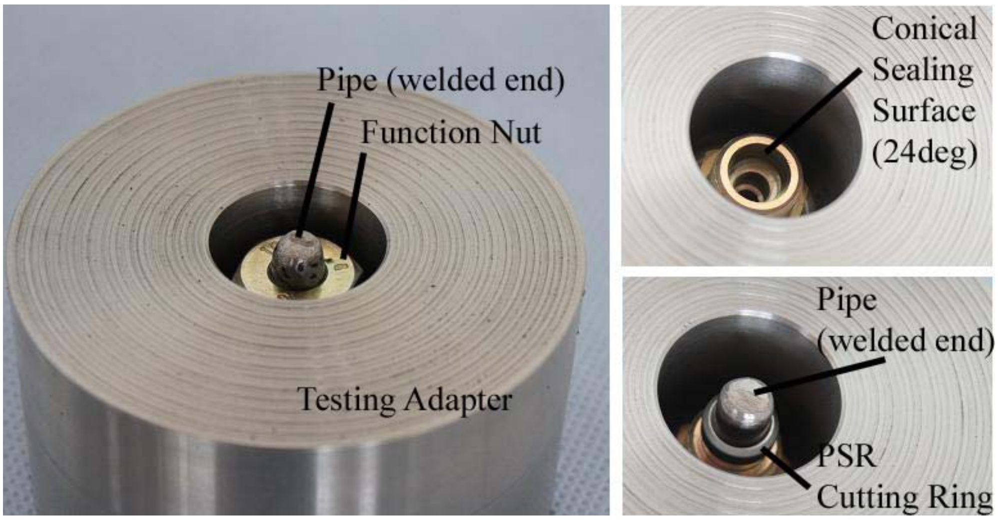


Figure 36: Lead-through test setup for reverse pressure

Design

Like for the other lead-through testing adapter, here also was the criterion that most of the components from the initial testing apparatus should be used for this testing setup. Due to the idea, of using as much standardized components as possible and the fact that some sort of pressure chamber would be necessary for testing the reverse pressure application, it was decided to build a pressure chamber that could fit into the initial testing apparatus instead of the composite coupon. To maximize the contact with the seal, the outside diameter of the testing adapter was a given. Also the pressure chamber on the inside, where the specimen is placed was simply determined by the necessity to keep it as small as possible, as it needs to be filled with oil and the hydraulic pump only has a limited oil reservoir, still it needed to fit all the tools for mounting the adapters and specimen. This resulted in a rather massive adapter, which seems somewhat overdesigned, but is more a result of boundary conditions and due to its design easily capable of the expected pressures. Since there are ready made adapters with a conical sealing surface available for this setup, which made the construction easier and possibly also more precise. In Figure 36 this adapter is labeled with “Conical Sealing Surface (24deg)”. Since this adapter is has an upset, not allowing a pipe with 10mm OD to pass through it, it was necessary to manipulate the end of the pipe that was put in the adapter. This became necessary, as an applied pressure in the pressure chamber, but also the assembly, would force the pipe down into the adapter, possibly resulting in an additional sealing effect which was not desired at this point as it would distort the measurement. Therefore, the described lower end of the testing pipe was perforated at the edge, generating a definite fluid pathway for a leaking fluid from the cutting ring.

Any fluid leaking through the cutting ring would therefore pass through the adapter and show on the backside.

Figure 37: Fully assembled testing adapter for reverse pressure testing

For testing, the lead-through adapter is placed in the testing apparatus. Unlike when placing a composite coupon, there is only one seal necessary on the high pressure side, as there is no pressure to seal on the other side and also shear forces are no problem like with the clamping of composite coupons. Figure 37 shows the fully assembled testing setup, which the lead-through testing adapter clamped in the initial testing apparatus. This setup is essentially very simple, as there are no further modifications to the testing apparatus necessary and all measurement equipment can be used in the already existing setup. Again, detailed blueprints and sketches of the testing assembly can be found in Appendix D.

Problems

Similar problems as with the testing at elevated temperatures were observed with this test setup. The seals seemed to be the weak part of the construction. Also before, when testing composite plates similar problems arose, especially when dealing with pressures around 450 to 500bar at room temperature. When testing the testing apparatus, initially steel plates were used instead of the composite coupons in order to verify if the testing apparatus is working, pressures of over 500bar seemed to be possible. This might have been a side effect of using plates bigger than the seals though, as they would provide a smaller gap between the upset of the top plate and the coupon for the seal to slip through due to the applied pressure.

When using the lead-through adapter, which has the same diameter as the seal, the said gap seems to be somewhat bigger, allowing the seal to slip through at pressures around 350 to 400bar.

To mitigate this problem, concentric grooves (1mm with, 0.1mm depth) were introduced at both sealing surfaces having contact with the seal in order to increase friction and avoid a slipping of the seal. This showed good results, leading to possible testing pressures of over 500bar. Initially, like for the direct pressure tests, the pressure should have been applied for at least 5min. Even though the said groves were introduced and it was possible to apply pressures of 500bar and more, the seals were squeezed out after some time and failed. However, it was repeatedly possible to maintain the pressure over approximately 1.5 to 2min. Other tested improvements with collars for supporting the seal showed no significant effect.

Testing Procedure

First of all, the initial working steps have to be carried out like described for the initial testing apparatus. This mainly involves the starting of the automated measurement.

This is followed by the repeated working steps for each test:

- ✓ Clamp the testing adapter in a bench vise for assembling

- ✓ Re-tighten the adapter with the conical sealing surface screwed into the testing adapter
- ✓ Place the cutting ring in the conical sealing surface
- ✓ Place the testing pipe in the adapter with the open end downwards
- ✓ Place the function nut in place and tighten it with 5 to 6 Nm
- ✓ Place a new seal in the testing apparatus
- ✓ Close the release valve at the hydraulic pump and fill the cavity in the top plate with oil
- ✓ Place the lead-through testing adapter on the seal, add the bottom plate and tighten the screws as tight as possible (exceeding 10Nm) in order to increase the friction on the seal
- ✓ Place the protective cover over the test setup
- ✓ Increase the pressure by pumping with the hydraulic hand pump, again the measurement will start at a 5bar threshold pressure
- ✓ Further increase the pressure as desired while observing the pressure on the pressure gauge and visually inspecting the testing adapter and specimen for any signs of leakage
- ✓ When the measurement is finished, open the release valve of the hydraulic pump
- ✓ Ensure that the pressure is released by checking the pressure gauge
- ✓ Disassemble the apparatus
- ✓ Store the recorded data as described for the testing apparatus

Further Applicability

Besides testing composite coupons, testing of any other coupon is easily possible with the given dimensions of 150x150mm and variable thickness. Therefore, the apparatus may be used for testing various materials, e.g. at increased temperatures, sealing layers, deformation behavior, etc.

However, due to the design many other pressure test applications may easily be applied to the testing apparatus. The most important criteria is that the added components can all withstand the desired testing pressure and that the construction is such that the pressurized side of the component has a sufficient sealing surface and geometry. The length of such components is a minor concern as the used screws can easily be exchanged for longer ones. When changing the design and especially when changing the length of the setup, please ensure that all pressurized components are covered with a protective shield.

Beside the simple pressure measurement also further sensors can be applied to the testing apparatus with minor effort. For this an additional I/O module for the programmable logic controller (PLC) needs to be installed to have further analog input ports available. This would for example allow the automated measurement of one or more temperature values, strain via a strain gauge resistor or the distance a coupon bends when pressure is applied. On the other hand, further output ports from the PLC may be used to control certain things in a measurement, for example the temperature in an oven, which might be very helpful for long term tests or even a pressure pump may be controlled by the PLC.

Long term tests, where a pressure should be kept at a certain level may also be easily adaptable to the existing testing apparatus. With the current setup, the main problem of holding a pressure seems to be the hydraulic pump, which releases some pressure over time. This can easily be mitigated by implementing a needle valve very close to the testing apparatus or adapter in order to only keep a very small oil volume pressurized over time, avoiding a distortion of the measurement by other effects.

Testing Leakage Behavior of Composite Plates

Initially the leakage behavior of composite materials should be tested. As previous tests and literature reviews showed, pressurized composites can leak fluid at certain threshold pressures. To verify the previous results and test possible solutions for this problem, the described composite leakage testing apparatus was designed. The idea behind was to find a way where the results from the previous test with composite tubes can be simulated with less cost intensive specimen. Having cheap specimen, like simple composite plates, available would allow numerous tests, with different coatings, plastics, and other solutions, at different temperatures and ambient conditions.

Test Setup

The test setup was rather straight forward. As planned, composite coupons with the dimension of 150x150mm and thicknesses of 1, 2 and 3mm were used. The tests were carried out at an ambient temperature of 18°C and the seals were exchanged for each test. Due to the construction, the pressure was applied on a circular area of 61mm diameter in the middle of the coupon. The measurements were recorded with a sampling rate of 50ms and a resolution of ±0.07bar. Each test was repeated three times, resulting in a total of nine tests.

With the given test setup, the pressurized plate would bend towards the low pressure side and stress the material, resulting in a strain, which should simulate the strain in a pipe due to an internal pressure causing a radial expansion.

Coupons

Fiber	Carbon fiber cloth, 410g/m^2
Resin	HEXION EPIKOTE ™ Resin MGS® LR285
Hardener	HEXION EPIKURE™ Curing Agent MGS® LH286
Curing temperature	75°C
Dimensions	150x150mm
Thickness	1, 2, 3mm (3 of each)
Fiber volume fraction	ca. 50%
Fiber structure	±45deg

Test Results

Figure 38 shows a typical pressure curve of when increasing the pressure the hydraulic pressure on the composite coupon with the hydraulic hand pump. The well noticeable interruptions in the curve result from the pumping motion, as a hydraulic hand pump can only pump a certain volume at one stroke, much like a bicycle pump, and must be recharged for further increasing the pressure.

Furthermore Figure 38 shows that at a certain pressure, the curve suddenly drops to zero (in the diagram to 5bar, which is the trigger level for recording data). This was due to the breaking or bursting of the composite plate. In this example, with a 3mm thick coupon, this happened at 133bar. Up to that pressure, there were no signs of leakage. Neither on the recorded pressure data, nor visually on the composite coupon, which could be visually inspected on the side of atmospheric pressure through the bottom plate, while the other side of the coupon was pressurized.

Repeating the measurement with 3mm coupons showed slight variations in the burst pressure, but also no signs of leakage could be observed. The same is valid for the coupons with 1 and 2mm thickness, which showed different burst pressures, but no sign of leakage.

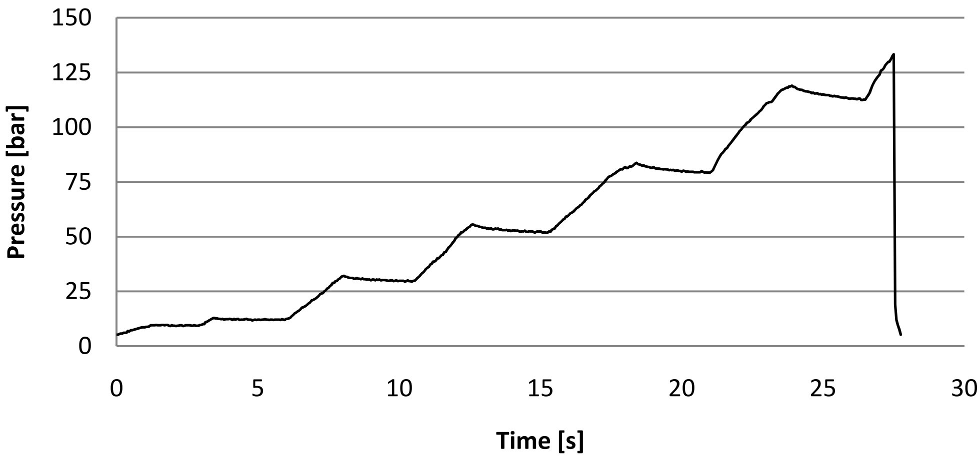


Figure 38: Pressure curve, 3mm composite coupon

The detailed burst pressures and their evaluation and interpretation can be found in the following chapters.

Figure 39 shows a 3mm coupon after retrieving it from the testing apparatus. The burst is clearly visible and affected the entire thickness of the coupon, so that the cracks could also be seen from the other side of the coupon. For the 3mm coupons, the crack was located in the middle of

Figure 39: Burst 3mm coupon

the circular testing area, which showed some variations for the other thicknesses. This is further discussed in the following chapters though.

Conclusion

Testing composite plates with different thicknesses showed that the used composite plates show no leakage, but break or burst at a certain pressure. The first thing to further evaluate was the actual structure of the used composite plate. Figure 40 shows a cross-section of a 3mm composite coupon. The grey fiber layers can be easily seen; also the very tight and compact structure is well noticeable. Comparing this with a cross-section of the pipe used for the previous pressure tests that showed a leakage in Figure 41, a big difference can be made out. The cross-section of the pipe shows a much less compact structure with holes.

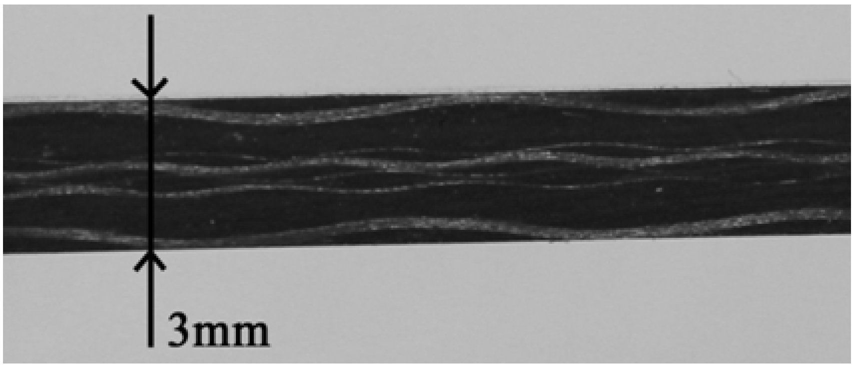


Figure 40: Cross-section of 3mm composite coupon

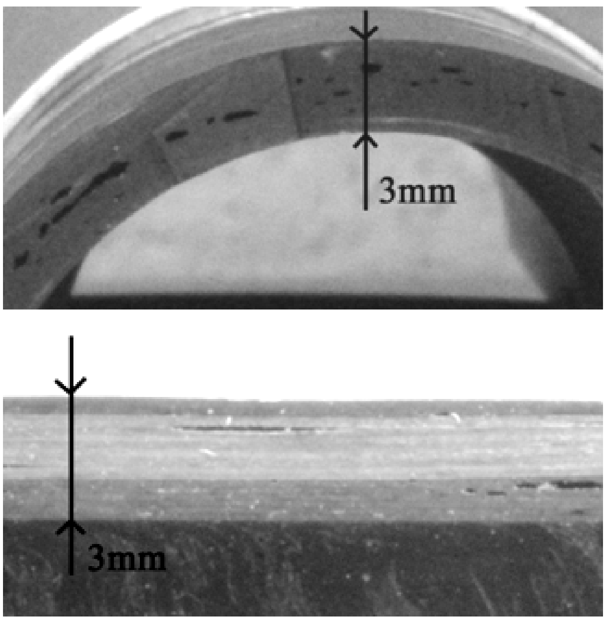


Figure 41: Cross-section of composite pipe, 3mm wall thickness

Considering that the holes in the pipe structure could form a network and so provide a way for the fluid to pass through, in combination with extension of the pipe due to the applied pressure might be one possible explanation for the leakage behavior of the pipe that could not be reproduced with composite plates.

To further prove this possible explanation tests with pipes of an increased quality, similar to the plates would be necessary. Should this fail, further investigations of tests e.g. with plates with poor quality would be necessary, which could then be extended with the testing of different sealing layers and their applicability to the problem. This could also verify if the used testing setup is really applicable for testing leakage of composite material.

The initial idea, that the pressure tests that resulted in a leakage of composite pipe can be simulated with composite plates which can bend due to the applied pressure and apply a strain on the material and therefore simulate the radial extension of a pressurized pipe, could not be verified.

Testing Breaking Behavior of Composite Plates

Since the leakage tests showed not leakage of the composite plates with the given test setup, a further step was to evaluate the breaking behavior of the given composite plates. Different composite plate thicknesses should for the first step be the only variable. A step further also the testing temperatures should be changed in order to get more variables and a better overview of composite behavior.

Initial Tests at Room Temperature

The initial tests were conducted at an ambient temperature of 18°C. Having only the coupon thickness as a variable, meant that the tests results should show the burst pressure in dependency of the coupon thickness. Depending on side effects influencing the breaking behavior and also a possible change in breaking behavior should therefore dominate a possible linearity of this relation.

Test Setup

The test setup was very similar to the setup for the leakage tests. In a total nine coupons were used, three of each thickness (1, 2, 3mm). Again the tests were carried out at an ambient temperature of 18°C and the pressure was recorded with a sampling frequency of 50ms (20Hz) and a resolution of ±0.07bar.

The bending of the composite coupon towards the low pressure side, with only atmospheric pressure, would mean an increasing strain with increasing pressure. Therefore, if the pressure exceeds a certain limit, the strain would exceed the breaking strain and the composite coupon would fail consequently.

The composite plates with the same properties as for the leakage tests were used for these tests. The composite plates with the dimensions of 150x150mm and thicknesses of 1, 2 and 3mm had a quasi isotopic structure with a fiber volume fraction of approximately 50%. The detailed fiber and resin properties can be found in the previous chapter, discussing the test setup for the leakage tests. Again, the seals needed to be changed after each test, ensuring the proper working order of the testing apparatus.

Results

Due to the previous leakage tests, the results were little surprising. The composite coupons broke or in other words burst at pressures presented below:

1	2	3	Coupon Thickness [mm]
78	113	133	
77	106	127	Measured Burst Pressure [bar]
67	107	122	
74	109	127	Calculated Average Burst Pressure [bar]
6.08	3.79	5.51	Standard Deviation [bar]

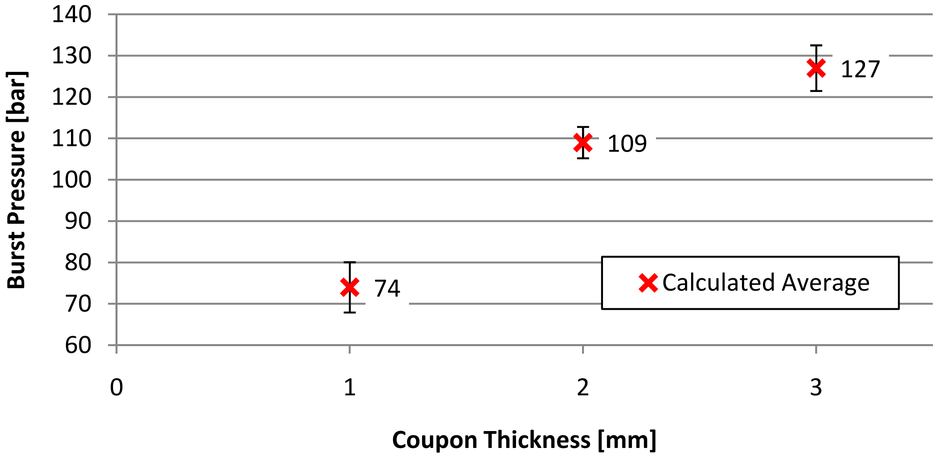
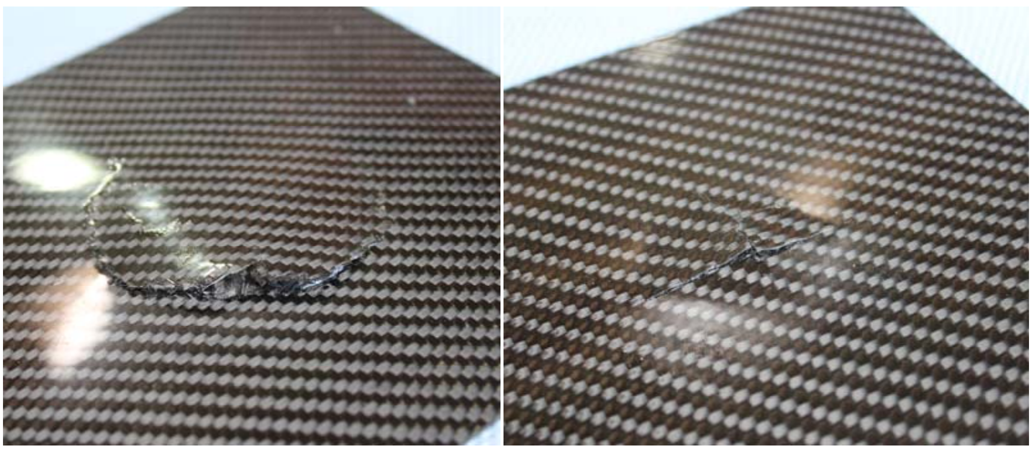


Figure 42: Results of breaking behavior tests at room temperature

While the burst pressures, with the error bars representing the standard deviation, presented in Figure 42 suggest an almost linear dependency of the burst pressure with the coupon thickness, this should not be understood as a given fact. First of all, the linearity might depend on the scaling of the axis but what was much more striking, when looking at the burst coupons was the different breaking behavior of the differently thick coupons.

As can be seen in the pressure curves for each test in Appendices E to I, most samples broke very rapidly once the breaking pressure was reached. On the other hand, three samples broke but could still maintain a fluid barrier, which resulted in a rapid pressure drop but then the pressure stabilized at a lower level, most probably due to the increased volume. When increasing the pressure again, these fluid barriers broke at a significantly lower pressure than the initial burst pressure.

What was an interesting outcome of the test was that not only the burst pressure depended on the coupon thickness, but also the breaking behavior. Figure 43 clearly shows the difference between the failure of a 1mm and a 3mm coupon. While the 3mm coupon on the right side breaks, like it would be expected in the middle, the 1mm coupon is less stiff and shows therefore more deformation or bending, while the 2mm coupons showed the same breaking behavior as the 3mm coupons. The smaller stiffness of the 1mm coupon and the increased bending seems to trigger a failure where the coupon has contact to the testing apparatus. Even though, the coupons are clamped with 3mm thick rubber seals, which should avoid the steel edge from damaging the composite structure, the shear force seems to be too high at the edge, causing the failure mode presented in the left picture.



1mm Coupon 3mm Coupon

Figure 43: Breaking behavior, 1mm vs. 3mm coupon

Also it needs to be noted, that the rubber seal that was meant to protect the coupon from the metal edge of the testing apparatus was most of the times cut at the metal edge due to the excessive forces applied and it has to be considered that the coupons were exposed to the edge, which might have a further influence in the breaking behavior. This is especially true, when considering that the 1mm plates which showed more bending and were damaged at the edge of the testing surface.

Calculated Verification of Results

Calculating the theoretical burst pressure is rather complex, since several tests would be necessary to verify all characteristics of the composite material and also implementing a three dimensional stress state in a laminate calculation is rather complex and would require a finite element simulation. On the other the following rather simple calculation allows the estimation of the fracture strain due to the applied pressure. Since the exact fracture strain of the composite is not known, the measured burst pressure is used to calculate the fracture strain at which the composite failed, which allows the comparison of the theoretically calculated fracture strain with typical values.

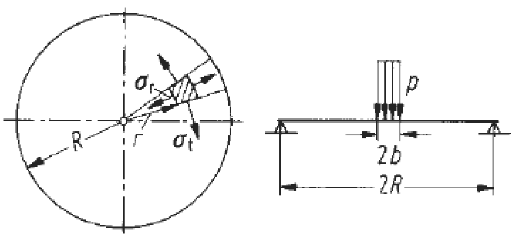


Figure 44: Sketch of round testing surface[26]

Figure 44 shows the theoretical test surface, where in this case the pressure is applied over the entire surface and therefore $R = b$. This results in the following already shortened equation for the maximum stress in the middle of the plate, considering only 3mm coupons for this calculation since they showed the clearest breaking behavior and broke in the middle of the testing surface.

$$\sigma_{max} = \alpha * \frac{p*R^2}{h^2} \quad \text{(Eq. 19)}$$ [26]

Where:

σ_{max} ... Maximum Tension [N/mm^2]

b … Radius of area where force is applied [mm]

R … Radius of total plate [mm]

p … Measured burst pressure [N/mm^2]

h … Thickness of plate [mm]

α .. Fracture mode factor (0.488 or 1.24, depending on fracture mode) [1] [26]

With:

$b = 30.5mm$

$R = 30.5mm$

$h = 3mm$

$p = 129bar = 12.9N/mm^2$

Results in $\sigma_{max} = 630\ to\ 1600 N/mm^2$

The stiffness matrix of the quasi isotropic composite plate was determined with LamiCens, a program for designing composites. The following calculations are made according to the classical laminate theory:[32]

$$[A] = \begin{bmatrix} 50317 & 15304 & 0 \\ 15304 & 50317 & 0 \\ 0 & 0 & 16832 \end{bmatrix} N/mm^2$$ (Eq. 20)[32]

Inverting the stiffness matrix allows the calculation of the strain for a given stress:

$$[A]^{-1} = \begin{bmatrix} 2.18E-5 & -6.66E-6 & 0 \\ -6.66E-6 & 2.18E-5 & 0 \\ 0 & 0 & 5.94E-5 \end{bmatrix} \frac{1}{N/mm^2}$$

The strain can then be calculated, setting $\sigma_x = \sigma_y = \sigma_{max} = 630\ or\ 1600\ N/mm^2$

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = [A]^{-1} * \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} 0.01 \\ 0.01 \\ 0 \end{bmatrix}\ or\ \begin{bmatrix} 0.024 \\ 0.024 \\ 0 \end{bmatrix}$$ (Eq. 21)[32]

Where:

σ ... Stress [N/mm²]

ε … Strain [1]

τ … Shear Stress [N/mm²]

γ … Shear Strain [1]

[A] … Stiffness Matrix [N/mm²]

Resulting in a fracture strain between 1.0 and 2.4%. Considering that the fiber used has a fracture strain of approximately 2%[10], these results are rather plausible. Especially when considering that impurities in the composite structure my cause a lower fracture strain, while using fiber in a quasi isotropic structure can increase the overall fracture strain.[32]

Further Tests at Elevated Temperatures

While for the first step only one parameter, the coupon thickness, was a variable, it was decided to repeat the tests at different temperatures, to see the effect of temperature on the composite material. Since the main temperature related properties of composite material depend on the resin used, obviously test results would not be adaptable to any other problem. Still, the trends seen can be expected to be similar, even the resin might be different and therefore the absolute values will consequently divert from the measure test results.

Evaluation of the Glass Transition Temperature

To get an idea at which temperatures measurements would make sense it was necessary to evaluate the glass transition temperature Tg. As already described, the glass transition temperature gives an idea of the temperature where a plastic material becomes soft. Therefore it was interesting to make measurements below and above the glass transition temperature. For measuring Tg, so-called dynamic mechanic analysis are used, which allow, besides more complex, the measurement of the elastic and shear modulus.

A dynamic mechanic analysis (DMA) generally applies a periodic, usually sinusoidal force on a specimen. The measurement samples the applied force, the deformation and the phase shift between these two signals, which allows the calculation of stress and strain and further on the elastic and shear modulus.[33]

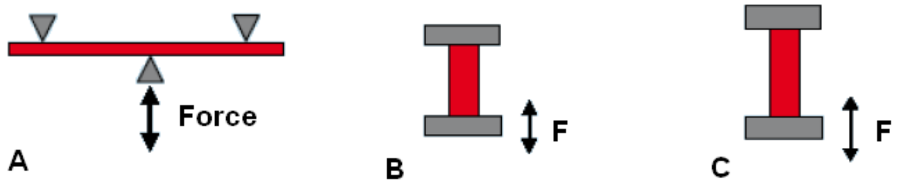


Figure 45: Principle of measurement (A: 3-point-bending, B: compression, C: tension)[33]

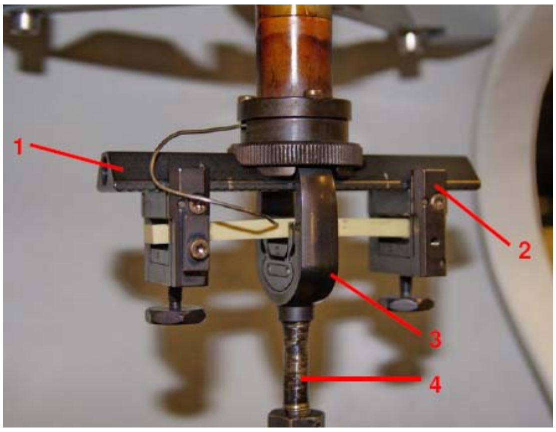


Figure 46: 3-point-bending setup with fixed, static clamping (1, 2) and the force application (3, 4)[33]

Figure 45 shows the three typically used principles of measurement for DMA. For the measurement, an offset force is typically applied, so that e.g. a sinusoidal force does not get negative. The measurement is repeated while slowly increasing the temperature, resulting in measurement of e.g. the shear modulus over an increasing temperature. A heating rate of 1K/min and a sampling rate of 1Hz are typical measurement setups, with a sample size of 10mm width, 80mm length and a thickness depending on the material available.[33]

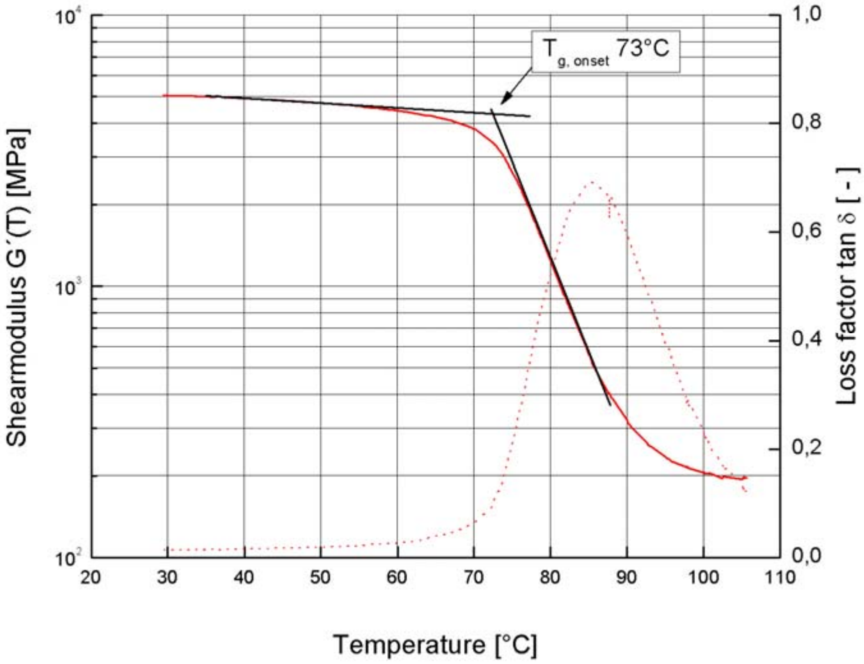


Figure 47: DMA results, with estimation of Tg (DIN 65583)

Evaluating a sample of the composite material used for the coupons to be tested was done with a 3-point-bending test (see Figure 46). The results of the measurement are presented in Figure 47. The solid red line hereby shows the shear modulus and the dashed red line the loss factor. The glass transition temperature was estimated with the tangent method (DIN 65583).[9]

The determined glass transition temperature of $Tg = 73°C$ should not be considered as an absolute value, but as a temperature where the material properties start to change.

Using this Tg of 73°C allowed setting the temperatures of interest for the following tests at elevated temperatures. 55°C, 70°C and 85°C were chosen as temperatures of interest. This had several reasons, first of all, it meant having one measurement (55°C) significantly below Tg, but also in an area where the shear modulus shows some change compared to 18°C at which the first measurements were carried out. On the other hand, the 85° was the measurement meant to be well above Tg. Since plastics are typically only used up to temperatures below the glass transition temperature, this should show how the material behaves at there elevated temperatures. The 70°C measurement was meant to measure more or less at the glass transition temperature. Besides that it is noticeable, that the given measurement temperatures, including the 18°C measurement of the first measurements, gives a change of shear modulus by roughly the order of a magnitude between the highest and the lowest temperature.

Test Setup

For testing the coupons at elevated temperatures, the tests at room temperature were repeated three times, at 55, 70 and 85°C. At each temperature coupons with 1, 2 and 3mm thicknesses were tested and each test was repeated three times, resulting in a total of 27 tests.

In order to get comparable results, the coupons had the same properties as for the tests at room temperature. Any other influencing factors were kept constant as well.

The temperature was measure in the oil filled chamber in the bottom plate. For each test, fresh, cold oil was used. Before testing, the entire testing apparatus was heated approximately to the desired testing temperature. The coupon to be tested was then mounted in the apparatus and the hole in the bottom plate was filled with cold oil. The oil temperature was measured while heating the entire system. Once the temperature has been reached, the temperature has been kept constant for 20 minutes before pressure was applied and the measurement was taken.

Due to the used temperature sensor and testing equipment, the temperatures could be reached with an accuracy of approximately ±1.5°C.

Results

While testing the coupons was nothing new, also handling the testing apparatus at increased temperatures in the oven was no problem and generated the data including the data from the measurements at room temperature are presented in the following table. Again the measured values were round and an average burst pressure and the according standard deviation was calculated to get a better feeling for the data.

	1	2	3	Coupon Thickness [mm]
	78	131	196	
	80	129	198	Measured Burst Pressure [bar]
85°C	85	128	178	
	81	129	191	Calculated Average Burst Pressure [bar]
	3.61	1.53	11.02	Standard Deviation [bar]
	66	106	147	
	63	111	142	Measured Burst Pressure [bar]
70°C	70	119	158	
	66	112	149	Calculated Average Burst Pressure [bar]
	3.51	6.56	8.19	Standard Deviation [bar]
	62	102	125	
	71	114	131	Measured Burst Pressure [bar]
55°C	59	106	138	
	64	107	131	Calculated Average Burst Pressure [bar]
	6.24	6.11	6.51	Standard Deviation [bar]
	78	113	133	
	77	106	127	Measured Burst Pressure [bar]
18°C	67	107	122	
	74	109	127	Calculated Average Burst Pressure [bar]
	6.08	3.79	5.51	Standard Deviation [bar]

Figure 48 presents the entire recorded burst pressure data visually. Interesting to observe is, that the burst pressure stays in the same region for the first two to three measurements (18, 55 and 70°C) for all thicknesses.

While the tendency that the burst pressures increase with increasing temperature, the burst pressure values for the different temperatures seem not be in the same, logic order as they are for the 3mm coupons, where an increasing temperature indicates an increasing burst pressure. For the other two coupon thicknesses, the first measurements seem to be in a mixed order. However, comparing this with the data and especially with the calculated standard deviations in the table, one explanation for this might be the fact that for the 1 and 2mm coupon thicknesses are generally closer together, while the standard deviation stays in the same range and therefore could cause this phenomenon.

However, also the breaking behavior, which also changes with temperature needs to be taken into account and is discussed in the following paragraphs. The recorded pressure curves can be found in Appendices E to I.

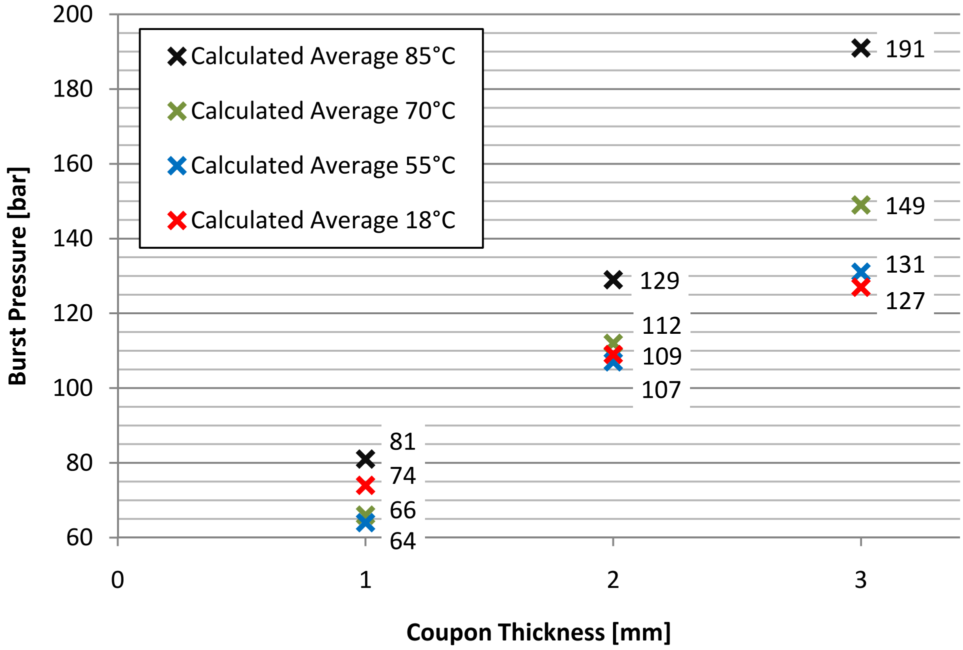


Figure 48: Summery of recorded data

What can be further observed and is better visualized in the following figures (Figure 49, Figure 50, Figure 51), is the increase in burst pressure according to an increase in testing temperature in general. The estimated glass transition temperature Tg is indicated in these figures with a blue line. While the temperature effect on the burst pressure seems to be the strongest for the 3mm coupons, the other coupons also showed this effect when the temperature approached the glass transition temperature.

For considering this effect, it needs to be kept in mind that the measurement for the glass transition temperature gives more an idea about where the material behavior changes rather than an exact absolute value. Also the slope of the shear modulus is very steep around the glass transition temperature, which can be seen in Figure 47. This consequently means that the measurement is strongly influenced by small changes in temperature. Therefore, the absolute measured values should be taken with care.

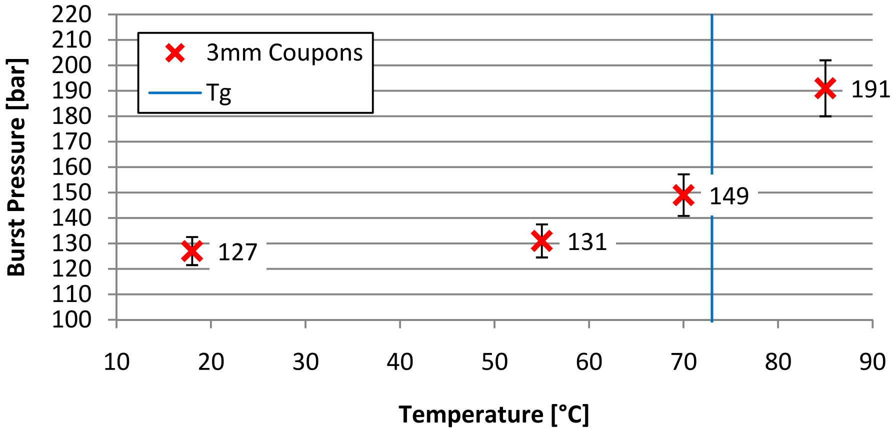


Figure 49: Burst pressure vs. temperature, 3mm coupon thickness

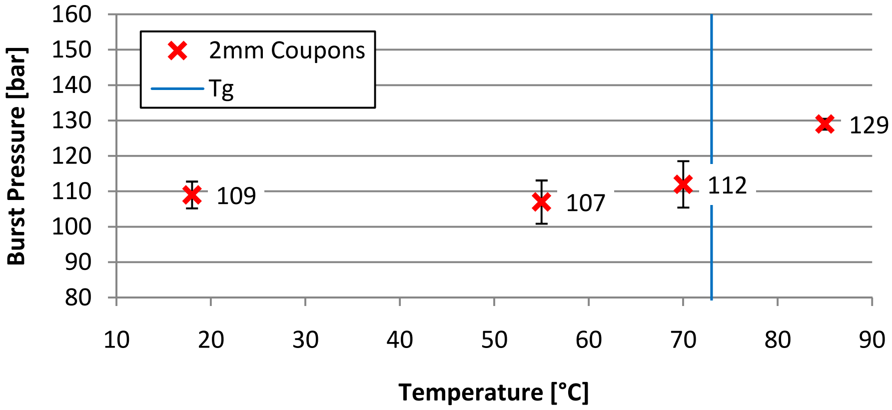


Figure 50: Burst pressure vs. temperature, 2mm coupon thickness

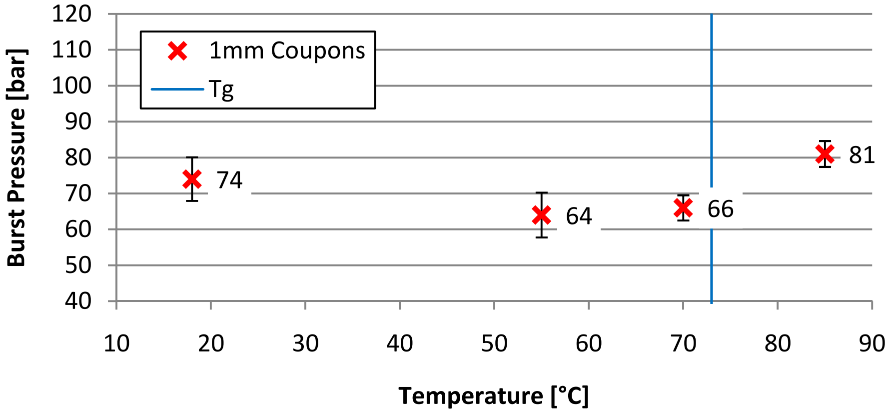


Figure 51: Burst pressure vs. temperature, 1mm coupon thickness

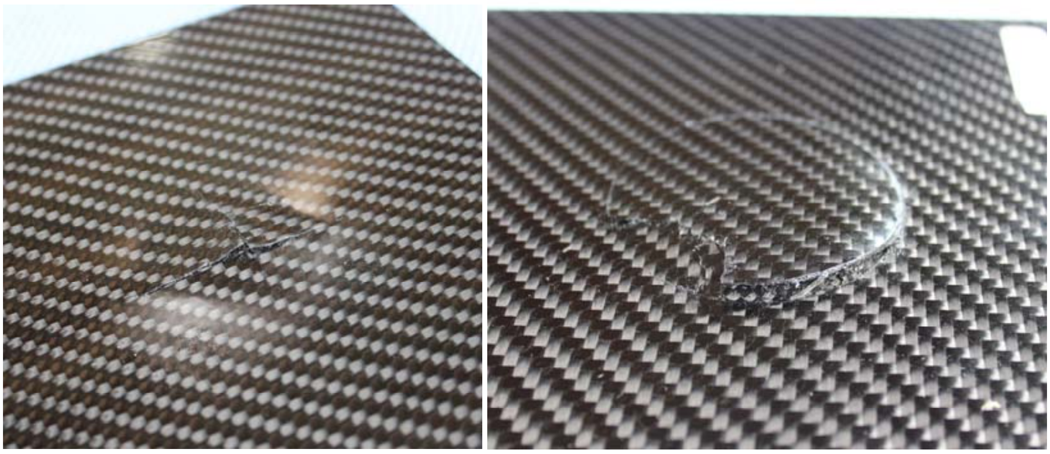
Besides the change in temperature influencing the burst pressures, also the burst behavior changed with increasing temperature which might have an additional effect on the burst pressures measured.

The 1mm coupons always broke at the edge of the testing surface, independent of the testing temperature. Though, the visually inspected deformation of the coupons increased with increasing temperature.

For the 2 and 3mm coupons the breaking behavior changed with increasing temperature. While for low temperatures, the coupons broke in the middle of the testing surface, for higher temperatures the coupons failed at the edge of the testing surface.

For the 3mm coupons, the breaking behavior only changed for the 85°C measurement. The difference between the breaking behaviors for different temperatures can be seen in Figure 52.

For the 2mm coupons, the change in breaking behavior already took place with the 55°C measurements, where 2 out of 3 coupons failed at the edge rather than in the middle of the testing surface like for lower temperatures.



3mm Coupon, 18°C 3mm Coupon, 85°C

Figure 52: Change in breaking behavior, 3mm coupons, 18 and 85°C

Figure 53 shows cross-sections of the different breaking behaviors. Picture A is a 2mm coupon, tested at 85°C, which behaved very similar to any other test where the coupon broke at the edge of the testing surface. Picture B shows a 3mm coupon, tested at 18°C, representing any coupon failing in the middle of the testing surface. For both pictures, the dashed line indicates the approximate center of the testing surface.

While both failure modes show some sort of delamination of the fiber layers, the failure at the edge of the testing surface in picture A clearly shows the shearing of the material.

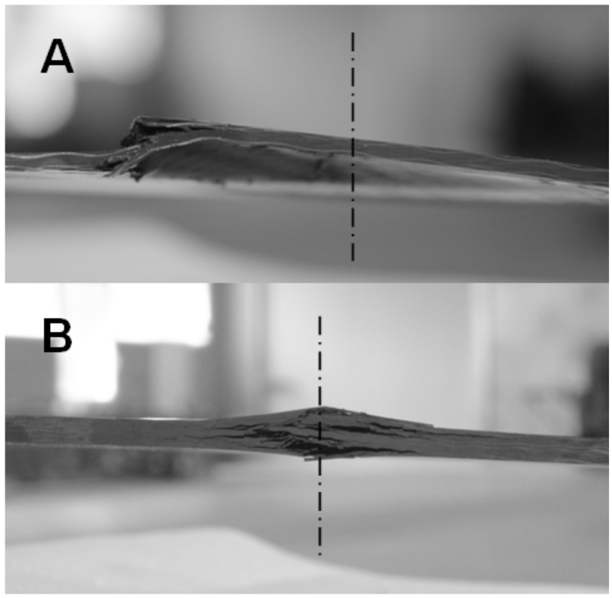


Figure 53: The different breaking behaviors

Conclusion

Even though not the same resin and fiber were used for the composite coupons as for a possible later drillpipe, the trends that can be observed with this measurement are still adaptable for other resin fiber combinations. For the use of composite material for drillpipe applications the main difference would be the resin which would need to have a much higher glass transition temperature in order to maintain the drillpipe properties at elevated temperatures that will occur in the drilling process due to increasing formation temperature with increasing depth.

The finding that the burst pressure for the tests with the composite coupons increases with increasing temperature is most likely an effect of the decreased stiffness of the material, which is caused by the applied temperature in combination with the used material and its behavior as described before. A decrease in stiffness would consequently allow more bending before failure when pressure is applied. This can also be observed with the 1mm coupons compared to the 3mm coupons, where the 1mm coupons are less stiff and bend more when pressure is applied.

The effect of stiffness seems also to influence the breaking behavior. While the 1mm coupons seem to be below the threshold stiffness where the breaking behavior changes as described, the 2 and 3mm coupons are stiffer due to their thickness and seem to approach this value only at increased temperature, where stiffness decreases.

The failure at the edge of the testing surface is clearly influenced by the edge of the testing adapter, interfering with the composite coupon. This could be seen when visually inspecting the tested coupons that failed at the edge of the testing surface, which in many cases showed cuts in the composite material from the contact with the metal edge of the testing adapter. Apart from that, this failure looks much like a shear failure. Considering, that the failing of the coupons for this failure mode might have been triggered by the general test setup and the testing adapter could consequently mean that the coupons could have withstood an even higher pressure.

A next step to see how these findings are adaptable for the development of composite drillpipe is to repeat selected tests with tubular specimen and evaluate their burst strength and behavior at temperatures around the glass transition temperature. However it is generally advisable to use a possible composite drillpipe well below the glass transition temperature.

Testing Possible Lead-Through Solutions

The selected lead-through solution needed to be evaluated for its applicability. Since the sealing with a cutting ring is typically used for hydraulic connections as they can be found in various applications. They generally have a good sealing capacity, however for these applications, where the pipe that is sealed typically contains a pressurized fluid, the load on the cutting ring is the most optimum. The pipe is internally pressurized, which means that due to a slight circumferential extension of the pipe, pressing the pipe further into the cutting ring, the sealing is further improved. Also, the pressure is applied against the front side of the cutting ring, where it can withstand the most pressure, and putting tension on the pipe even further improves the sealing capacity. For the lead-through solution this is a bit more difficult. On the one hand, the pipe is not internally pressurized, but externally, which consequently compresses the pipe and reduces the sealing capacity of the cutting ring. Also, depending on the direction, the cutting ring is applied; either the pressure is applied to the front of the cutting ring, which allows less tension on the pipe, or vice versa.

Therefore, the applicability of the lead-through solution with the cutting ring needed to be further evaluated and tested. Since there are two options for the pressure application on a cutting ring, from the front side, applying direct pressure and from the back side, applying reverse pressure.

The Specimen

For testing the lead-through solutions, essentially cutting rings that are available for a low price and usually used for hydraulic pipe connections were used. In this case however, the applied load is not coming from inside of the pipe, but from the outside, and the pipe needs to be sealed against that pressure. This results in two possible ways of applying the cutting ring. These two ways both have the already described advantages and disadvantages.

However, for testing the cutting ring lead-through solution, pieces of pipe for testing were necessary. As first criteria they were chosen due to their size and capability of wires to fit through. The design of the two testing adapters resulted in the following specimen specifications:

Outer Diameter	10mm
Length	25 and 40mm
Steel Grade	E235N

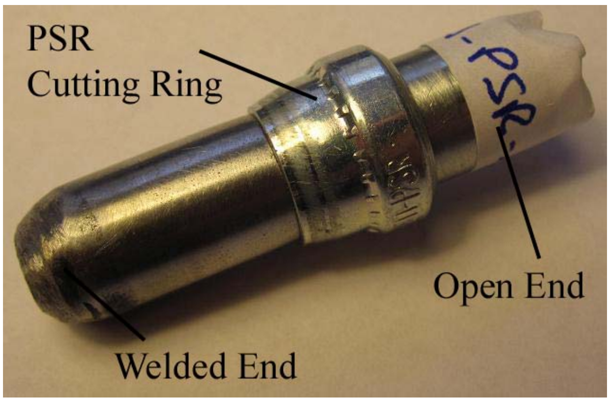


Figure 54: Lead-through specimen, 40mm

Figure 54 shows a specimen for the lead-through testing adapter for direct pressure application. Since pressure needs to be applied in axial direction, one end of the pipe needed to be closed and therefore a approximately 3 to 5mm steel stub was weld into one end. The pressure is in both cases of testing applied to the welded end, meaning that there was no threat of tension fracturing the weld and it could therefore be kept as minimal as possible in order not to influence the collapse strength of the pipe too much. Imagining the conical sealing surface of the testing adapter around the cutting ring shows, that the part of the pipe between the welded end and the cutting ring is under hydraulic compression if pressure is applied.

The specimen for the reverse pressure tests are the said, shorter, 25mm ones. The principle is the same as for the already described 40mm specimen. Through, these specimen have perforations at the edge of the open end of the pipe as fluid pathway for a possible leaking fluid from the cutting ring. This is due to the direction of pressure application and the risk to generate and artificial sealing effect at an upset in the testing adapter.

Strength Calculations

Important to notice is, that beside the sealing function of the cutting ring, also the strength of the testing or armoring pipe is essential for a well working system. On the one hand, the pipe needs to withstand a possible applied pressure, so the collapse strength needs to be sufficient in order to protect the wires led through the armoring pipe. Beside the protective function for the wires, the collapse strength also needs to be sufficient so that no deformation occurs, which would lead to a loss of the sealing effect, as the cutting ring can only seal a round cross section.

For testing an OD 10mm pipe with a wall thickness of 1.5mm was chosen. Which was essentially a compromise between the inside diameter capable of a certain wire cross section and an outside diameter that that can be dealt with inside a drillpipe.

What is also important and somewhat a fact complicating the armoring pipe selection is that the material for the armoring pipe needs to be a rather soft steel. Hence reducing the compressive strength and making a higher wall thickness necessary to reach comparable collapse strengths. This is due to the fact that the sealing function is a result of the cutting ring grapping into the pipe material and, as the name already says, cutting the material. This however can only be achieved if the pipe material is rather soft compared to the cutting ring.

The collapse pressure calculation was taken from the API collapse calculation for casing when axial stress is zero:[34]

First of all, the D/t ratio has to be determined to select a failure mode from the table below.

Steel Grade	Yield Strength Collapse		Plastic Collapse		Transition Collapse		Elastic Collapse
H-40	<	16.40		27.01		42.64	>
J-55	<	14.81		25.01		37.31	>
N-80	<	13.38		22.47		31.02	>
P-110	<	12.44		20.41		26.22	>

The table shows the different collapse modes and ranges of the D/t-ratios

Table taken from Reference 34.

$$D/_t = 6.67 \quad \text{(Eq. 22)}^{34}$$

Where:

D … Outside diameter [mm]

t … Wall thickness [mm]

With:

$D = 10mm$

$t = 1.5mm$

Having a steel grade of E235N for the testing tube, which is close to the H-40 steel grade of the US system, “Yield Strength Collapse” can clearly be selected as failure mode.

This results in the following equation for determining the collapse pressure:

$$P_{Yp} = 2 * Yp * \left[\frac{D/_t - 1}{(D/_t)^2}\right] \sim 590bar \quad \text{(Eq. 23)}^{34}$$

Where:

Yp … Yield point [MPa]

P_{Yp} … Collapse pressure for yield strength collapse [MPa]

With:

$D = 10mm$

$t = 1.5mm$

$Yp = 235MPa$ (for steel grade E235N)

The resulting collapse pressure of approximately 590bar gives an application limit for given armoring pipe. If a higher collapse pressure rating is required, either the pipe dimensions can be changed, or what might also be possible, but has to be tested is a higher steel quality for the armoring pipe.

Test Setup

As already mentioned, two ways of pressure application on the cutting ring lead-through construction needed to be tested. For this reason, two testing adapters were planned and manufactured as already described in the previous chapters.

For the tests with direct pressure application, the measuring equipment of the initial testing apparatus was attached to the new testing adapter. The tests were carried out at an ambient temperature of 21°C. The measurements were recorded with a sampling rate of 50ms and a resolution of ±0.07bar. Each test was repeated three times.

For the reverse pressure application, the initial testing apparatus was used, clamping the testing adapter, and resulting in the described pressure chamber. Again, the tests were carried out at an ambient temperature of 21°C. The measurements were recorded with a sampling rate of 50ms and a resolution of ±0.07bar. Each test was repeated three times.

Two sets of specimen were prepared for the different testing adapters.

Although hydraulic oil was used as a testing fluid, it needs to be noted, that for both construction, the highest point in the hydraulic system is the cutting ring assembly in a pressure chamber that could not be vent and therefore, besides hydraulic oil also compressed air might have been exposed to the cutting ring and lead-through solution when the system was pressurized.

The function nuts, forcing the cutting rings in their final sealing position, were fastened with approximately 6Nm, the function nut and the adapter with the conical sealing surface were visually inspected after each test and reused, while the cutting ring and the testing pipe were exchanged.

Test Results

While no leakage was recognized for any of the tests with the PSR cutting rings, the two test setups should nonetheless be considered separately.

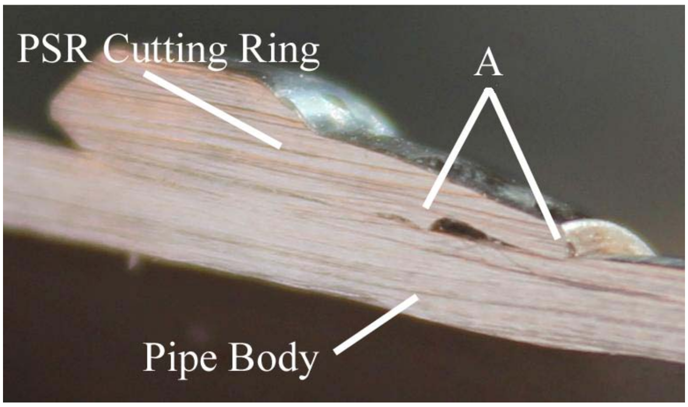


Figure 55: PSR cutting ring - cross-section

Figure 55 shows a cross-section of a PSR cutting ring in a setup like it was used for the tests, using a tightening torque of the function nut of 6Nm. It clearly can be seen where the cutting ring bites into the pipe (A) and even slightly deforms the pipe in this area. Since the pipe was not toughing any counterpart in the testing adapter, there was no resistance holding the pipe and allowing a better shear action of the cutting edges as it can be observed with hydraulic applications, where more material in front of the cutting edges is sheared out.

Direct Pressure

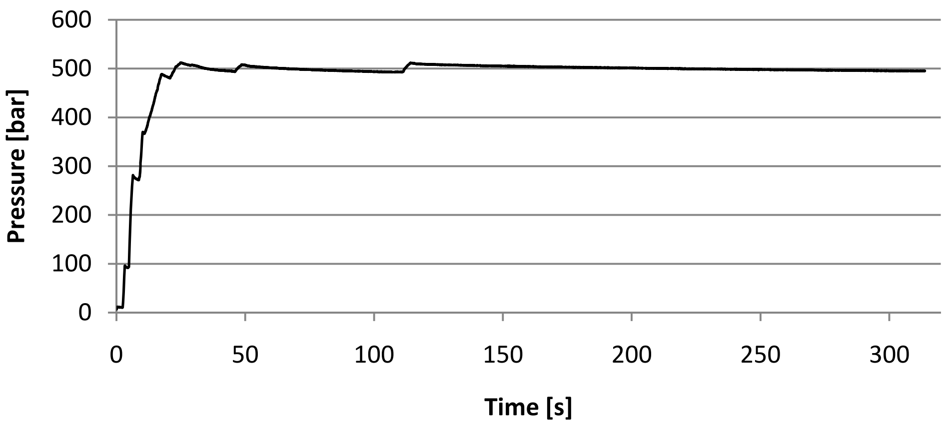


Figure 56: Lead-through test curve - direct pressure

The measurement for direct pressure application could be very well handled, with no failure of the testing adapter. Figure 56 shows a recorded pressure curve of a test with direct pressure.

What needs to be noted here is that even though the pressure drops slightly over time, there was no leakage observed by visual inspection. Therefore, and due to the fact that this behavior was observed with other tests as well, this effect is most probably resulting from the hydraulic hand pump. The results for the three tests, which all applied a pressure of over 500bar for a approximately of 5 minutes, are as follows:

Specimen Number	Tightening Torque	Pipe OD	Maximum Pressure	Result
A-PSR-1	6.5Nm	10.05mm	511bar	No leakage
A-PSR-2	6Nm	10.05mm	547bar	No leakage
A-PSR-3	6Nm	10.00mm	512bar	No leakage

Reverse Pressure

After initial problems with the testing apparatus were solved, measurements were possible, though slightly more complicated. Pressurizing the specimen to 500bar and then maintaining the pressure over approximately 1.5 minutes was possible, when maintaining the pressure over a longer period of time, the seal tended to fail. The initial problems that the seal failed at even lower pressures was solved by introducing concentric cuts in the sealing surface and further supporting the seal with a ring put around the part of the seal above the seal groove of the top plate. Keeping the pressure constant was more complicated than for the direct pressure tests. This was probably again due to the hydraulic hand pump, but for these tests also a result of the slowly expanding seal. However, no leakage could be visually observed. The results for the tests, maintaining a pressure of approximately 500bar over at least 1.5 minutes gave the following results:

Specimen Number	Tightening Torque	Pipe OD	Maximum Pressure	Result
B-PSR-1	6Nm	10.00mm	517bar	No leakage
B-PSR-2	6.5Nm	10.05mm	511bar	No leakage
B-PSR-3	6Nm	10.00mm	513bar	No leakage

Conclusion

Even tough the tests showed good results regarding the leakage resistance to pressures that might occur in a drillstring, there are several things to note. The tests only simulated the application of one force on the cutting ring. Applying the pressure in two different setups gives a good overview of what the cutting rings can withstand. Still it is very important to introduce the second force that will most likely be applied on the armoring pipe, if this solution will be at a later stage used for wiring drillpipe. The armoring pipe will, depending on the way of running in through the drillpipe, experience a not negligible tension. As described, this needs to be considered as it may counteract the sealing capacity. Therefore, pressure tests in combination with a pipe under a realistic tensile stress are a highly recommended.

Furthermore, long term tests need to evaluate if the setup can withstand pressures over longer periods of time without leakage and retightening of the connection. This test can theoretically be carried out with the existing test setup, by only adding a needle valve close to the testing adapter in order to separate the hydraulic hand pump once the desired pressure has been applied.

To ensure long term integrity of the sealing, it might also be advisable to consider sealing glue added to the cutting ring, to counteract the effects of a possible setting of the cutting ring or threads by the introduction of a second, adhesive fluid barrier.

While introducing an armored pipe with wires inside for wiring drillpipe is a first step, higher pressure ratings should also be considered for the future. This can be very important, as drillpipe typically has a given burst pressure which must not be exceeded under normal operations. However values in this pressure area have to be expected when thinking of the entire lifetime of a drillpipe. Taking for example a common 5in drillpipe with a nominal weight of 19.5lb/ft the burst pressure may be as high as e.g. 964bar for S135 steel.[35] Having this burst pressure consequently means that the armoring pipe and lead-through solution should withstand this pressure in order to maintain the operational limits of the pipe according to the API rating.

Conclusion

Composite drillpipe and also wired drillpipe clearly have many advantages. Their use still needs to be investigated for its technical and economical feasibility. Therefore, very similar pressure tests for the evaluation of composite materials and testing of new ideas and solutions for wired drillpipe, were developed, conducted and evaluated.

The tests carried out on composite material for a later composite drillpipe development led to some surprising results. First of all, the leakage behavior could not be reproduced and therefore no sealing solutions could be tested. On the other hand, having non-leaking composite coupons and comparing the structure with the previously leaking specimen, allows the conclusion that the leakage behavior highly depends on the quality of the composite.

Also the burst tests with composite coupons at increased temperatures showed an interesting composite behavior. The tests were carried out above, around and below the temperature at which the resin in the composite looses its strength and gets soft. The results showed that for increasing temperatures, where the coupons get softer, consequently, the burst pressures also increased. Generally, a composite drillpipe should still only be operated at temperatures well below that temperature, in order to maintain the mechanical properties of the pipe, knowing this behavior is still important. While more extensive tests will be necessary, the results might allow the calculation of more accurate temperature ranges for the application of a drillpipe and an optimized use of the material, besides having an idea how composite drillpipe might behave at temperatures that it is not designed for.

Two setups were tested as possible solutions for sealing armoring pipe for wired drillpipe. The lead-through solutions with so-called progressive stop rings, which are typically used for hydraulic applications, were tested for both possible mounting directions. While each has advantages and disadvantages, first tests showed that either way has a good sealing capacity, as no leakage or failure was observed. Though, further tests that also apply tension on the armoring pipe will be necessary.

Considering these results, it can be said that both, composite drillpipe and wired drillpipe, have significant potential for the future. While the conducted tests are small steps in the development of the said drillpipes, there will be several more tests necessary to find the optimum materials, components and their use.

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[33] R. Karpf: "Optimierung dynamisch-mechanischer Analysen (DMA) für ungesättigte Polyesterharze," Studienarbeit, University of Leoben, 2008, Chapter 2

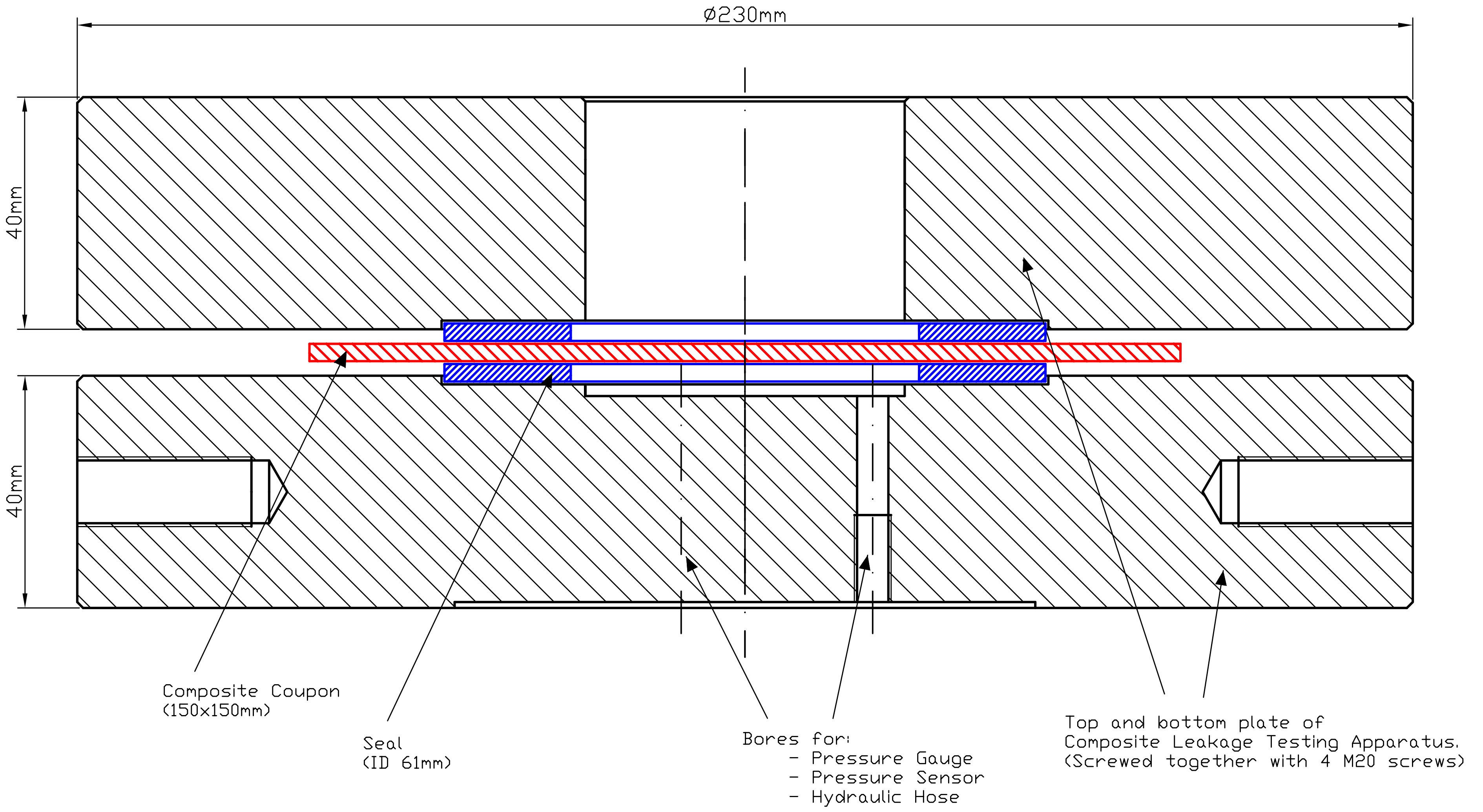
Appendix A: Abbreviations

API	American Petroleum Institute
CPU	Central Processing Unit
CrN	Chromium Nitride
deg	Degree
DIN	translated: German Institute for Standardization
DMA	Dynamic Mechanic Analysis
I/O	Input / Output
ID	Inner Diameter
LED	Light Emitting Diode
LWD	Logging While Drilling
MWD	Measurement While Drilling
OD	Outer Diameter
PLC	Programmable Logic Controller
PLC	Power Line Communication
PSR	Progressive Stop Ring
PVD	Physical Vapor Deposition
TCP/IP	Transmission Control Protocol / Internet Protocol
Tg	Glass Transition Temperature
TiAlN	Titanium Aluminum Nitride
TiCN	Titanium Carbon Nitride
TiN	Titanium Nitride
WOB	Weight on Bit

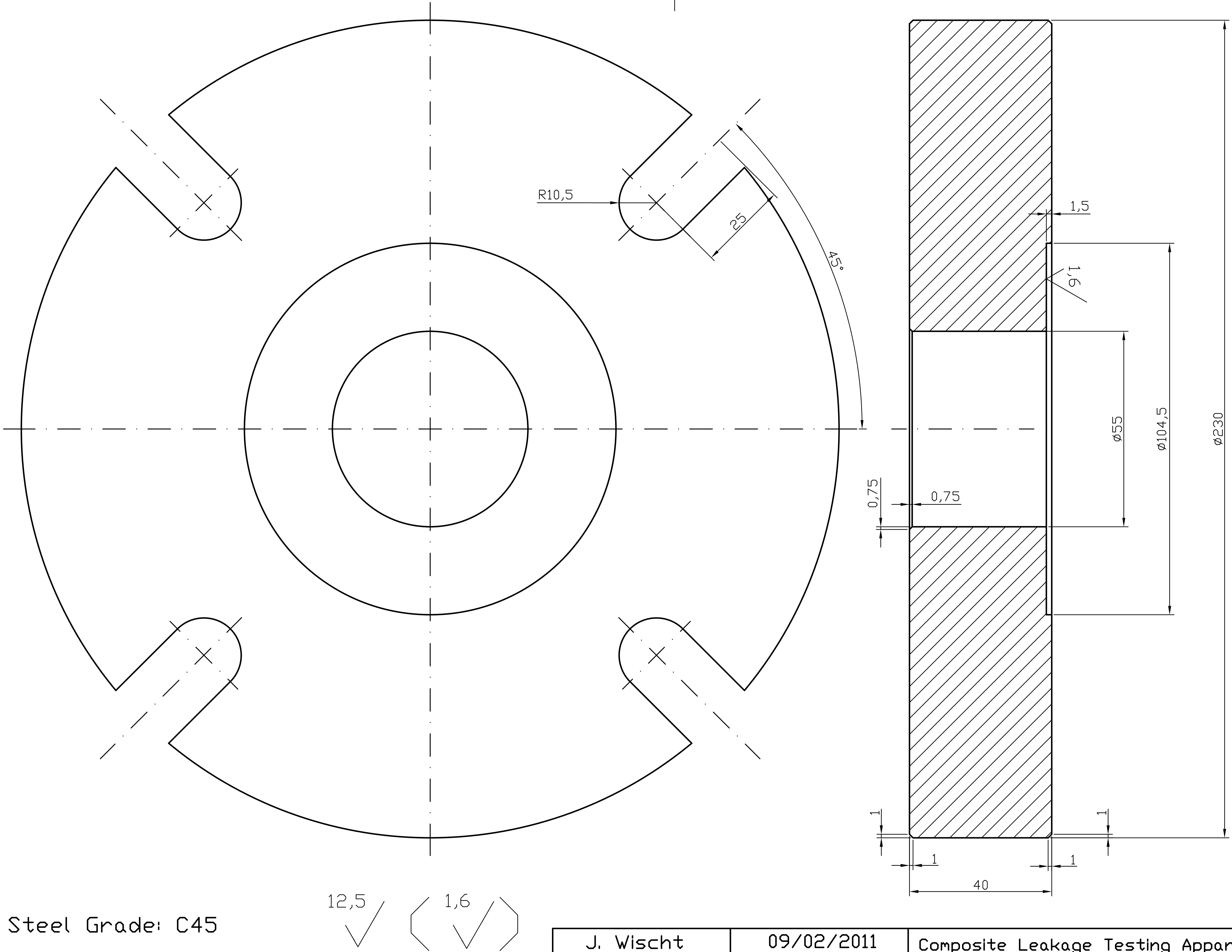
Appendix B: Blueprints – Leakage Testing Apparatus

Please find A3 blueprints on the following pages:

- Top Plate
- Bottom Plate
- Sketch of assembled components

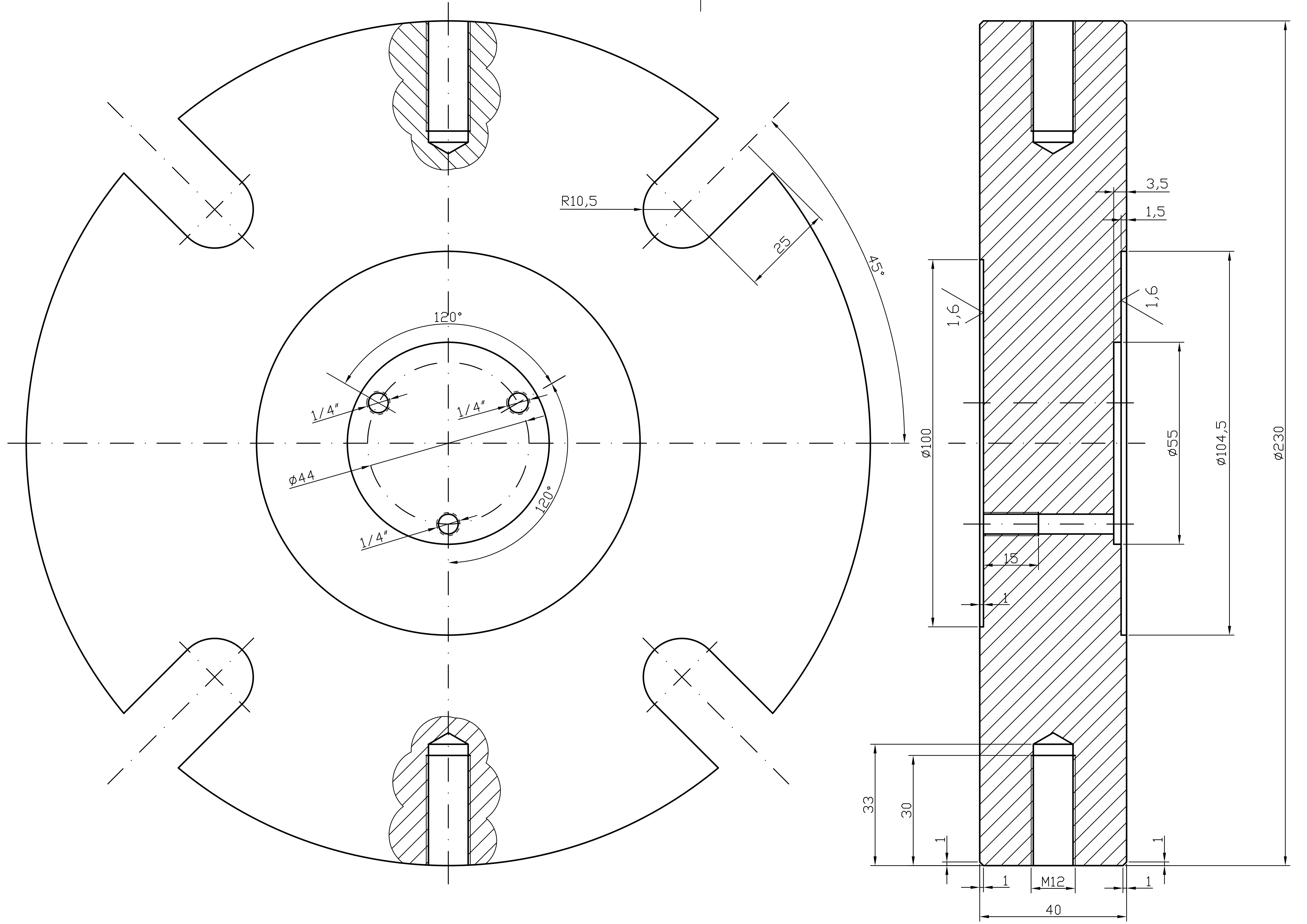


J. Wischt	09/02/2011	**Composite Leakage Testing Apparatus**
MUL	M 1:1 (A3)	**Design Sketch**



Steel Grade: C45

J. Wischt	09/02/2011	Composite Leakage Testing Apparatus
MUL	M 1:1 (A3)	Bottom Plate



Steel Grade: C45

12,5 √ (1,6 √)

J. Wischt	09/02/2011	Composite Leakage Testing Apparatus
MUL	M 1:1 (A3)	Top Plate

Appendix C: Code for Measurement Automation

Cyclic Program for Measurement and Sending

```
/********************************************************************
 * COPYRIGHT --
 ********************************************************************
 * Program: CompositeProject
 * File: CompositeProjectCyclic.c
 * Author: Johannes Wischt
 * Created: March 18, 2011
 ********************************************************************
 * Implementation of program CompositeProject
 ********************************************************************/
#include <bur/plctypes.h>
#ifdef _DEFAULT_INCLUDES
 #include <AsDefault.h>
#endif

void _CYCLIC CompositeProjectCyclic( void )
{
	/* calculate pressure value from I/O port */
	PressureInputREAL=PressureInput;
	PressureValue=0.01831055*PressureInputREAL;
	/* PressureValue=(600/32768)*PressureInputREAL */

	/* generation of time stamp */
	counter++;
	Time=counter*CycleTime;
	Time=Time/1000;

	/* LED control */
	LEDred=1;

	/* trigger criteria if pressure value is below trigger level */
	if(PressureValue<TriggerValue)
	{
	LEDgreen=0;
	counter=0;
	}

	/* trigger criteria if pressure value has reached trigger level or is above */
	else if (PressureValue>=TriggerValue)
	{

		/* generating data set for every recorded pressure value */
		StringCounter++;
		ftoa(PressureValue, (UDINT) &DataToSend);
		ftoa(Time, (UDINT) &CounterString);
		strcat(SaveString, CounterString);
		strcat(SaveString, ";");
		strcat(SaveString, DataToSend);
		strcat(SaveString, "\r\n");
```

```
                /* generate data set for sending and set indicator "SEND" to start sending */
                if(StringCounter==5)
                {
                        strcpy(SendString, SaveString);
                        strcpy(SaveString, "");
                        StringCounter=0;
                        SEND=1;
                }

                /* LED control, indicate recording and if the internal memory (for immediate display of
                the data) is about to be exceeded (blinking green LED) */
                if(counter<21000)
                {
                        LEDgreen=1;
                }
                else if(counter>=21000)
                {
                        if(counter<=31000)
                        {
                                if((counter*CycleTime)%500==0)
                                {
                                        if(LEDgreen==1) LEDgreen=0;
                                        else LEDgreen=1;
                                }
                        }
                        else if(counter>31000)
                        {
                                if((counter*CycleTime)%100==0)
                                {
                                        if(LEDgreen==1) LEDgreen=0;
                                        else LEDgreen=1;
                                }
                        }
                }
        }

        /* if indicator SEND is set, the generated data set is sent via the TCP/IP connection */
        if(SEND==1)
        {
                FUB_TCPsend.enable=1;
                FUB_TCPsend.ident=ClientIdent;
                FUB_TCPsend.pData=(UDINT) &SendString;
                FUB_TCPsend.datalen=strlen((UDINT)SendString);
                TcpSend(&FUB_TCPsend);
                if(FUB_TCPsend.status==65535) {}

                /* if sending is finished, the data set generating for sending is cleared and SEND
                indicator is reset */
                else if(FUB_TCPsend.status==0)
                {
                        SEND=0;
                        strcpy(SendString, "");
                }
        }
}
```

Note: The variables and function blocks are defined in separate variable files.

Program for Establishing the TCP/IP Connection

```
/********************************************************************
 * COPYRIGHT --
 ********************************************************************
 * Program: TCP
 * File: TCPCyclic.c
 * Author: Johannes Wischt
 * Created: March 29, 2011
 ********************************************************************
 * Implementation of program TCP
 ********************************************************************/
#include <bur/plctypes.h>
#ifdef _DEFAULT_INCLUDES
 #include <AsDefault.h>
#endif

void _CYCLIC TCPCyclic( void )
{
	switch(state)
	{

	/* open TCP/IP connection */
	case 1:
	FUB_TCPopen.enable=1;
	FUB_TCPopen.pIfAddr=(UDINT)"172.16.100.200";
	FUB_TCPopen.port=50000;
	TcpOpen(&FUB_TCPopen);

	if(FUB_TCPopen.status==65535) {}
	else if(FUB_TCPopen.status==0)
	{
		state=2;
		TCPident=FUB_TCPopen.ident;
	}
	else state=250;
	break;

	/* establish TCP server */
	case 2:
	FUB_TCPserver.enable=1;
	FUB_TCPserver.ident=TCPident;
	FUB_TCPserver.pIpAddr=(UDINT)"172.16.100.198";
	TcpServer(&FUB_TCPserver);
	if(FUB_TCPserver.status==65535) {}
	else if(FUB_TCPserver.status==0)
	{
		ClientIdent=FUB_TCPserver.identclnt;
		state=3;
	}
	else state=250;
	break;
```

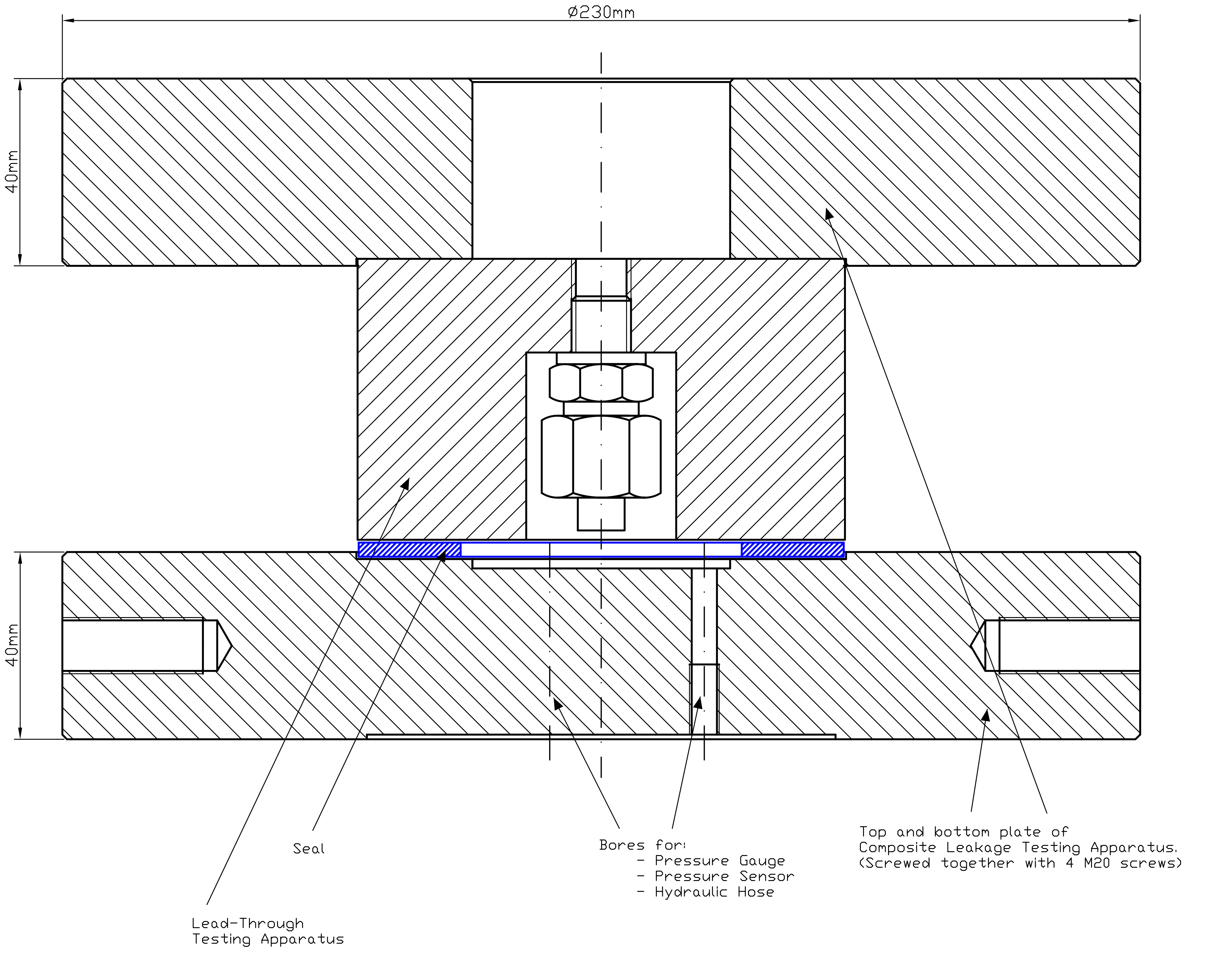
```
        /* test send routine */
        case 4:
        FUB_TCPsend.enable=1;
        FUB_TCPsend.ident=ClientIdent;
        FUB_TCPsend.pData=(UDINT)"Test";
        FUB_TCPsend.datalen=6;
        TcpSend(&FUB_TCPsend);
        if(FUB_TCPsend.status==65535) {}
        else if(FUB_TCPsend.status==0)
        {
                state=3;
        }
        else state=250;
        break;

        /* close TCP/IP connection */
        case 5:
        FUB_TCPclose.enable=1;
        FUB_TCPclose.ident=TCPident;
        TcpClose(&FUB_TCPclose);
        if(FUB_TCPclose.status==65535) {}
        else if(FUB_TCPclose.status==0)
        {
                state=3;
        }
        else state=250;
        break;
        }
}
```

Note: The variables and function blocks are defined in separate variable files.

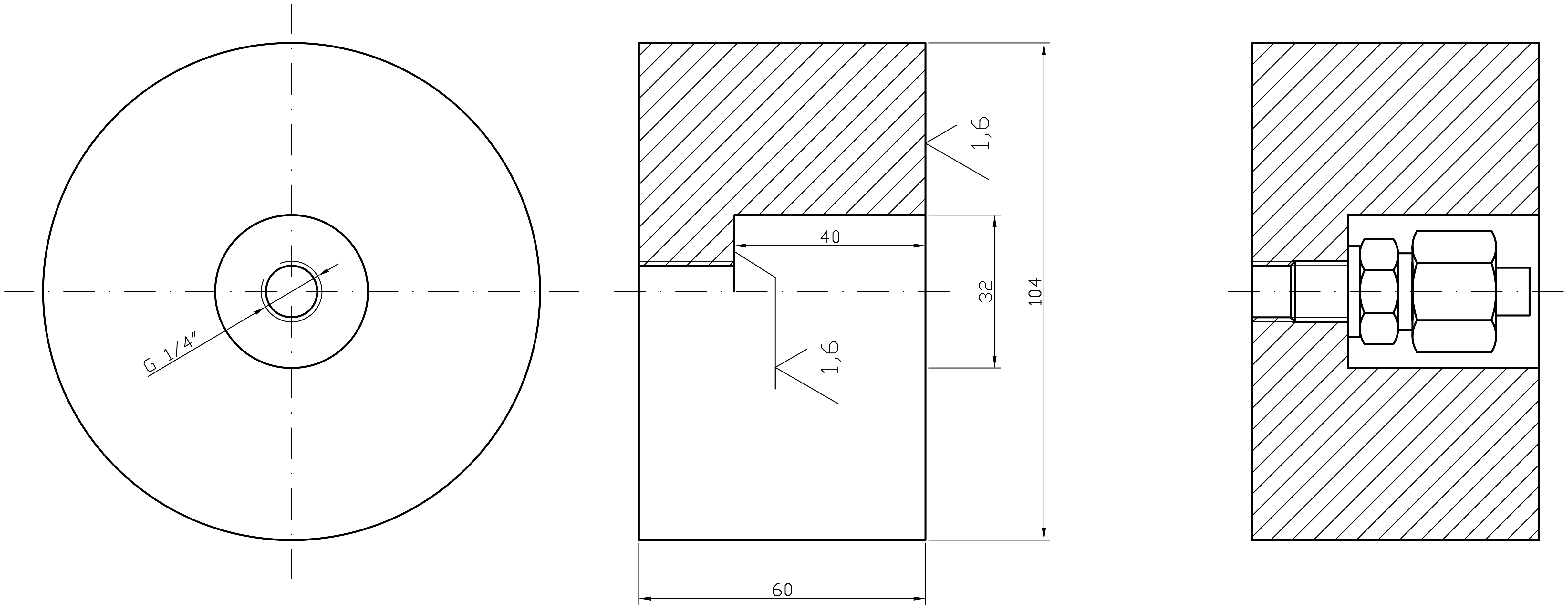
Appendix D: Blueprints – Lead-Through Testing Apparatus & Solutions

Please find A3 blueprints on the following pages:

- Lead-Through Solutions & Testing Adapter for Direct Pressure
- Lead-Through Testing Adapter for Reverse Pressure
- Lead-Through Solutions for Reverse Pressure
- Lead-Through Testing Adapter for Reverse Pressure – Design Sketch



J. Wischt	29/04/2011	Lead-Through Testing Adapter
MUL	M 1:1 (A3)	**Reverse Pressure - Design Sketch**

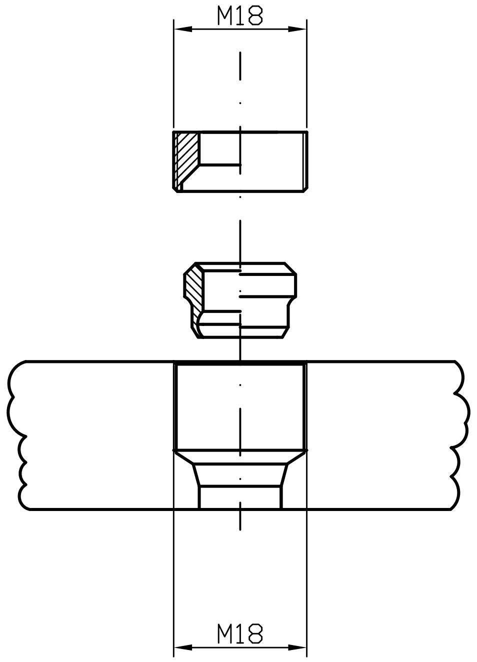


Steel Grade: C45

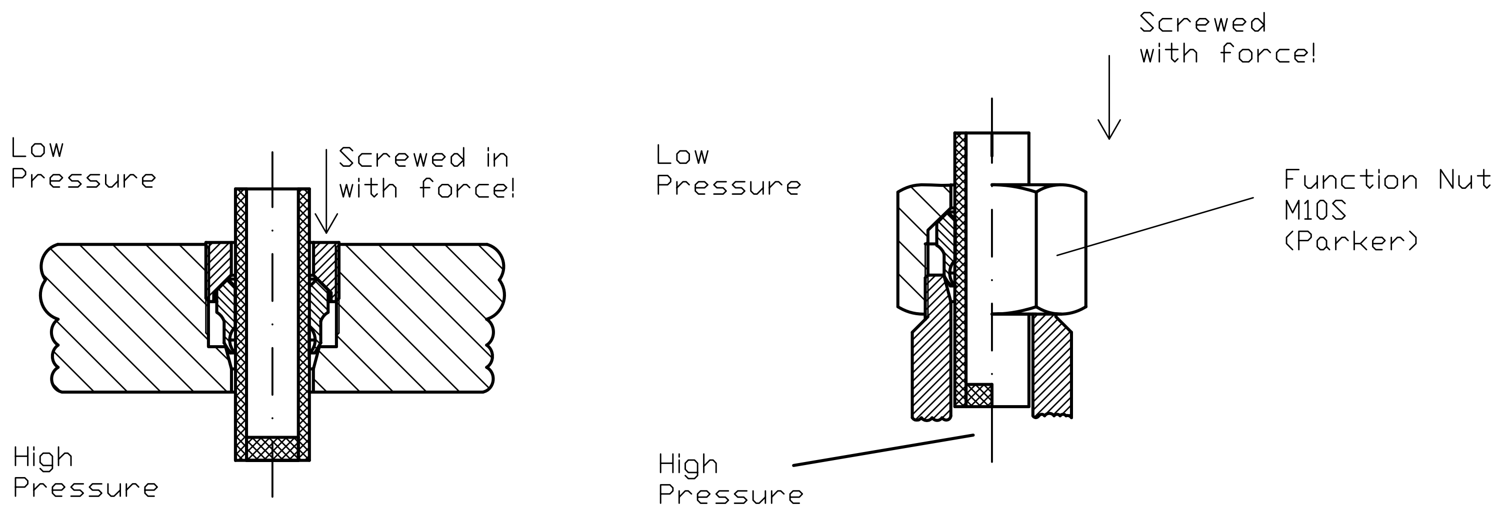
12,5 (1,6)

J. Wischt	29/04/2011	Lead-Through Testing Adapter
MUL	M 1:1 (A3)	Reverse Pressure

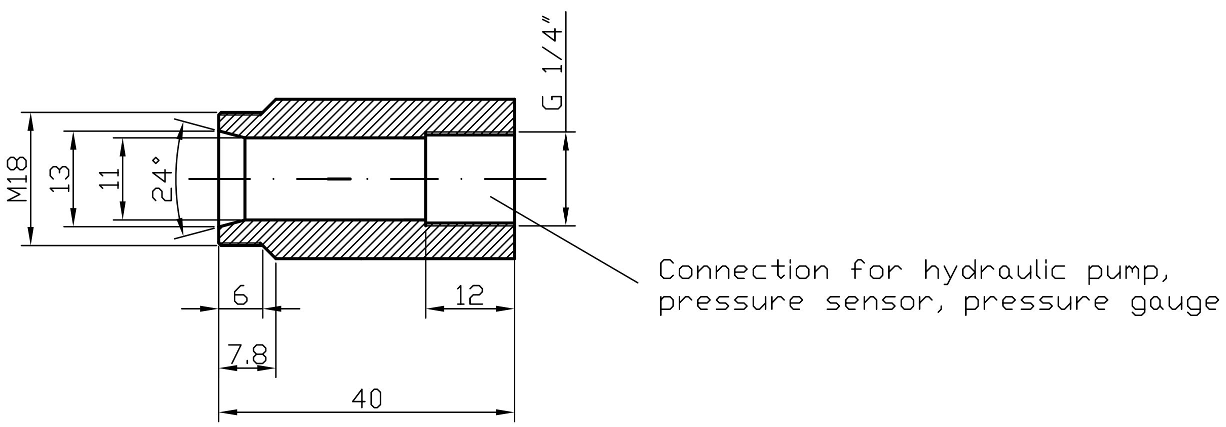
Lead-Through Solution for Tooljoints



Lead-Through Solutions For Tooljoints vs. Setup for Testing



Lead-Through Testing Adapter

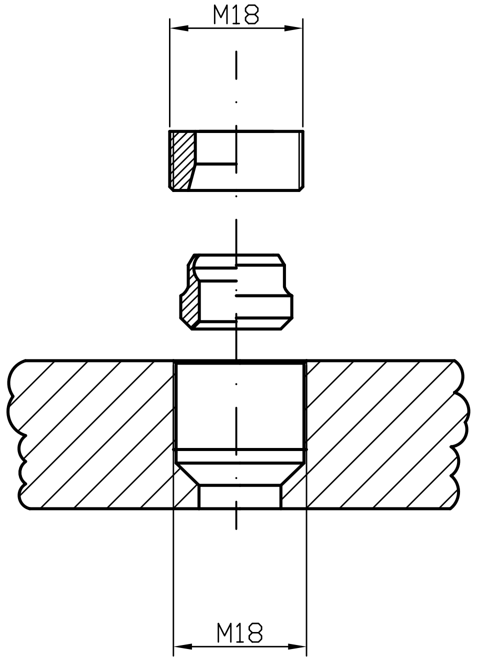


Steel Grade: C45

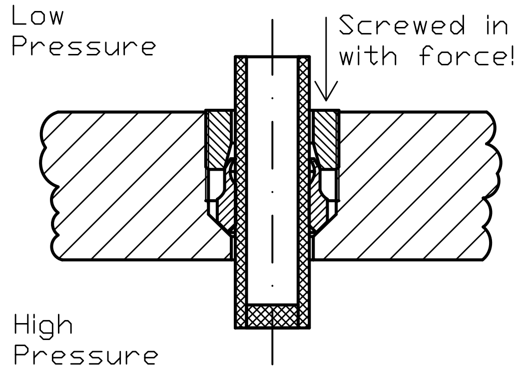
12,5

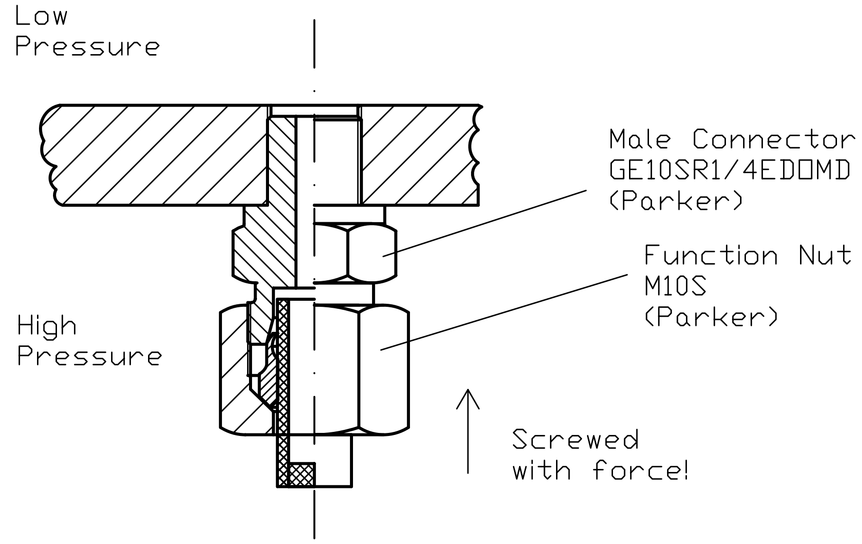
J. Wischt	29/04/2011	Lead-Through Solutions & Testing Adapter
MUL	M 1:1 (A3)	**Direct Pressure**

Lead-Through Solution for Tooljoints



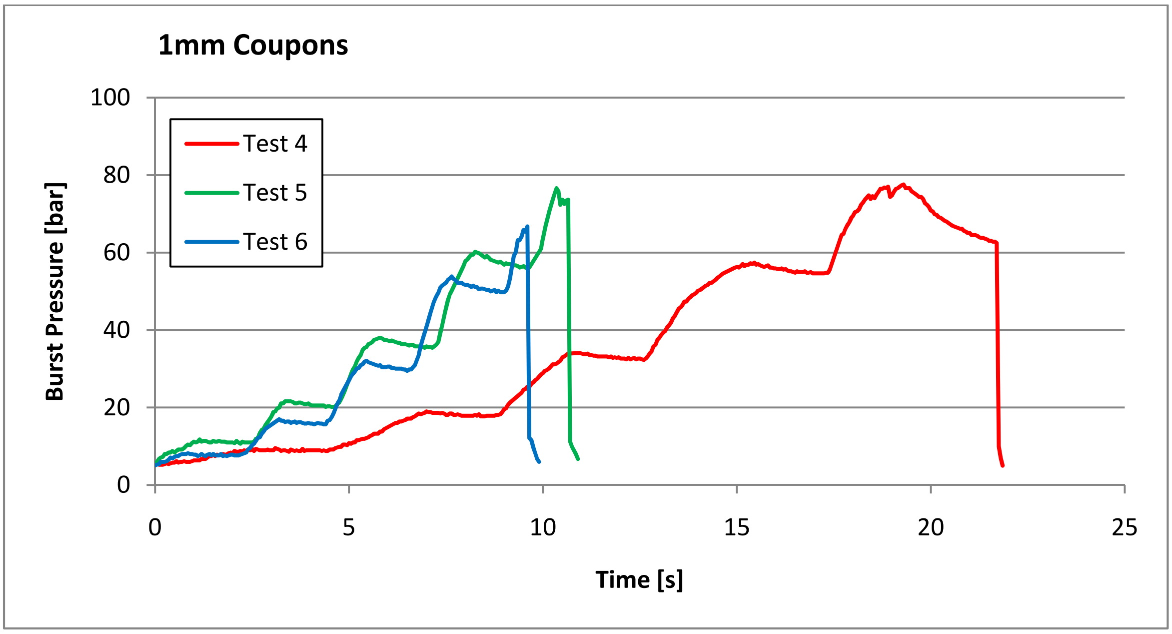
Lead-Through Solutions For Tooljoints vs. Setup for Testing

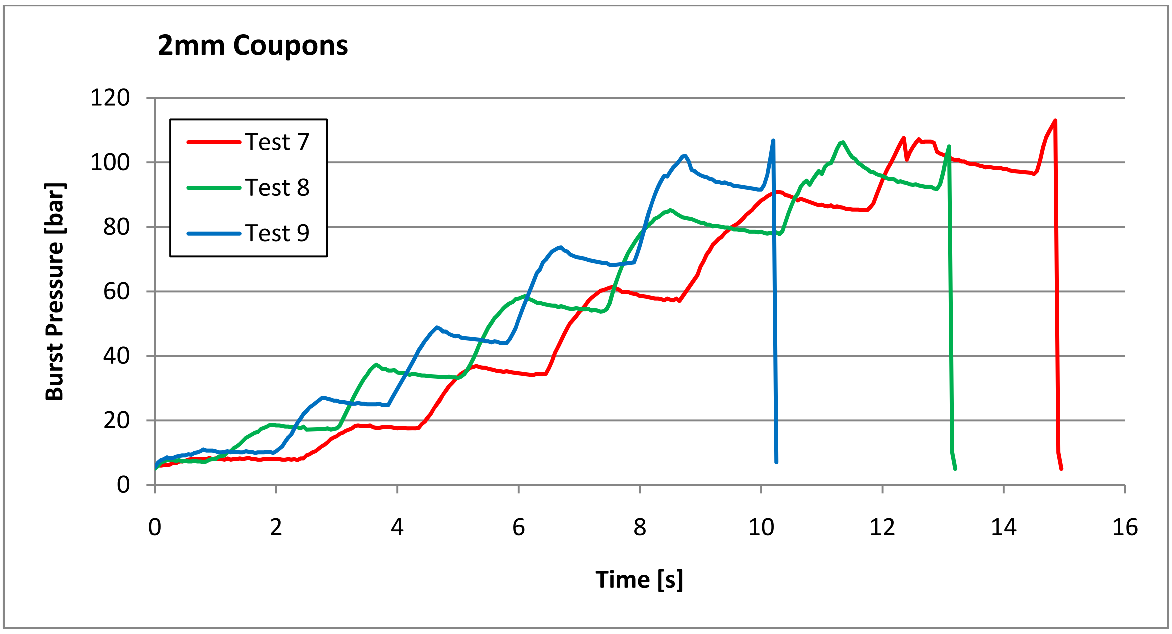


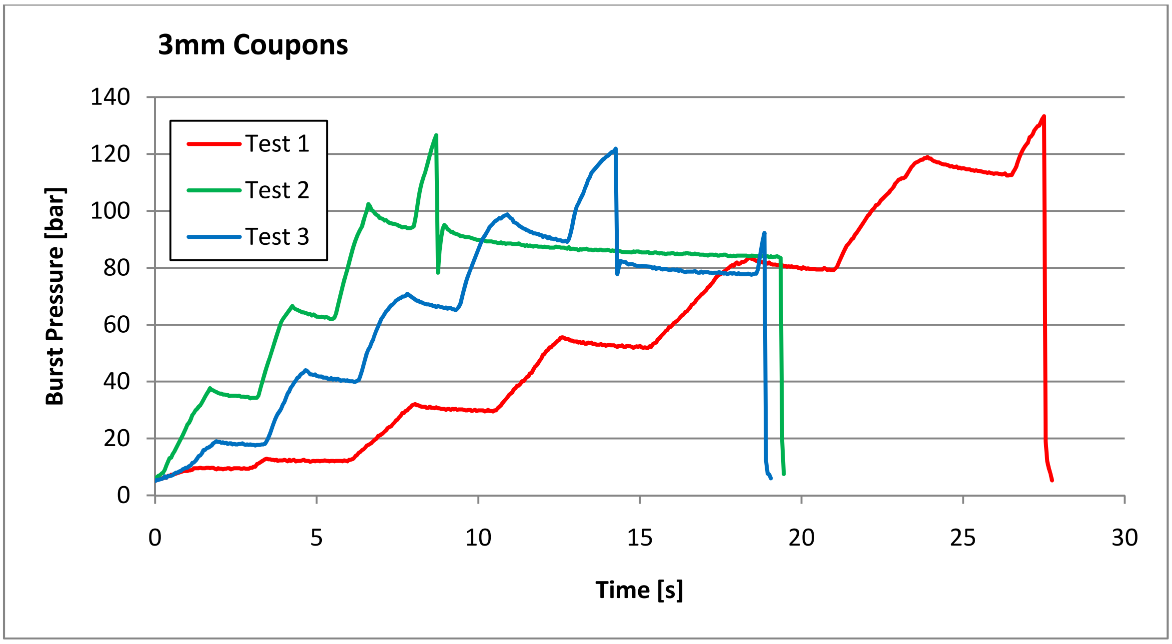


J. Wischt	29/04/2011	**Lead-Through Solutions**
MUL	M 1:1 (A3)	**Reverse Pressure**

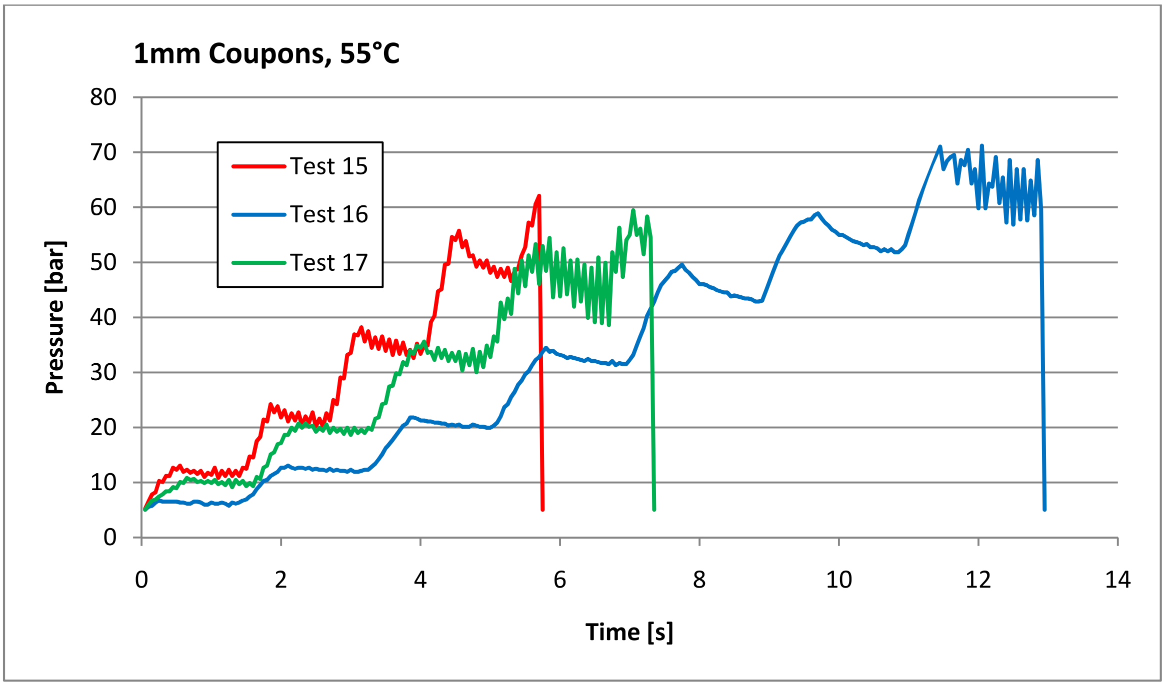
Appendix E: Pressure Curves – Room Temperature (18°C)

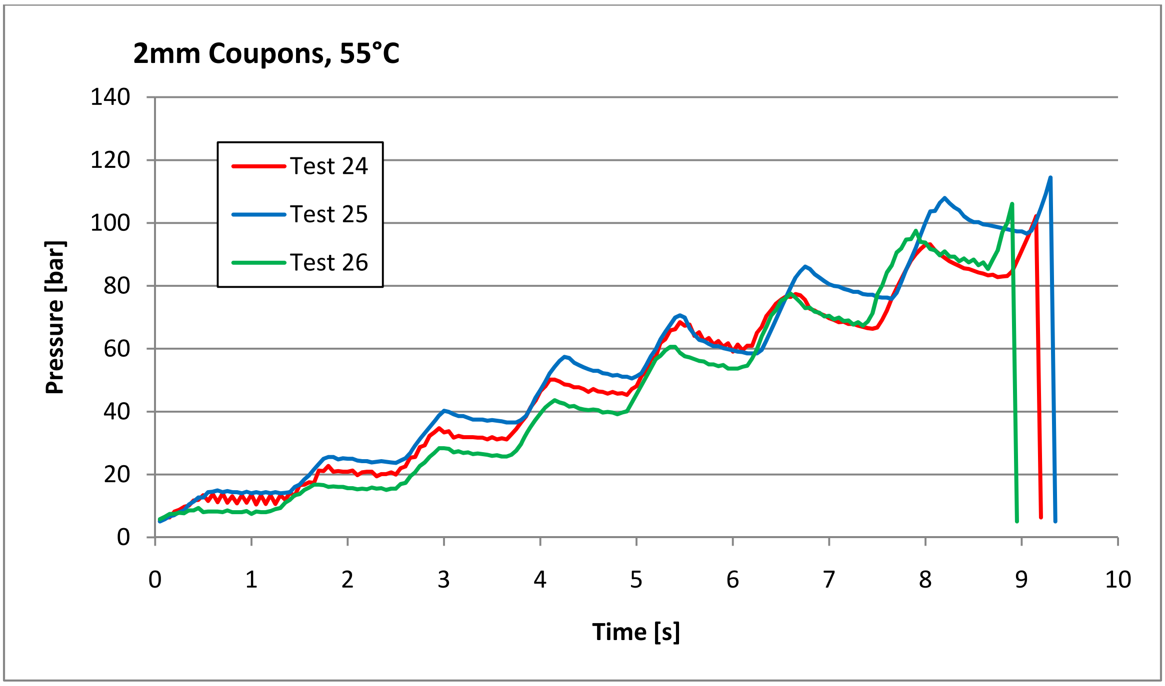


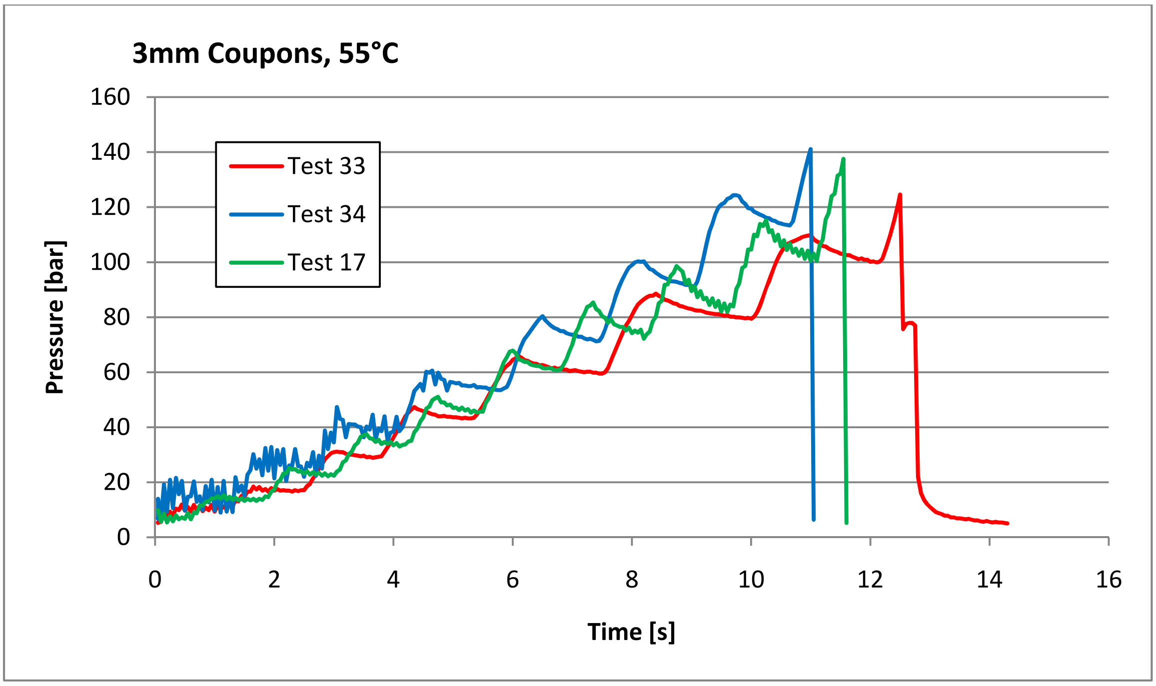



3mm Coupons
Test 1
Test 2
Test 3
140
120
100
80
60
40
20
0
Burst Pressure [bar]
0
5
10
15
20
25
30
Time [s]

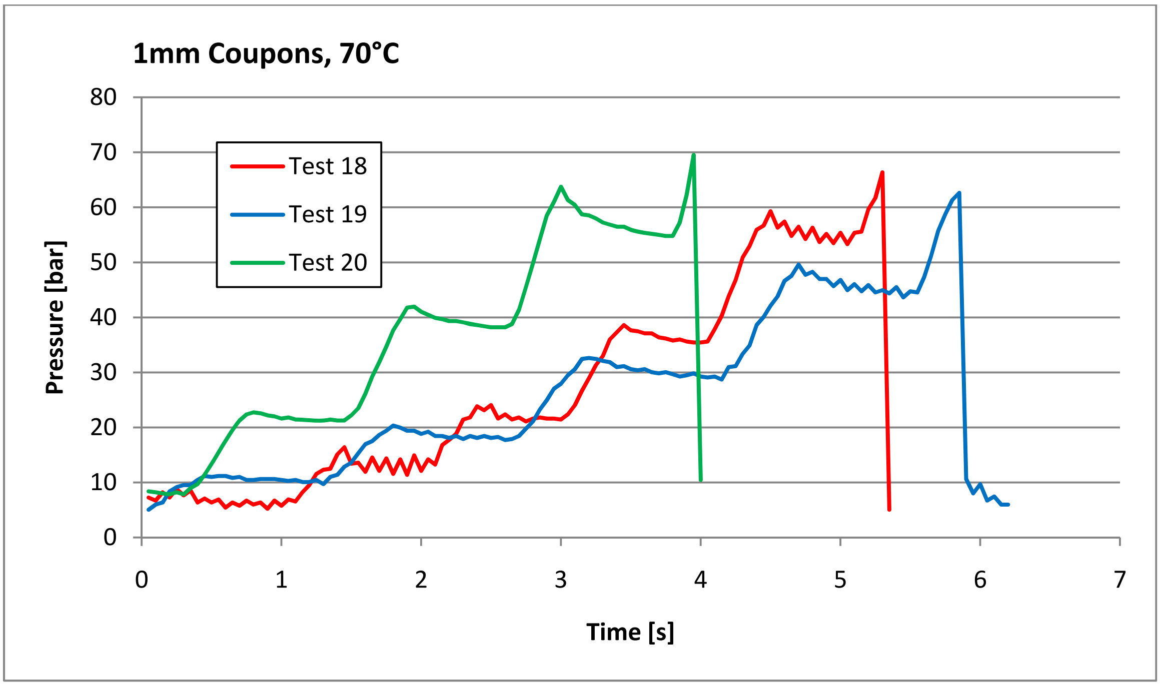
Appendix F: Pressure Curves – 55°C

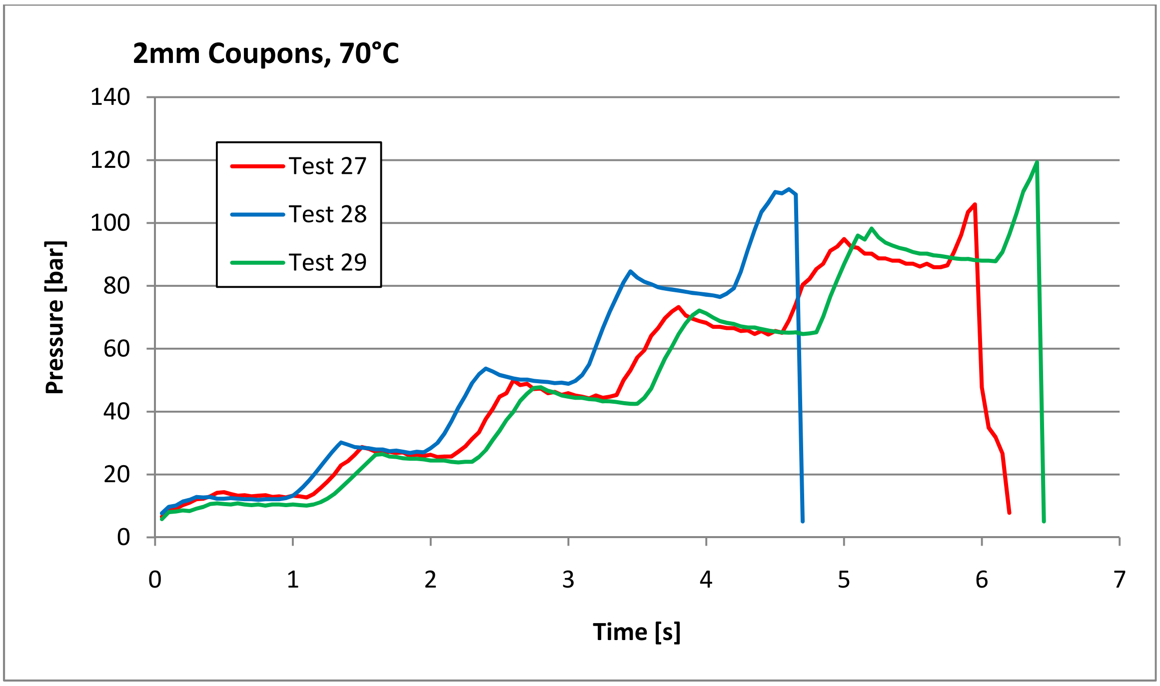


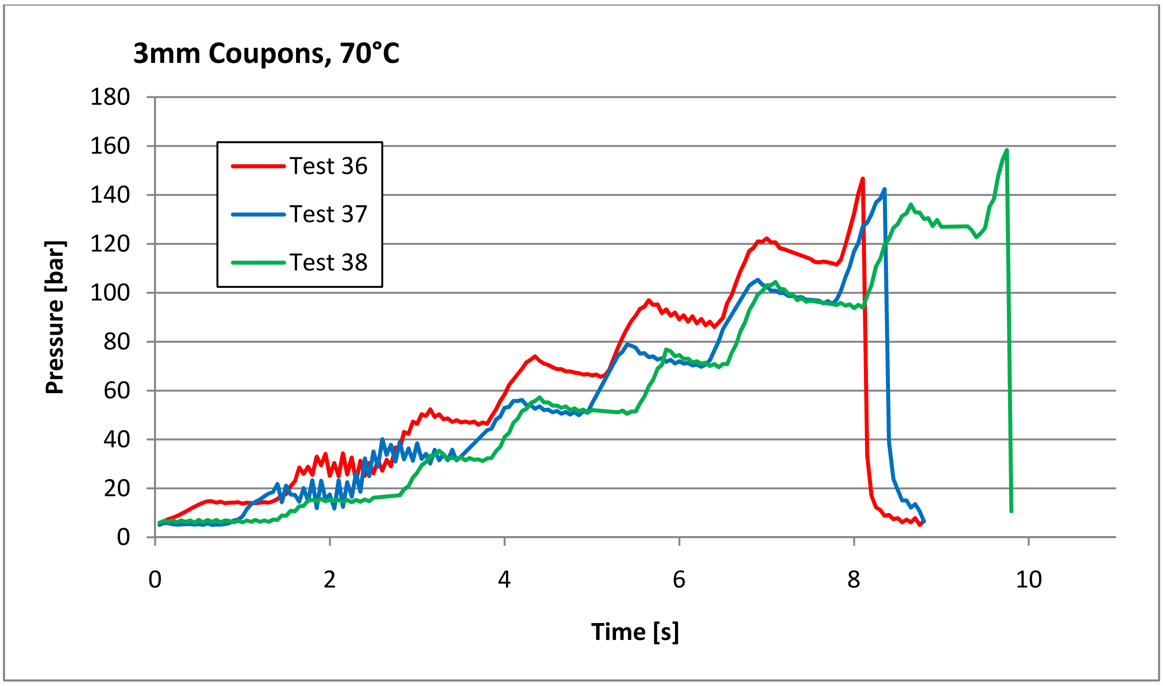



3mm Coupons, 55°C
Pressure [bar]
Time [s]
Test 33
Test 34
Test 17
0
20
40
60
80
100
120
140
160
0
2
4
6
8
10
12
14
16

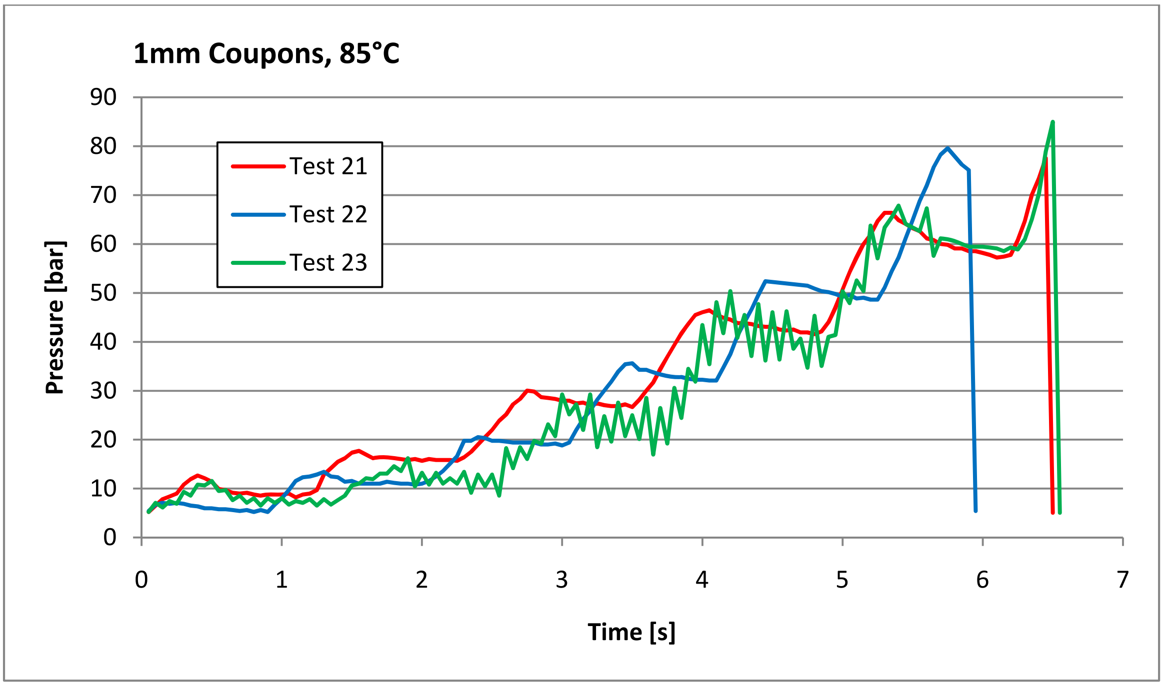
Appendix G: Pressure Curves – 70°C

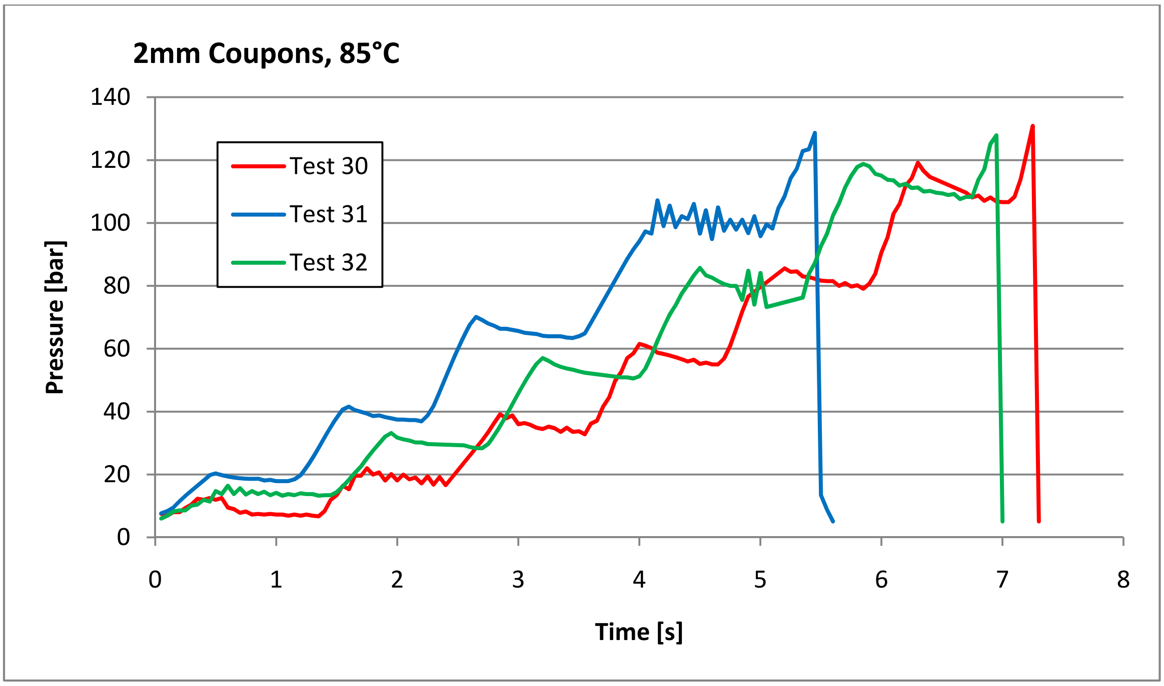


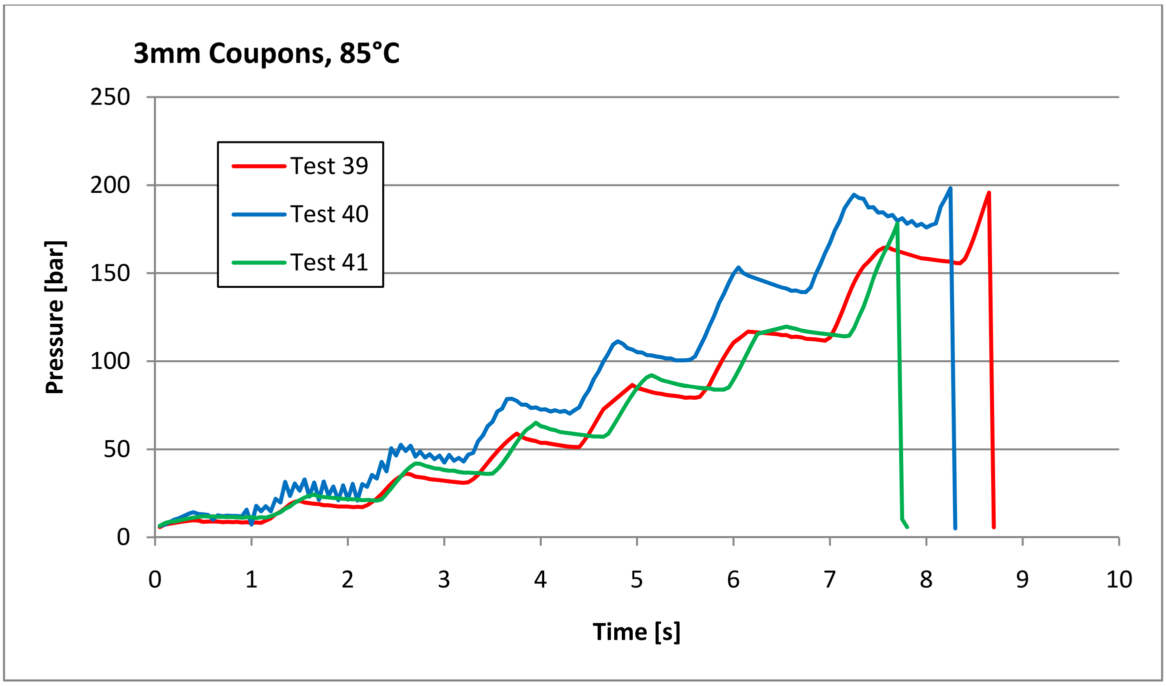



3mm Coupons, 70°C
Pressure [bar]
Time [s]
Test 36
Test 37
Test 38
0
20
40
60
80
100
120
140
160
180
0
2
4
6
8
10

Appendix I: Pressure Curves – 85°C






3mm Coupons, 85°C
250
200
150
100
50
0
Pressure [bar]
Test 39
Test 40
Test 41
0
1
2
3
4
5
6
7
8
9
10
Time [s]