Master Thesis

Bleeding of Hydraulic System

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Division of Machine Design • Department of Design Sciences
Faculty of Engineering LTH • Lund University • 2014

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ISRN LUTMDN/TMKT 14/5507 SE

Preface

Thanks to BorgWarner for the opportunity to do this thesis and especially Kristoffer Nilsson for all guidance and help. We would also like to thank everyone else at TTM and in the test lab for answering our numerous questions.

We also thank our supervisors Per Kristav and Per-Erik Andersson at the department of machine design at LTH.

Lund, August 2014

Erik Sköld och Oscar Tedenstad

Abstract

This master thesis is conducted in cooperation with BorgWarner in Landskrona, where they develop and assemble four wheel drive systems for passenger cars. The purpose of the thesis is to investigate new or alternative solutions to bleed the hydraulic system used to apply force to a limited slip coupling used to control torque transfer. The aim is to lower the cost and weight while maintaining the same function.

The current solution for bleeding the system is done through an overflow valve. The valve is situated at the highest point of the hydraulic circuit, which results in a de-airing of the coupling every time max pressure is reached. The overflow valve has previously, apart from being a de-air valve, been used as a pressure reference to the regulating system. Due to the implementation of a new control strategy this function is no longer needed and therefore it should be possible to simplify or change the bleeding valve.

A wide range of possible solutions are generated by benchmarking of similar products and by gathering inspiration from patents regarding similar valves in other applications. The concepts are then narrowed down to three final designs by using screening and scoring matrices influenced by Ulrich and Eppinger [1].

The three final concepts are produced as prototypes and tested to validate their function. A cost estimation for full scale production of the prototype valves are also made to verify if they might be a interesting alternative for replacing the current valve. The three prototypes were all proven to work during the tests even if they need to be further optimized to meet the specifications. Two of them are estimated to be able to produce to a lower cost than the current valve and are considered to be interesting alternatives for future generations of the coupling.

Keywords:

Overflow valve, bleeding, Haldex coupling, BorgWarner

Sammanfattning

Detta examensarbete är utfört i samarbete med BorgWarner i Landskrona vid institutionen för maskinkonstruktion på Lunds Tekniska Högskola.

Företaget som tidigare gick under namnet Haldex Traction producerar och utvecklar system för fyrhjulsdrift. Komponenten som behandlas i denna rapport är en kombinerad avluftnings- och övertrycksventil som används i 5:e generationens koppling (Gen V) som varit i produktion sedan 2012.

Kopplingen är en lamellslirkoppling som används för att överföra ett drivande moment till bakaxeln på en bil som i första hand är framhjulsdriven. Vid normal körning i konstant hastighet är bilen framhjulsdriven men vid behov skickas en viss del eller hela momentet över till bakaxeln. Sensorer detekterar om något hjul roterar med högre hastighet än de andra vilket indikerar att momentet bör omfördelas.

Inkopplingen sker genom att en elektriskt driven hydraulpump bygger upp ett tryck som verkar på en kolv som i sin tur pressar samman ett lamellpaket mellan kardanaxeln och bakaxeln. På så vis överförs kraft från bilens främre axel till den bakre. I hydraulsystemets högsta punkt sitter en övertrycksventil som begränsar trycket till 44bar, vilket motsvarar max momentöverföring. Placeringen av ventilen gör att eventuell luft i systemet kommer att avlägsnas varje gång ventilen öppnar. Ventilen har även i uppgift att agera som tryckreferens till det reglersystem som styr inkopplingen, men genom introducerandet av en ny kontrollstrategi kommer denna funktion inte längre behövas. Ventilens enda uppgift blir därmed att avlufta hydraulsystemet vilket leder till att det borde finnas det utrymme för att förenkla eller omforma dess geometri och funktion.

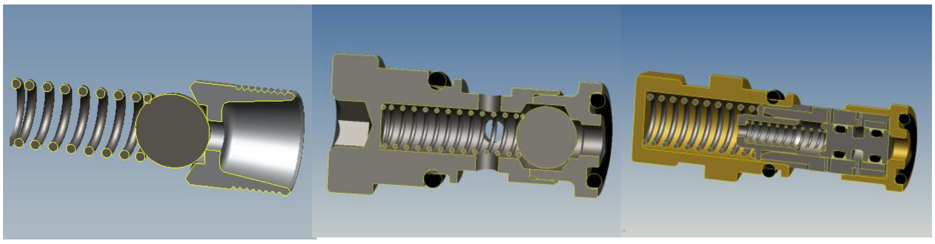
Målsättningen med den nya lösningen är framförallt att sänka kostnaden, men även minskad vikt är önskvärt. Detta genom att undersöka alternativa metoder för avluftning men även förenkling av nuvarande funktion.

För att hitta en lösning som uppfyller de önskemål och krav som ställs på produkten används valda delar av metodiken i *Product Design and Development* av Ulrich och Eppinger [1].

Arbetet inleds med att undersöka och förstå systemet för att kunna upprätta korrekta och relevanta krav, önskemål och specifikationer. Därefter görs efterforskning av liknande produkter och tekniker genom sökning i patentdatabaser och att studera konkurrenters system för fyrhjulsdrift. Baserat på insamlad kunskap och inspiration görs en första bred konceptgenerering med avsikt att utvärdera så många olika tekniker som möjligt. Koncepten utvärderas mot uppställda krav och specifikationer

för att identifiera styrkor och svagheter bland lösningsförslagen. De mest lovande förslagen vidareutvecklas till mer väldefinierade geometrier med en tänkt teknisk funktion. Dessa utvärderas och jämförs noggrannare mot kriterier viktade efter relevans för att utse den eller de koncepten som bäst uppfyller de mest relevanta kraven.

Urvalsprocessen diskuteras med handledare och beslut om att gå vidare med tre koncept tas. Koncepten dimensioneras för önskade öppningstryck och geometrin för Intervallventilen och Slussventilen anpassas för montering i befintligt kopplingshus, koncepten illustreras i figur 1.



Figur 1 De tre slutgiltiga koncepten: Förenklad övertrycksventil(t.v.), Intervallventil (m) och Slussventilen(t.h.).

Den förenklade övertrycksventilen har samma funktion som den nuvarande ventilen men utformningen består av färre komponenter och storleken har reducerats. Montering är tänkt att ske genom att komponenten som agerar ventilsäte expanderas i monteringshålet.

Intervallventilen är dimensionerad för att öppna vid låga tryck och släppa ut en liten mängd olja och eventuell luft varje gång kulan förflyttar sig mellan sätena. Sätena har olika diametrar vilket kommer att ge en hystereseffekt, alltså att kulan kommer falla tillbaka till sin ursprungsposition vid ett lägre tryck än vad som krävs för att öppna den. Detta för att förhindra att kulan hamnar i ett ostabilt läge när trycket hålls runt öppningstrycket.

Slussventilen är mer komplex än de två föregående koncepten. Ventilen består av en fjäderbelastad slid i ett cylindriskt lopp och är tänkt att ha två funktioner. Huvudfunktionen skall använda samma princip som en sluss d.v.s. att lagra en viss volym som sedan släpps ut. Detta sker vid ett relativt lågt tryck. Den andra funktionen är att även agera som övertrycksventil på samma vis som den nuvarande ventilen.

Prototyper tillverkas för de tre slutgiltiga koncepten. Intervallventilen tillverkas i två olika varianter där skillnaden är spelet runt om kulan. Detta görs för att undersöka vilken påverkan på ventilens uppförande spelet har. Till den förenklade övertrycksventilen tillverkas även en adapter för att kunna montera prototypen i existerade kopplingshus och testrigg.

Prototyperna testas i två olika riggar, först i en pumprigg där öppningstryck, täthet och returflöde kan undersökas. Sedan testas de även i en komplett koppling där returflödet har letts om via en genomskinlig slang för att bättre kunna utvärdera hur stora mängder luft som avlägsnas, samt för att kunna uppskatta hur lång tid det tar att avlufta en koppling.

Av testerna framgår det att den förenklade övertrycksventilen fungerar som den befintliga Gen V ventilen förutom att den öppnar vid tryck ca 2bar högre samt att den påvisar visst läckage strax innan öppning, vilket eventuellt kan härledas till otillräcklig prägling av ventilsätet. Intervallventilen med det större spelet runt kula fungerade inte på grund av att för mycket olja tillåts passera runt kulan istället för att pressa den mot det andra sätet. Ventilen med det mindre spelet fungerade som avsett även om det går att hitta ett instabilt läge i den ena riggen. Den släpper igenom en mindre mängd olja främst under tryckfall då kulan faller tillbaka till det första sätet. En långsam ökning av trycket visar att ventilens öppning och stängning inte påverkar tryckkurvan nämnvärt. Slussventilens övertrycksfunktion fungerade väl och visade sig dessutom ge en betydligt lägre ljudnivå än den befintliga ventilen. Slussfunktionen fungerade som tänkt men volymen som släpps ut verkar vara mycket liten.

En kostnadsuppskattning för vad prototyperna skulle kosta vid fullskalig produktion visade på att det fanns stora kostnadsbesparingar i att förenkla övertrycksventilen och att intervallventilen förmodligen skulle gå att producera till ungefär samma kostnad som den nuvarande. Slussventilen är en betydligt mer komplex lösning och kommer därför att medföra en större kostnad än den nuvarande ventilen.

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1 Introduction

1.1 Background

BorgWarner Torque Transfer develops advanced all-wheel drive systems and are currently producing their fifth generation (Gen V) coupling. The main component of the system is a limited slip coupling that transfers torque to the rear wheels on demand. The system is mounted between the rear differential and the drive shaft. When the front wheels lose traction the system builds up a hydraulic pressure that actuates the coupling and thereby supplying the rear axle with torque.

The control unit uses an overflow valve as a max pressure reference, the overflow valve also acts as an air bleeder situated at the highest point of the hydraulic system. With a new improved control strategy the valve won’t be necessary as a pressure reference anymore which means that there might be possible to simplify the air bleeding mechanism.

1.2 Aims

With the current control system is the opening pressure of the valve very critical. If it would be too low, that would result in an unsatisfying amount of torque transferred to the rear axle. In case that the opening pressure is to high there is a risk that the system won’t be bled and therefore loses its function.

The overflow valve is a spring loaded ball valve. The factors that mainly determines the opening pressure is the spring force and the inlet area. This places high demands on the subcontractor that delivers the springs since every spring have to be tested individually to ensure that the force is within the tolerances.

With the introduction of the new control strategy the opening pressure won’t be as critical anymore. This means there should be a potential cost and weight reduction by redesigning or replacing the valve component.

1.3 Delimitations

This thesis will primarily consider the design of the valve and the suggested designs are meant to, with small or no modifications of the housing, be replaceable with the current overflow valve in Gen V. The equipment for production will not be investigated in detail but when evaluating the concepts the manufacturability will be considered.

2 Method

This chapter describes the overall work process throughout this thesis. It is based on the methods described in Product Design and Development by Ullrich and Eppinger [1].

2.1 Investigate and understand the system

In order to understand what kind of solutions that are of interest it is important to have a good overall understanding of the structure of the system. The first step is to study the functions of the different components of the clutch and how they are designed. Once this is done it will be possible to understand which functions that have to be incorporated in the design of the new air bleed valve.

2.2 Establish target specifications

When the basic functions of the new solution is established these are translated into specifications. The needs and requirements are translated into measurable quantities and given an importance factor. The factor is set depending on how relevant the specification is considered to be to ensure a satisfying solution.

2.3 Search and analyze existing solutions for bleeding hydraulic systems

A general research is done to gather knowledge about techniques performing similar tasks in hydraulic systems. The research is primarily performed by searching in patent databases, benchmarking and by discussions with experienced designers.

2.4 Concept generation

From the information gathered from research, benchmarking and specifications different solution concepts are generated. Both concepts that are similar to existing solutions as well as new techniques of fulfilling the specifications will be generated. At this point the concepts don't need to be technically assured as long as their intended function is substantial. During the generation process the concepts are first illustrated with simple hand drawings and later by 3D sketches.

2.5 Concept selection

Concept selection is done by the use of concept screening and scoring matrices and by consultations with experienced design engineers within the company. The criteria from which the concepts are evaluated are mainly influenced by the specifications. In the screening matrix a first rough elimination is done by estimating how well the concepts are believed to fulfill the criteria compared to the current solution. The concepts that pass the screening are then given a second thought and then once again compared in a scoring matrix where the criteria are weighted due to their importance.

2.6 Final designs

The concept or concepts which are considered to fulfill the specifications best and got the highest chance to be a good replacement to the existing valve will be designed and dimensioned. The final design shall be fully thought out so that it would be possible to be produced as a prototype.

2.7 Concept testing

Prototypes are produced and tested to validate their functionality. The cost is estimated for the prototypes if they were to be produced in full scale of 1.5 million units a year.

3 General Information about the System

To understand what the valve needs to perform it is important to look at the product it is a part of. The valve is a key component and essential for the function of the coupling. In this chapter the complete product is presented shortly, the parts of the valve, its specifications and also why it is important to bleed the system.

3.1 Function of the coupling

The coupling is mounted between the rear differential and the prop shaft and its basic function is to distribute torque, on request, to the rear axle. When wheel slip occurs, the electronic control unit sends a signal to the axial piston pump. The pump builds a hydraulic pressure that activates the apply piston and when force is applied to the clutch package, torque is distributed between the input shaft and output hub. The coupling and its different parts is illustrated in figure 3.1.

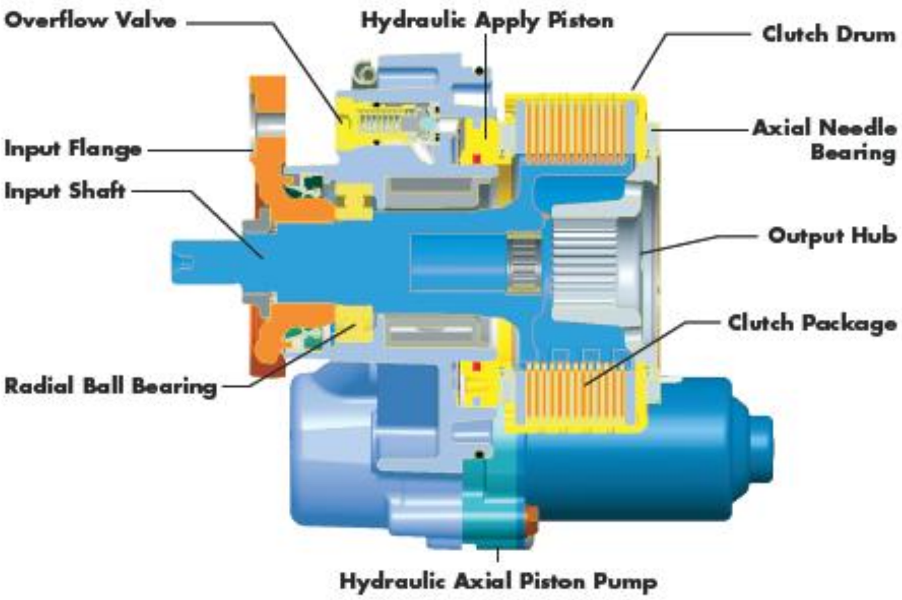

Figure 3.1 The layout of the Gen V coupling [2]

3.2 Analysis of existing valve

The spring loaded ball valve that opens at 44bar acts both as a overflow valve and air bleed mechanism. Since the valve is placed at the highest point of the hydraulic circuit all the air that might be present in the circuit will gather at the inlet and will be bled every time the overflow valve opens.

3.2.1 The components of the valve

The existing valve, illustrated in figure 3.2, is designed in seven parts:

1. Cap
2. O-ring
3. Spring
4. Support plate for spring
5. Safety valve housing
6. O-ring
7. Ball

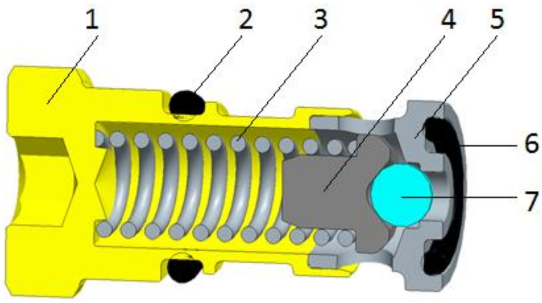

Figure 3.2 The current overflow valve

3.2.2 Assembling the valve

During the assembly of the valve the ball is pressed into the safety valve housing to make sure a perfect fit in the valve seat. Since the spring is critical for the function every spring needs to be tested individually by the supplier to make sure the spring force is within the tolerances. The valve housing and the safety valve housing are press fitted together.

In the last step of the assembling process the valve is tested in a rig to ensure that the opening pressure is correct and accurate enough.

3.3 Why bleeding is necessary

Hydraulic oil is an incompressible fluid and this is a fundamental property to guarantee performance and precision in a hydraulic system. Air is however compressible, so if air is present in the system it will be elastic, less precise or in worst case, lose its function completely. This especially applies to systems working at relatively low pressures [3]. Apart from the compressibility, air can also cause other problems such as cavitation and erosion which most commonly occurs in systems with high flow rates or in areas with rapid pressure changes [4]. This causes internal damage of the components and may affect their efficiency and shorten their longevity.

Some hydraulic circuits, for example brake circuits in cars, are only bled once when installed. Other requires continuous bleeding or to be bled every time the system starts.

3.4 Establishing target specifications

The target specifications for the bleeding mechanism can partially be set by studying the product specifications for the coupling. Some specifications regarding vibrations and temperature for example are specifications that are shared for all the components of the Gen V coupling.

General specifications:

- Temperature - All the specifications must be fulfilled in the temperature span that the system is subjected to.
- Vibration proof - The solution has to be fully functional for the level of vibration that is specified for the rest of the system.
- Longevity - The solution is not going to be changed during the lifetime of the system
- Corrosion resistance - The solution and all its components has to be chemically resistant to the surrounding environment. It will mainly be subjected to oil and air but also water and salt spray if mounted from outside of the housing.
- Withstand pressure - The solution will be exposed to high hydraulic pressures and therefore needs to be able to withstand the stresses that arise.

Specifications specific for the air bleeding mechanism:

- Bleeding - The solution is supposed to bleed air from the system at start-up and when assembling the system on the rear axle. With the current solution the air bleeding process during assembly is done by running a ramp up cycle that takes about 20 seconds. This criterion is mainly considering the time for bleeding the air during assembly but it is assumed that the time for a solution to bleed the system on start-up can be directly derived from the time it takes during assembly. The solution is also, to some extent, supposed to bleed the system during driving
- Rapid pressure build-up - In order to allow the system to react as quickly as possible on a sudden torque request the solution mustn't prevent a fast pressure build.
- Insensitive to particles - Due to wear of the friction plates and other components of the coupling some particles might be present in the oil.
- Dimensions - The new solution cannot claim more space than the current valve.
- Cost - Refers to the manufacturing and material cost for the solution but also the cost related to the assembling and mounting of the solution.
- Weight - The total weight of the solution is desired to be lower than the current.

3.5 Specifications for the current solution

Table 3.1 below shows specifications for the current solution [5].

Table 3.1 Specifications for the current overflow valve

No.	Specification	Unit	Value
1	Temperature	ºC	0-105[1]
2	Vibration proof	Y/N	Y
3	Longevity	km	300000[2]
4	Corrosion resistant	Y/N	Y
5	Withstand pressure	Bar	>44
6	Bleed the system	-	-
6.1	Bleed at start and assembly	s	20[3]
6.2	Bleed during driving	Y/N	Y
7	Rapid pressure build-up	s	0.25[4]
8	Insensitive to particles	mm	0.05
9	Dimensions x*y*z	mm	18*18*35.5
10	Cost[5]	%	100
11	Weight	g	31
12	Components	Qty	7

3.6 Target specifications for the new solution

For the new solution each specification is given an importance factor, a marginal and an ideal value.

The importance factor will be useful when choosing between different solution concepts since many different concepts may satisfy all the specifications, then the concepts that satisfy the most important ones can be distinguished.

The marginal values constitutes the limit of which the product must be within in order to fulfill the function and the ideal gives the most advantageous value of the specification.

The values presented in table 3.2 has been set given the performance of the existing valve when possible and if not through discussion within the project group and by consulting experts in the mechanical development department.

[1] The valve should limit the pressure to 44±1.3bars at a flow of 1100ml/min in the temperature interval of 0°C to 105°C.
[2] Overall longevity for the system, 90% of the components shall survive 300000km
[3] 20 seconds during the assembly process
[4] The longest reaction time for 0–100% of max torque capacity is 250ms at 60-105ºC
[5] Described as a percentage of the cost for the current valve, the actual cost is confidential.

Table 3.2 Specification for the new solution

No.	Specification	Imp.	Unit	Marginal value	Ideal value
1	Temperature	5	^{o}C	-40 - +140	-40 - +140
2	Vibration proof	3	Y/N	Y	Y
3	Longevity	5	km	300000	>300000
4	Corrosion resistant	4	Y/N	Y	Y
5	Withstand pressure	5	Bar	50	>50
6	Bleed the system	-	-	-	-
6.1	Bleed at start and assembly	5	s	20	<20
6.2	Bleed during driving	2	Y/N	Y	Y
7	Rapid pressure build-up	5	s	0.15	<0.15
8	Insensitive to particles	4	Y/N	Y	Y
9	Dimensions x*y*z	3	mm	20*20*40	0*0*0
10	Cost	4	%	100	<50
11	Weight	4	g	50	<31
12	Components	3	Qty	10	<7

4 Concept Generation

In this chapter the problem is clarified using concept combination trees to get a clearer view over the range of possible solutions. An external search of similar products is done through benchmarking of a few competitors and searching in patent databases.

Based on the external search and having the specifications in mind a first quantitative concept generation is done.

4.1 Clarify the problem

In order to investigate a wide range of alternative solutions regarding the function and manufacturing of the product, classification trees are drawn.

Figure 4.1 presents different alternatives to at which point in the pressure cycle the de-airing could be executed. Each branch brings different pros and cons. For example bleeding at high pressure, as the current solution, brings the advantage of a high flow rate and thereby a rapid bleeding process. On the other hand the bleeding could be done continuously and result in that the flow rate can’t be very high as that would counteract pressure build up, but when it is done continuously that might not matter.

A classification tree regarding manufacturing and mounting of the product is presented in figure 4.2. The process is first split into four subcategories which in its turn are divided in different solutions for each branch.

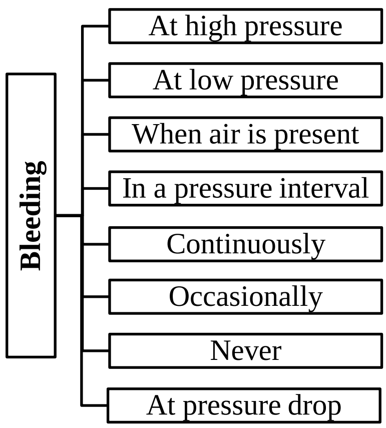

Figure 4.1 Classification tree for when the bleeding can be done.

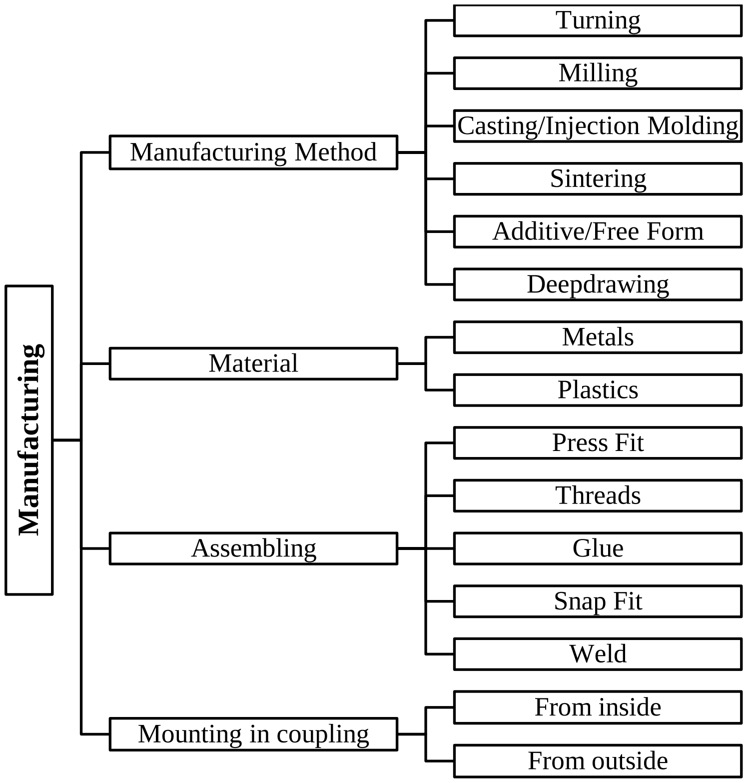

Figure 4.2 Classification tree for manufacturing and assembling methods.

4.2 Investigation of techniques

The technology of hydraulics is an old and well defined science. The most functions needed in a hydraulic system are already developed. But since the most common use of hydraulics is in heavy machinery where large forces are desired, many standard components are oversized and bulky.

The challenge in this project is to investigate the underlying principles in different components and systems to see if any could be adapted to fit the requirements of de-airing the coupling.

4.2.1 Patents

Below follows some of the patents that has been used to gathering inspiration about existing techniques.

- Patent issued by R. Stevenson regarding “Automatic air bleeder valve for hydraulic systems” that closes because of the viscosity difference between air and oil [5]. The design is illustrated in figure 4.3. A small gap between part number 26 and the housing allows air to pass but the gap is designed so that when oil enters part number 26 will move due to the flow resistance and the O-ring will seal the valve.

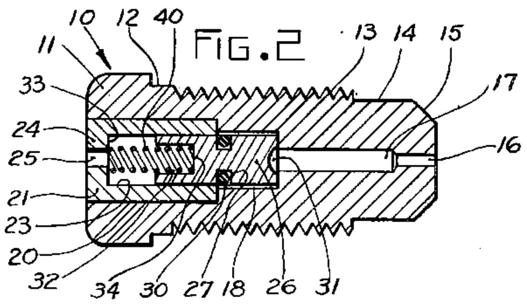

Figure 4.3 Patent image from “Automatic air bleeder for hydraulic systems”.

- Another valve that work under the same principle as R.Stevenson’s is “Automatic bleed valves” issued by Pall Co. Instead of a small gap between two components this solution uses a small capillary channel to get the flow resistance needed to close the valve [6]. The design is illustrated in figure 4.4.

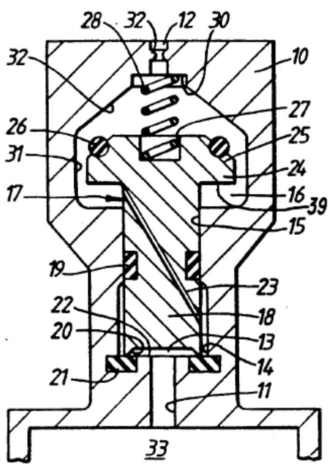

Figure 4.4 Patent image from “Automatic bleed valves”.

- "Automatic bleed valve assembly" issued by Hale Products is a patent regarding a valve for de-airing fire hoses between the source of water and the pump to avoid cavitation problems in the pump [7]. It is open in a pressure interval so that the air first is removed from the system under a relatively low pressure and when this is done full pressure is applied causing the valve to close and the system is ready to use. The design is illustrated in figure 4.5.

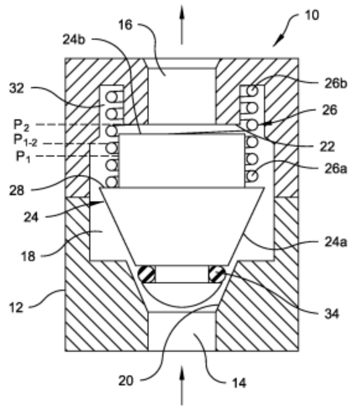

Figure 4.5 Patent image from "Constant flow rate orifice devices".

- "Constant flow rate orifice devices" issued by Wester Brass Works. In the patent specification it reads:

  "An object of this invention is to provide an orifice device which will pass a fluid at an essentially constant rate throughout a wide range of fluid pressures. A further object is to provide an orifice device which will stop flow of liquids there through if the device is subjected to suddenly applied pressure surges" [8].

  The restrictor consist of a rigid plate mounted between two flexible ones. When pressure is applied on either side of the valve the flexible plate will flex and act as a regulator of the flow. The design is illustrated in figure 4.6.

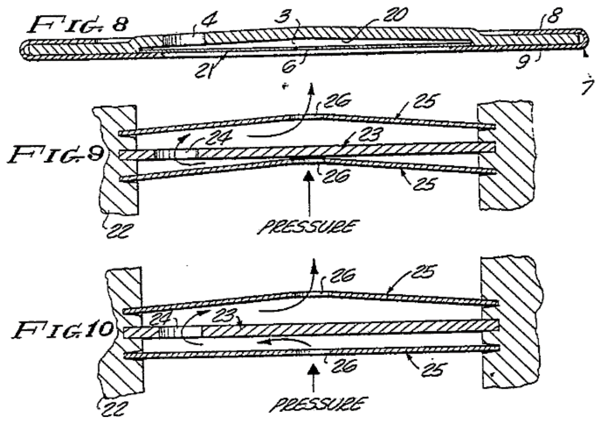

Figure 4.6 Patent image from "Constant flow rate orifice devices".

4.2.2 Benchmarking

Two similar products are examined to gather inspiration of how the de-airing has been solved.

- Product 1
  The overflow valve has a seat integrated in the housing and is situated at the highest point of the piston apply chamber. The overflow valve is believed to have a bleeding function much like the current one on Gen V. A photograph from a competitive assessment teardown of the coupling is shown in figure 4.7 [10].

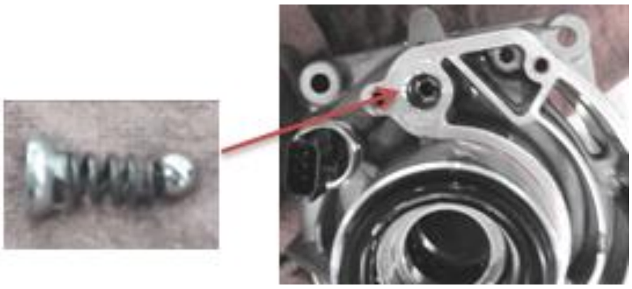

Figure 4.7 Product 1 disassembled.

- Product 2
  Figure 4.8 shows the piston apply chamber and the different valves used in a similar coupling. The system is integrated in the rear axle but otherwise functions in a similar way as the Gen V. Valve number one is a solenoid valve used for reducing the pressure and also de-airing as it is situated at the highest point of the chamber. The second one is a pressure accumulator and the third an overflow valve. The two remaining holes in the chamber are connected to the pump and to a small chamber with pressure and temperature sensors. The de-airing in this coupling is solved in a practical and controlled way with the solenoid valve but is more expensive than by using an overflow valve. Worth noticing is that the overflow valve had its valve seat integrated in the housing and that it is very small, approximately around five millimeters in diameter.

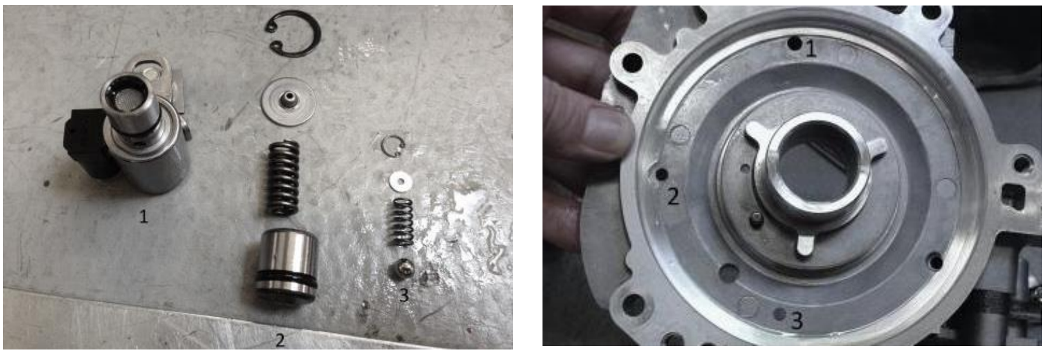

Figure 4.8 Product 2 disassembled.

4.2.3 Interview

Sales engineers Thorbjörn Brännström, specialized in hydraulics, and Stefan Berg, specialized in pneumatics, on Bosch Rexroth were consulted [9]. They both pointed out that a spring loaded ball valve is one of the simplest valve types available and that any other type of valve most likely would be difficult to manufacture cheaper.

Thorbjörn has previously worked with developing hydraulic systems for Volvo Excavators. When designing valves and other components on Volvo they used the thumb rule to never design orifices smaller than 0.8 millimeter to avoid clogging.

4.3 Conceptual designs

This first concept generation is quantitative to try to find and investigate all possible ways of de airing the system, therefore are not the technical feasibility of the concepts considered at this stage.

Some of the concepts require functions to be integrated in the housing, such as sealing surfaces. This is an advantage in terms of reducing the number of parts and thereby reducing the manufacturing costs, but it often requires more advanced machining of the housing. Another aspect to account is whether the valve can be tested before it is mounted or not. Since the parts is manufactured by a subcontractor and then mounted at BorgWarner in Landskrona it is favorable to be able to test its function close to the manufacturing process which is harder if it isn’t a separate, fully functional, component.

4.3.1 Concept 1: Simplified overflow valve

This concept has the same basic function as the current overflow valve. The goal with this concept is to reduce the number of components as far as possible. This is done by integrating the valve seat in the housing, removing the spring support plate and letting the ball rest directly on the spring. To secure the components in the housing a simple plug is used. This solution also eliminates the use of O-rings. The number of parts has been reduced but this will also require a more accurate machining operation of the housing. The design is shown in figure 4.9.

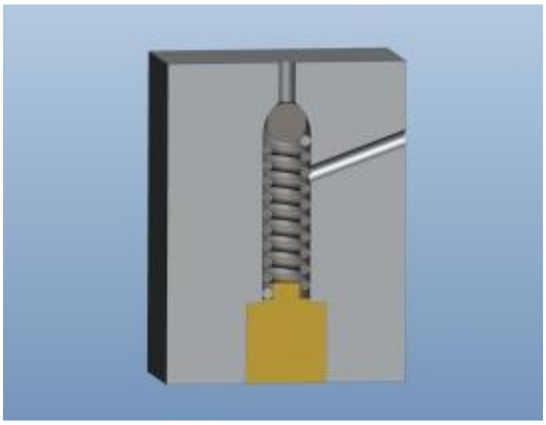

Figure 4.9 Concept 1 – Simplified overflow valve.

4.3.2 Concept 2: Redesigned overflow valve

Since the valve isn't intended to be replaced during the lifetime of the coupling it might as well be mounted internally. This would result in one less location where oil leakage possibly could occur. In this concept the ball is replaced by a cone in order to get the inlet closer to the highest point of the system which will be a problem when mounting the valve internally. The number of components can be reduced compared to the current solution. The design is shown in figure 4.10.

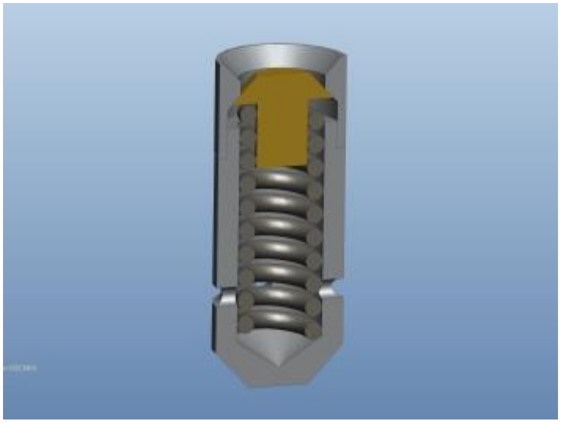

Figure 4.10 Concept 2 – Redesigned overflow valve.

4.3.3 Concept 3: Valve that closes due to viscosity change

The de-air strategy with this solution is to remove air when it actually is present. Between the valve body and the housing, illustrated in figure 4.11, there is a small gap which allows air to pass through but when oil with significantly higher viscosity than air enters the gap the flow resistance will cause the valve to shut. The number of parts can be reduced if it is mounted directly in the house.

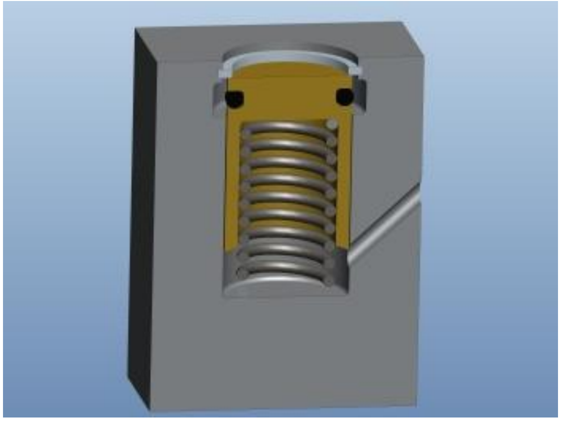

Figure 4.11 Concept 3 – Valve that closes due to viscosity change.

4.3.4 Concept 4: Float valve

This concept has the same strategy as the previous, concept 3, which is letting air out when it is present in the system. The valve will be kept open as long as air is passing through but when oil enter the valve the float will shut it. It is a simple solution with few parts. The design is illustrated in figure 4.12.

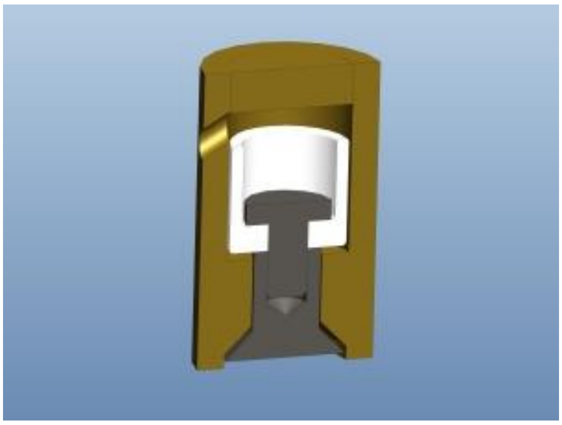

Figure 4.12 Concept 4 – Float valve.

4.3.5 Concept 5: Valve that closes at a certain pressure

A spring loaded poppet valve. The de-air strategy of this concept is to let out air at low pressures and that the valve will be kept shut for higher pressures. The pressure at which the valve closes is determined by the spring force. If the valve is mounted in the housing the number of parts can be kept low. The design is illustrated in figure 4.13.

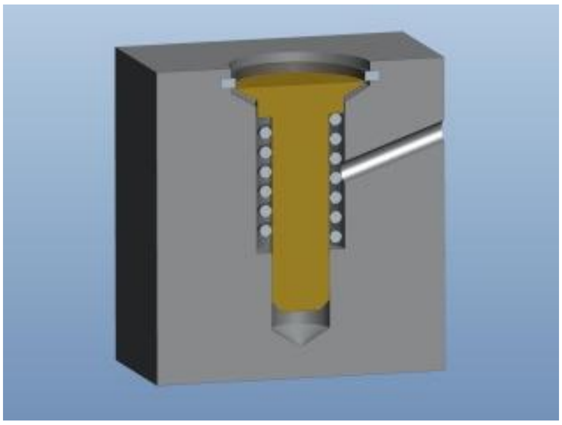

Figure 4.13 Concept 5 – Valve that closes at a certain pressure.

4.3.6 Concept 6: Valve that opens for a certain pressure interval

Works under the same principle as concept 5 with the difference that it instead is shut until the pressure has reached a specific value and the in the same way as the previous closes for higher pressures. The design is shown in figure 4.14.

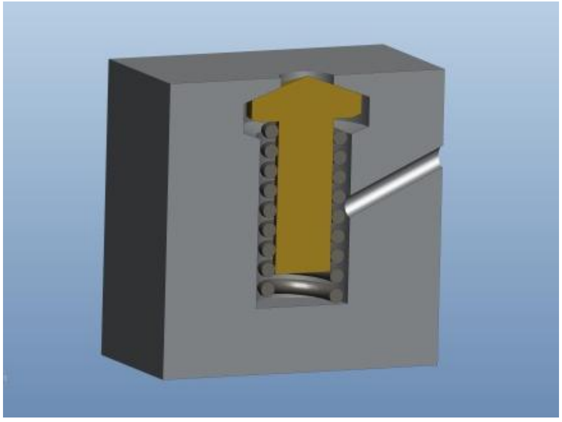

Figure 4.14 Concept 6 – Valve that opens for a certain pressure interval.

4.3.7 Concept 7: Elastic ball valve

The idea of this concept is to design an overflow valve without the use of a spring. In this solution some kind of elastic ball is meant to keep the valve shut until a predefined pressure and then at that pressure deform and thereby letting oil and potential air to pass through the valve. The design is shown in figure 4.15.

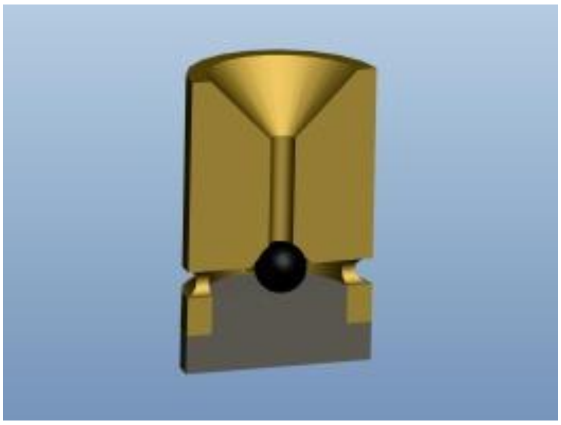

Figure 4.15 Concept 7 – Elastic ball valve.

4.3.8 Concept 8: Check valve with flexible flap

Same principle as the previous, concept 7, to act as an overflow valve without the use of a spring, where a flexible plate bends for a specific pressure difference to let oil end eventual air out. The design is shown in figure 4.16.

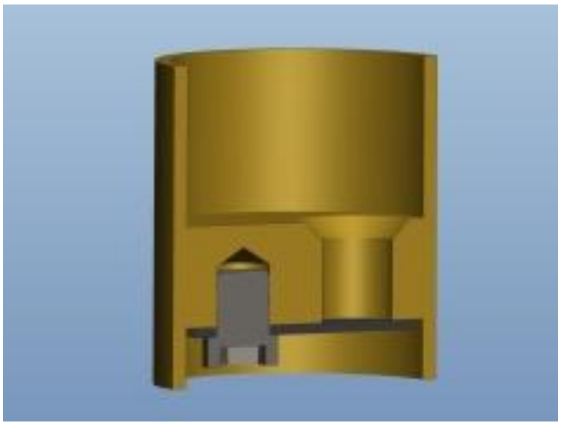

Figure 4.16 Concept 8 – Check valve with flexible flap.

4.3.9 Concept 9: Solenoid valve

A controlled valve that opens when it gets an electrical signal, easy to control and bleeds the system when needed.

4.3.10 Concept 10: Orifice

Having a small orifice at the highest point of the system will result in a continuous flow when the coupling is pressurized. The orifice has to be designed so that it doesn’t prevent the system to rapidly build the requested pressure. The design is illustrated in figure 4.17.

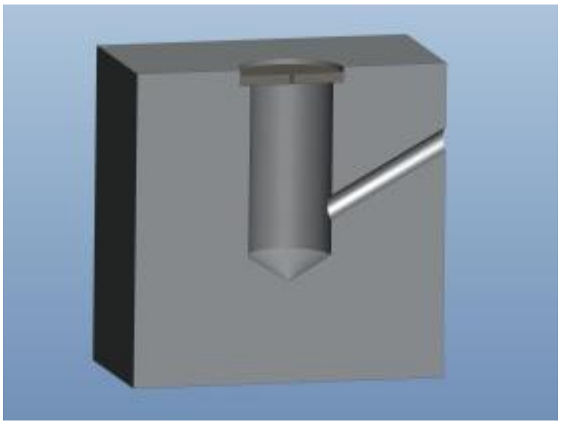

Figure 4.17 Concept 10 – Orifice.

4.3.11 Concept 11: Needle valve

This concept has the same principle that the orifice with a continuous flow to de-air the system. The needle is placed in a small opening so that the flow rate is kept sufficiently low. It is easier to control small flow rates with a needle type of valve rather than with an orifice [10]. The design is shown in figure 4.18.

Figure 4.18 Concept 11 – Needle valve.

4.3.12 Concept 12: Labyrinth

Another way of achieving a low but continuous flow is by designing a labyrinth for the oil to flow through. By introducing bends along the flow, the channels doesn’t have to be as small as an orifice. This is advantageous as it decreases the risk of particles clogging up the de-air function. The principle design is shown in figure 4.19.

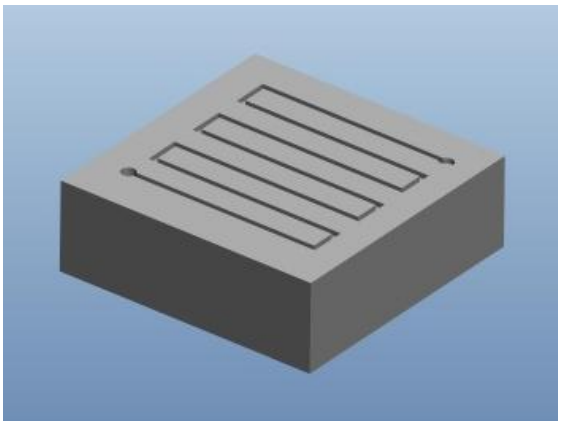

Figure 4.19 Concept 12 – Labyrinth.

4.3.13 Concept 13: Groove at the highest point of the piston

A small groove on the outer radius of the piston would allow a small flow from the high pressure side of the piston and would have the same basic function as an orifice.

4.3.14 Concept 14: Redesign the channels

It could be possible to redesign the channels so that air would escape via the same channels as the oil return. This requires a relatively small volume of the return channel since the oil volume that returns even at max pressure is approximately 3ml [5].

4.3.15 Concept 15: Lock

This concept is supposed to work under the same principle as a floodgate. A certain volume at the highest point of the system will be enclosed between two valves that never opens at the same time. The de-air process is divided in two steps. The first valve opens while the other is closed and the space between them fills up with oil and potential air. In the second step the first valve is closed and the second one is open, letting the volume to be emptied to the reservoir. This solution is in this stage not yet technically assured.

4.3.16 Concept 16: Vacuum

If all air is extracted from the coupling at assembly, creating a vacuum inside the housing, the system wouldn’t be in need of de-airing.

4.3.17 Concept 17: Valve open at pressure drop

The idea of this concept is to bleed the system at decreasing pressure, this would not affect pressure build-up and at the same time speed up the deactivation time. This solution is not technically assured.

4.3.18 Concept 18: Membrane

This concept is intended to work in the same fashion as a Gore-Tex jacket, allowing the garment to “breath” but still keeping it rain proof [11]. If a membrane could be designed so that air is allowed to pass but not the oil this could serve as a de-air mechanism. This solution is not technically assured.

5 Concept Selection

In this chapter the number of concepts will be reduced by using a screening matrix according to the method described by Ullrich and Eppinger. The matrix will give a first hint of which concepts that won't be able to fulfill the requirements.

The matrix method is a simple way to get a first hint of which concepts are most likely to be successful and which of the concepts that might lack some qualities. The result of the matrix will be complemented by discussion. A group of experts will be gathered to get their opinions on the concepts.

With the results from the matrix and comments from the experts in mind some of the concepts are improved and once again evaluated to decide which concept or concepts that should proceed for further evaluation.

5.1 Concept screening

The screening matrix will evaluate the concepts by comparing them to the current overflow valve. The criteria are divided in four main categories and each category has subcategories chosen to correspond to the most crucial properties the de-air mechanism needs to have.

The current solution are used as a reference and then the concepts are rated with a plus if they are considered to fulfill the criteria better, a minus if they are worse and a zero if they are considered to be equal to the reference.

1. Simplified overflow valve
2. Redesigned overflow valve
3. Valve that closes due to viscosity change
4. Float valve
5. Valve that closes for a certain pressure
6. Valve that opens for a certain pressure interval
7. Elastic ball valve
8. Flexible plate valve
9. Solenoid valve
10. Orifice
11. Needle valve
12. Labyrinth
13. Grove at the highest point of the piston
14. Redesign the channels
15. Lock
16. Vacuum
17. Valve opens at pressure drop
18. Membrane

Table 5.1 Concept screening matrix.

Selection Criteria	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Functionality																			
Fast bleeding at assembly	0	0	0	-	0	-	0	0	0	+	-	-	-	-	-	-	+	-	+
Fast bleeding at start-up	0	0	0	+	+	+	0	0	0	+	+	+	+	+	0	0	+	0	+
Rapid pressure build-up	0	0	0	0	0	-	-	0	0	0	-	-	-	-	0	0	0	0	0
Low sensitivity to eventual particles	0	0	0	-	0	0	0	0	0	0	-	-	-	-	0	0	0	0	-
Durability																			
Longevity	0	0	0	0	0	0	0	-	0	-	+	+	+	+	+	0	+	0	-
Low sensitivity to vibrations	0	0	0	0	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Low sensitivity to temperature differenses	0	0	0	-	0	0	0	-	0	0	-	-	-	-	0	0	0	0	0
Complexity																			
Low number of components	0	+	+	+	+	+	+	+	+	-	+	+	+	+	+	-	+	-	+
Manufacturability	0	+	0	-	0	0	0	+	+	-	+	0	+	+	-	-	-	-	?
Other																			
Low cost	0	+	+	0	+	+	0	+	+	-	+	+	+	+	+	0	+	-	?
Low weight	0	+	0	0	0	0	0	0	0	-	+	+	+	+	+	0	+	-	+
Small dimensions	0	+	0	0	-	0	0	0	0	-	+	+	+	+	+	0	+	-	+
TOT:	0	5+	2+	2-	1+	1+	0	1+	3+	4-	3+	2+	3+	3+	3+	3-	6+	6-	3+2?

5.2 Expert consultation

All the generated concepts where presented to a group of five persons working with mechanical development within BorgWarner, Landskrona.

Comments and discussions during the meeting revealed several difficulties but also opportunities in some of the concepts.

- Small orifices and tight gaps will most likely cause clogging problems if not some kind of filter is used or if the orifice could be flushed in some way.
- Introducing a grove in the piston is fundamentally a possible solution but it ruins the whole concept of hydraulic pistons i.e. they're supposed to have minimum leakage for maximum efficiency.
- Redesigning the channels is interesting but requires the returning channel to be designed in a specific way to function. The de-airing in generation 4 worked in a similar fashion.
- To apply vacuum to the system is an interesting approach but would require a vacuum pump since it can't be guaranteed that the housing is completely airtight.
- The concept about having a flexible plate is suitable as a check valve rather than withstanding high pressures.
- The lock principle is interesting. An example of a valve used in a similar way for removing vaporized water in pressurized air tanks was brought up.
- De-airing in a pressure interval or having a valve that closes for a certain pressure was also considered interesting alternatives. It might cause problems for the regulating system since the pressure build-up curve will have a sudden irregularity when the valve opens or closes.
- The solution to de-air at pressure drop is interesting as it wouldn't interfere the pressure build-up and at the same time enhance the deactivation time.

5.3 Reflection of the screening process

From the screening matrix all concepts that got two pluses or more are considered to fulfill the requirements good enough for continued development. The results from the matrix can however not be trusted blindly [1, pp. 156-157]. Some concepts that seems less promising when looking in the matrix is still worth investigating more closely. The same goes for some of the concepts that were rated high but most likely won't reach any success for other reasons.

Concept number 13 and 16 stood out as good candidates according to the matrix but when discussing them these concepts are considered to have a low potential to solve the problem.

The concepts 5, 6, 15 and 17 are all concepts that more or less failed in the matrix but still will be considered as possible solutions. The reason why they got low scores has different explanations but mostly that they are estimated to require many different parts and will therefore be difficult to manufacture and assemble. Their intended function is however interesting and will be given further consideration.

5.4 Detailed designs

Based on feedback on the first concepts the most promising ones are developed to more detailed designs. The function and the separate parts of the valves is given more thought and they are designed to be more compatible with the housing.

Concept 5 and 6 is working under the almost same principles but during consultations it emerged that it is preferable if the valve works as a check valve. If concept 5 is redesigned to have that function it will be very similar to concept 6. Concept 5 will therefore not be given further consideration.

Below follows detailed designs of the concepts 1, 2, 6, 10, 11, 12, 15 and 17.

5.4.1 Concept 1: Simplified overflow valve

This concept is developed to mount from inside the housing. The valve seat is integrated in the same part used to secure the spring and the ball in the housing. The part is meant to be inserted and pressed down to a small edge and then be expanded to lock its position in the housing. The bore is done in an angle to get the inlet at the highest point. The design is shown in figure 5.1.

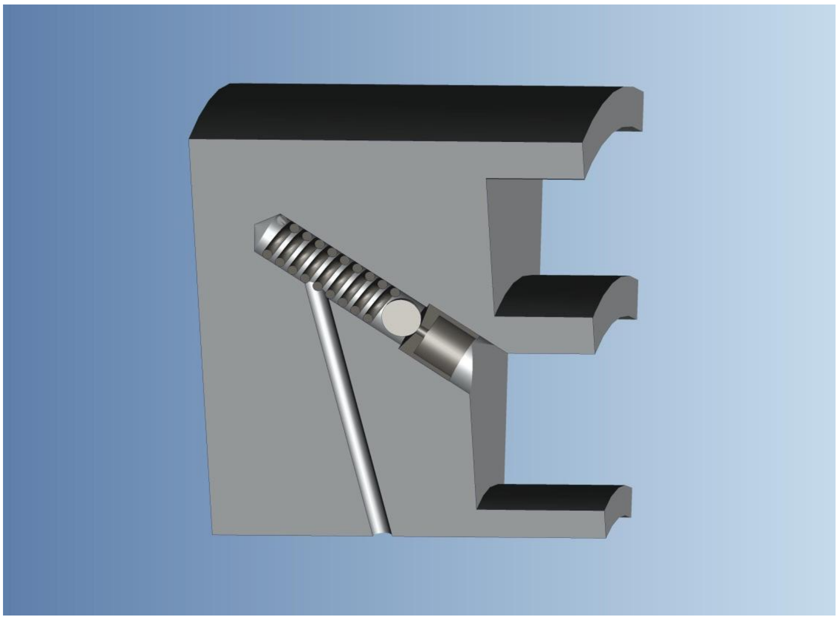

Figure 5.1 Concept 1 – Simplified overflow valve.

5.4.2 Concept 2: Redesigned overflow valve

This concept is meant to be mounted from the inside and secured by either treads or by expanding one of the parts. An O-ring makes sure that there is no leakage between the inlet and outlet. If the expanding solution, illustrated in figure 5.2, is used the O-ring might not be needed. With the threads placed at the bottom of the body, illustrated in figure 5.3, the outer diameter will be kept as small as possible.

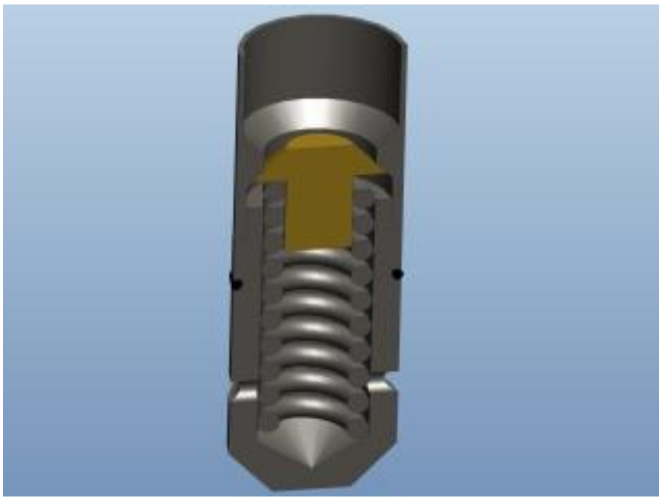

Figure 5.2 Concept 2 – Redesigned overflow valve with the alternative of expanding the top to secure its position.

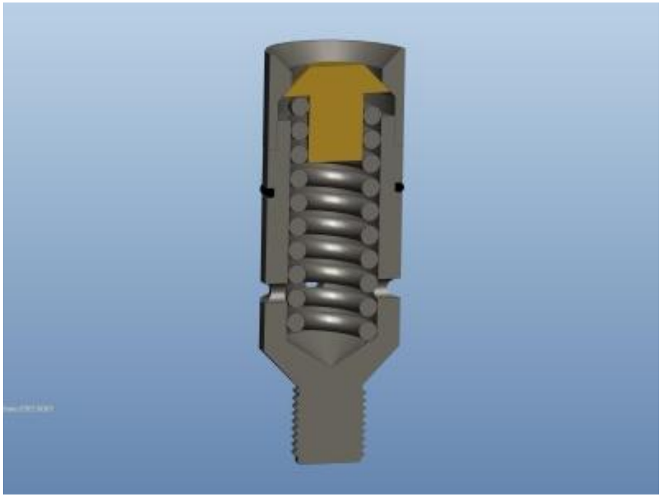

Figure 5.3 Concept 2 – Redesigned overflow valve with treads at the bottom.

5.4.3 Concepts 6: Valve that opens for a certain pressure interval

This concept has been developed to two different solutions with the same basic function, to be open for an interval specified by the spring force. The concept illustrated in figure 5.4 is meant to be mounted from inside with threads in the bottom of the bore. The concept illustrated in figure 5.5 has a simpler geometry and is meant to be mounted from outside. From now on these concepts will be referred to as concept 6.1 and 6.2.

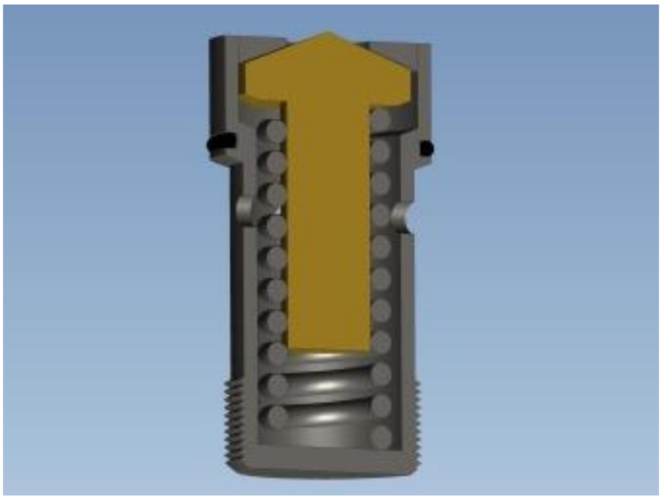

Figure 5.4 Concept 6.1 – Valve that opens for a certain pressure interval.

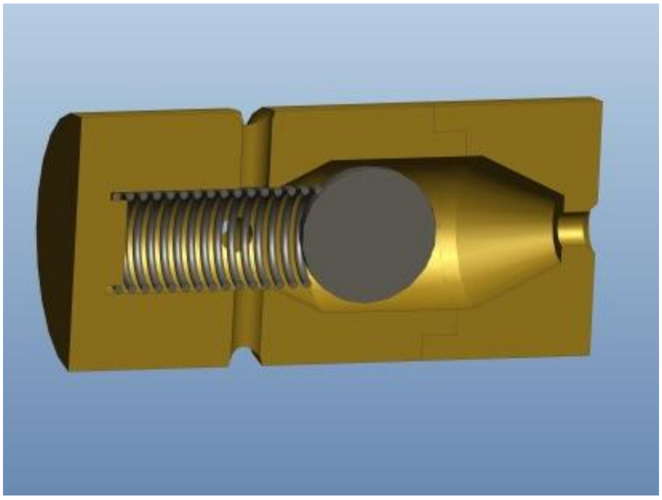

Figure 5.5 Concept 6.2 – De-air interval valve.

5.4.4 Concept 10: Orifice (with filter)

Since the orifice has to have a very small diameter the use of a filter is inevitable so a part for fixing the filter has been added. The design with filter added is shown in figure 5.6.

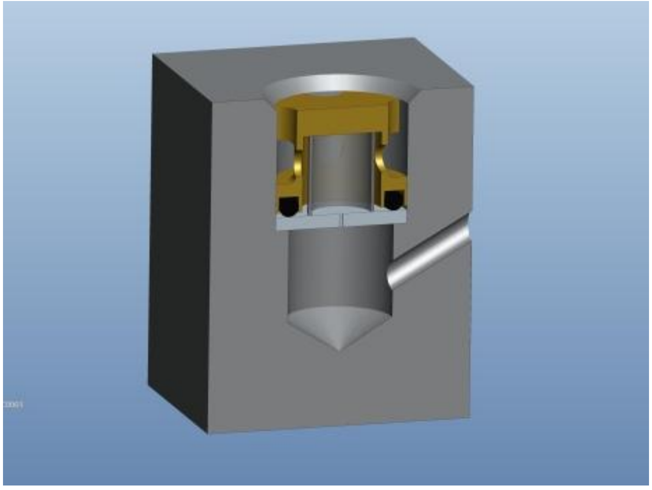

Figure 5.6 Concept 10 – Orifice (with filter).

5.4.5 Concept 11: Needle valve

To avoid clogging issues the needle valve has been made flushable. The spring will be defined so that the needle opens at max pressure. The concept is meant to be mounted in a similar way as the current overflow valve. The design is shown in figure 5.7.

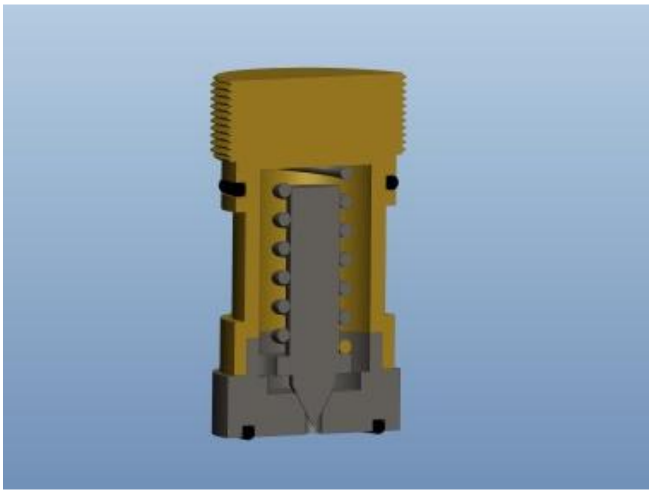

Figure 5.7 Concept 11 – Needle valve.

5.4.6 Concept 12: Labyrinth

This concept is redesigned according to figure 5.8 to be easier to mount in the housing by making it rotationally symmetric. It is meant be mounted in similar way as the current valve.

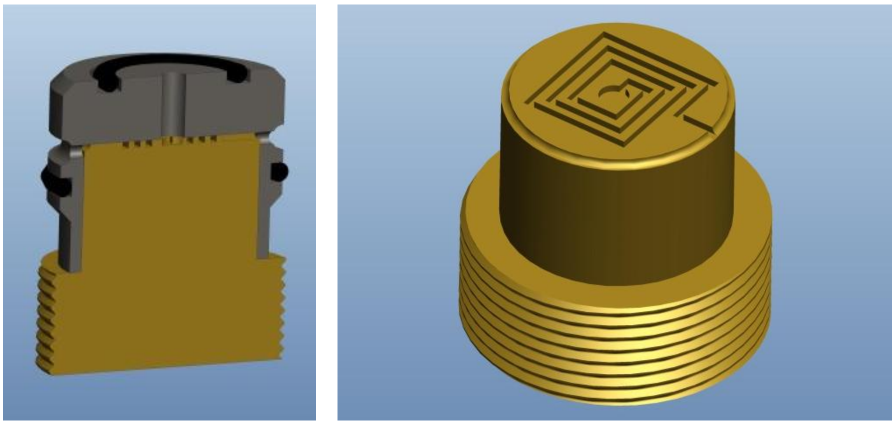

Figure 5.8 Concept 12 – Labyrinth.

5.4.7 Concept 14: Redesign the channels

The layout of the channels could be changed in various ways to possibly eliminate the need of an air-bleed valve. Three different alternatives are presented and illustrated in figures 5.9-5.11.

- Two check valves makes sure that the oil at the highest point of the system leaves the piston apply chamber gets bled of when deactivating the clutch.

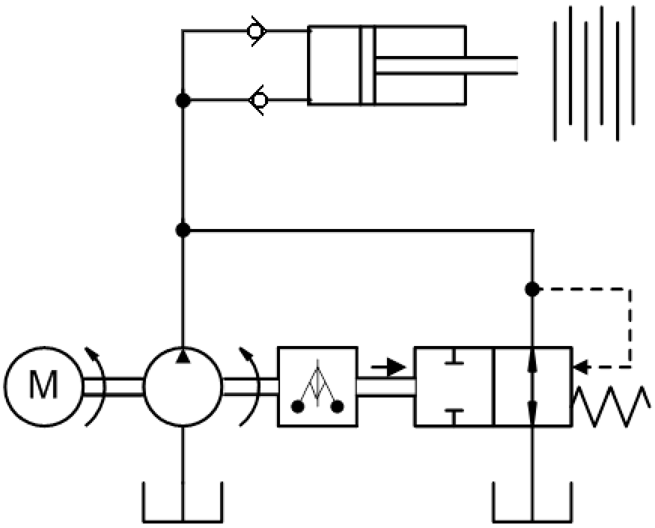

Figure 5.9 Concept 14 – Solution with two check valves.

- Inlet and outlet through the same channel situated at the highest point of the system. If the channel is made narrow enough the air bubbles that might be present will be bled of together with the oil when deactivating the clutch.

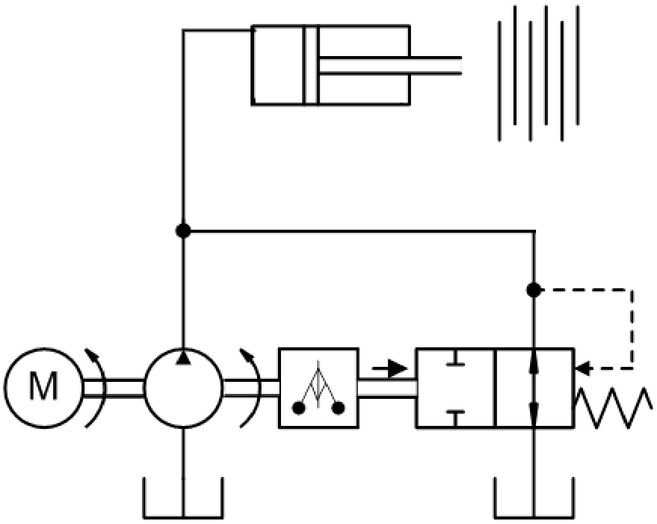

Figure 5.10 Concept 14 – Solution with narrow channel at the highest point.

- Redesigning the channels so that the pump flow is connected directly to the lower part of the piston chamber and connecting the centrifugal overflow valve to the highest point will create a continuous flow through the chamber and thereby free from air bubbles.

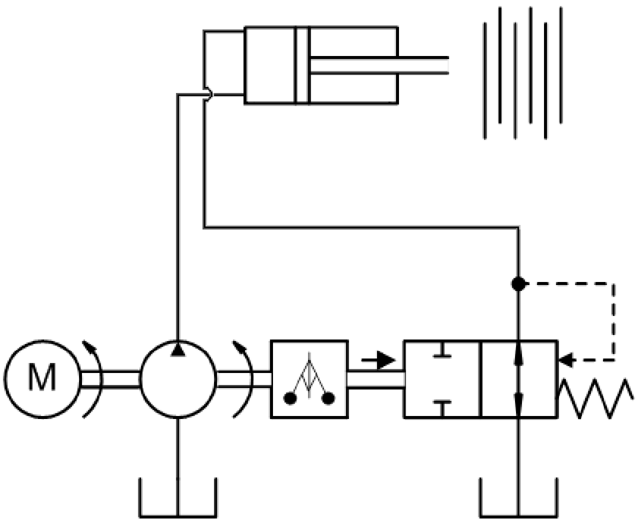

Figure 5.11 Concept 14 – Solution with the pump and centrifugal overflow valve separated.

5.4.8 Concept 15: Lock

This solution operates in two steps. Step one is to pressurize a chamber at a relatively low to medium high pressure, illustrated in Figure 5.12 to the left. Step two is performed under high pressure. When the piston is pushed further into the housing the pressurized volume is connected to the outlet, letting oil and potential air escape. The design is illustrated in figure 5.12 to the right.

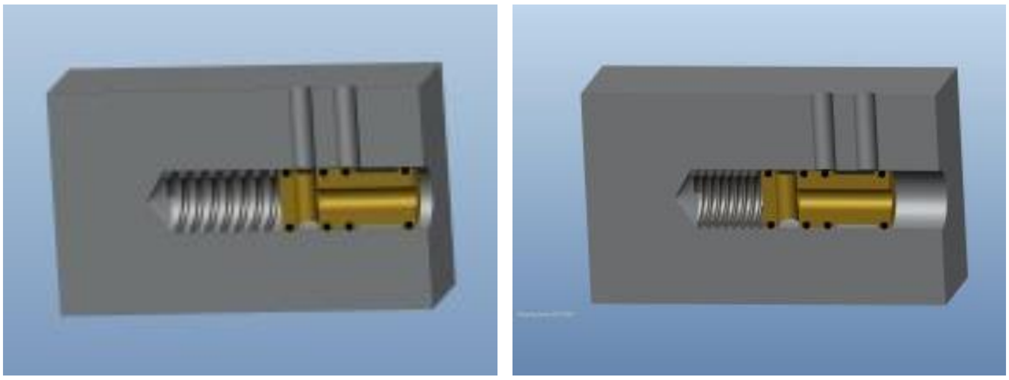

Figure 5.12 Concept 15 – Lock

5.4.9 Concept 17: Valve that opens at pressure drop

This design consists of two chambers where the upper always is connected to the piston chamber. The lower chamber has a check valve which makes sure that its pressure can’t escape back into the piston chamber. This means that when the pressure drops in the piston chamber it will also drop in the upper chamber but be kept high in the lower. This pressure difference will open the slide valve and connect the pressurized chamber to the outlet. The design is illustrated in figure 5.13.

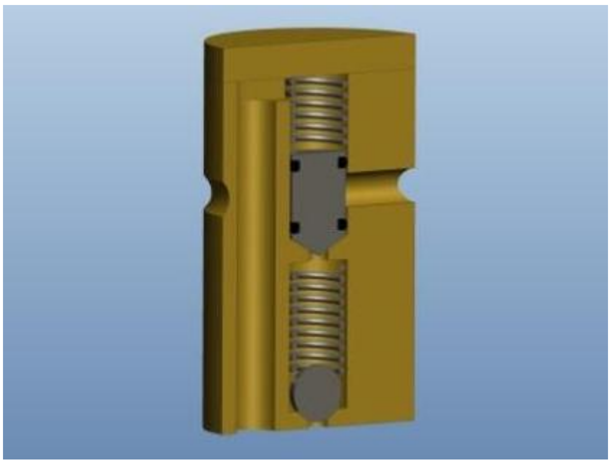

Figure 5.13 Concept 17 – Valve that opens at pressure drop.

5.5 Concept scoring

In the concept scoring matrix the criteria has been given weight factors based on their relevance. The current overflow valve is used as a reference and the concepts are scored on a scale between one and five described below.

1 Much worse than reference
2 Worse than reference
3 Same as reference
4 Better than reference
5 Much better than reference

The weight of the criteria has been set after discussions with supervisor for this thesis Kristoffer Nilsson and will make sure that the concepts which target the criteria most valuable for the company will be found.

The score given for a concept is multiplied with the weight factor and the all scores for the different criteria are then summed up and rounded to a total score for each concept. The concept scoring matrix is shown in table 5.2.

The list below describes which number each concept is related to.

1. Simplified overflow valve
2. Redesigned overflow valve
5. Valve that closes for a certain pressure
6.1. Valve that opens for a certain pressure interval
6.2. De-air interval valve
10. Orifice
11. Needle valve
12. Labyrinth
14. Redesign the channels
15. Lock
17. Valve opens at pressure drop

Table 5.2 Concept scoring matrix.

Concept Scoring		Reference		1		2		6.1		6.2		10		11		12		14		15		17	
	Weight	Score	Weighted score	score	Weighted score	score	Weighted score	score	Weighted score	score	Weighted score	score	Weighted score	score	Weighted score	score	Weighted score	score	Weighted score	score	Weighted score	score	Weighted score
Function	**30**																						
Fast bleeding at start-up	5	3	0,15	3	0,15	3	0,15	2	0,1	2	0,1	2	0,1	3	0,15	2	0,1	2	0,1	2	0,1	2	0,1
Fast bledding at assembly	8	3	0,24	3	0,24	3	0,24	2	0,16	2	0,16	2	0,16	3	0,24	2	0,16	2	0,16	1	0,08	1	0,08
Bleeding frequency	4	3	0,12	3	0,12	3	0,12	4	0,16	4	0,16	5	0,2	5	0,2	5	0,2	4	0,16	4	0,16	4	0,16
Rapid pressure build-up	8	3	0,24	3	0,24	3	0,24	3	0,24	3	0,24	2	0,16	2	0,16	2	0,16	3	0,24	3	0,24	3	0,24
Sensitivity to temperture difference	5	3	0,15	3	0,15	3	0,15	3	0,15	3	0,15	1	0,05	2	0,1	1	0,05	3	0,15	3	0,15	3	0,15
Longevity	**15**										0												
Low particle sensitivity	10	3	0,3	3	0,3	3	0,3	3	0,3	3	0,3	1	0,1	3	0,3	2	0,2	3	0,3	3	0,3	3	0,3
Risk of failure/Reliability	5	3	0,15	2	0,1	3	0,15	3	0,15	3	0,15	2	0,1	3	0,15	2	0,1	4	0,2	2	0,1	2	0,1
Cost	**50**										0												
Low number of components	10	3	0,3	5	0,5	4	0,4	4	0,4	4	0,4	5	0,5	3	0,3	5	0,5	3	0,3	1	0,1	1	0,1
Material cost	30	3	0,9	5	1,5	3	0,9	2	0,6	3	0,9	4	1,2	2	0,6	4	1,2	4	1,2	2	0,6	2	0,6
Amount of maching in the housing	10	3	0,3	2	0,2	4	0,4	3	0,3	3	0,3	4	0,4	3	0,3	3	0,3	1	0,1	2	0,2	3	0,3
Other	**5**										0												
Size	2	3	0,06	4	0,08	3	0,06	3	0,06	3	0,06	5	0,1	3	0,06	4	0,08	3	0,06	2	0,04	2	0,04
Weight	3	3	0,09	4	0,12	3	0,09	3	0,09	3	0,09	5	0,15	3	0,09	4	0,12	3	0,09	2	0,06	2	0,06
Weighted Sum:	100		3		3,7		3,2		2,71		3,01		3,22		2,65		3,17		3,06		2,13		2,23

5.6 Consultation

The detailed designs where presented to supervisor of this thesis, Kristoffer Nilsson, and head of the mechanical department Måns Ranåker. They agreed on that concept 1 certainly is an effective simplification of the current valve and is worth further consideration. Since it is working under the same principle as the current valve it shouldn't be too complicated to dimension it to work just as good.

Some of the other designs that don't work under the same principle as the current were also considered interesting to test even though they are more complicated and probably more expensive.

The concepts that bleed continuously would be very effective on keeping the system free of air but their downsides are that they either are very sensitive to particles or that there is a risk of air getting in when the piston chamber isn't pressurized.

To redesign the channels so that any air bleed valve wouldn't be necessary is interesting if it could be done in a way so that it could be implemented on all the different house designs with just minor adjustments. This requires a lot of effort and knowledge about the different layouts.

Concepts 6.1, 6.2, 15 and 17 are all concepts that operates in another, lower, pressure span than the current. They could therefore be worth investigating since the motor generates unwanted noise at startup when high pressure needs to be built up for de-airing.

5.7 Final selection

With comments from the consultation and the result of the Concept Scoring matrix it is decided that concept 1 is the most efficient way to reduce the costs and fulfill the requirements and will be dimensioned and tested.

Of those of the concepts that uses another technique than the current, i.e. to bleed at maximum pressure, concept 6.2 got the highest score and are considered to have a good chance of fulfilling the requirements.

Concepts 15 and 17 are concepts that are considerably more complex than the others and neither of them are likely to be produced to a lower cost than the current. Nevertheless they both have interesting functions and it could therefore still be worth testing them even if they aren't competitive candidates of replacing the current valve. It is decided that concept 15, lock valve, has a better potential to work than concept 17, valve that opens at pressure drop.

6 Final Designs

In this chapter the concepts ”Simplified overflow valve”, “De-air interval valve” and “Lock valve” will be tested to validate their function. The final designs are modified for manufacturability and dimensioned to fit the housing of the coupling to be able to use existing test rigs. Spring calculations for the final designs are presented in Appendix B and complete assembly drawings in Appendix D.

6.1 Design 1: Simplified overflow valve

The inlet of the valve is narrower than the inlet of the current valve. A smaller area of the ball subjected to pressure means that the spring can be made smaller. Equation (1) shows the relation between the spring force, the pressure and the area subjected to the pressure [12, p. 73].

$$P = \frac{F}{A} \Leftrightarrow F_{Spring} = P * A_{Inlet} \tag{1}$$

Making the valve as small as possible allows it to be mounted from inside of the coupling. This will reduce the number of components needed as the housing of the coupling is used instead of having a separate housing for the valve. Mounting it from the inside also eliminates the risk for leakage out of the housing. The valve seat will be made in steel in able to get a sharp and solid edge for the ball to seal against. The design is illustrated in figure 6.1.

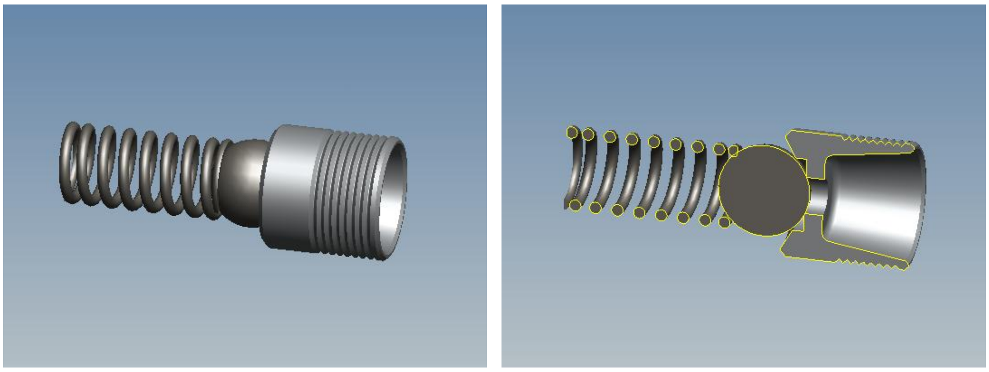

Figure 6.1 Final design of the simplified overflow valve.

The valve seat is meant to be secured in its mounting hole by using a punch that will cause the top of the valve seat to expand, illustrated in figure 6.2.

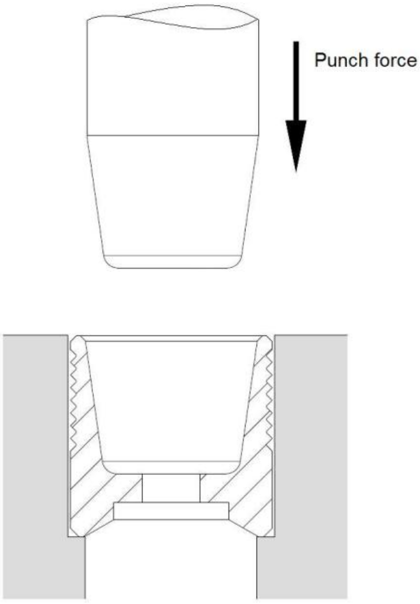

Figure 6.2 Mounting of the simplified overflow valve.

6.1.1 Adapter

Making changes to the housing is hard as it would either require changes during the casting process or complicated rework of the housing. An adapter is designed so that the valve can be mounted in the same hole as the current valve, the design of the adapter is shown in figure 6.3. The material of the adapter is aluminum, just as the housing of the coupling, mounting the valve in the adapter will verify if the expansion fitting works as intended. A cross section of the adapter with the simplified overflow valve mounted is shown in figure 6.4.

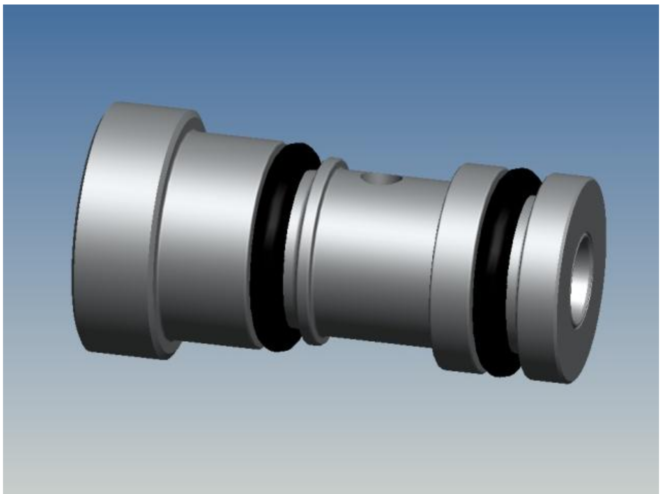

Figure 6.3 The adapter.

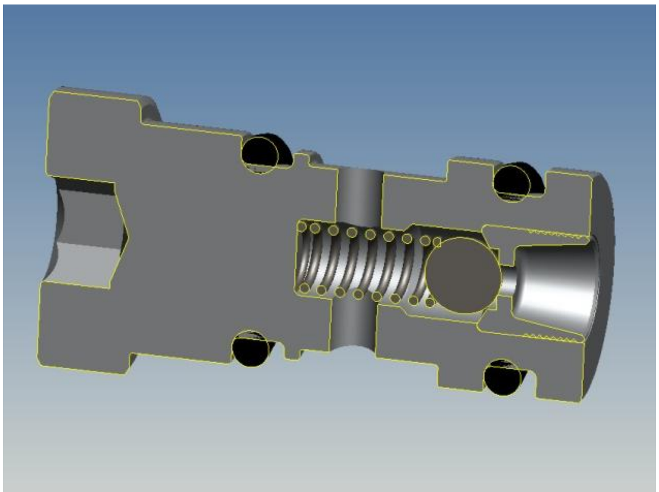

Figure 6.4 A cross section of the adapter.

6.2 Design 2: De-air interval valve

The valve seat at the inlet has a smaller area than the valve seat at the outlet. This will create a hysteresis effect that will cause the ball to move directly from one seat to the other. Which means that when the pressure reach a certain level the valve will open and since the outlet has a larger area, and therefore requires a lower pressure to shut, it will close immediately and only let a small amount of oil to pass through. To let the ball fall back from the outlet seat the pressure has to be reduced to a level below the opening pressure of the inlet which means that the ball will travel directly from the outlet to the inlet seat in the same way as on pressure build-up. The valve will be made in steel to make sure a tight seal between the ball and the seats. The de-air interval valve is shown in figure 6.5 and a cross section of the valve is shown in figure 6.6.

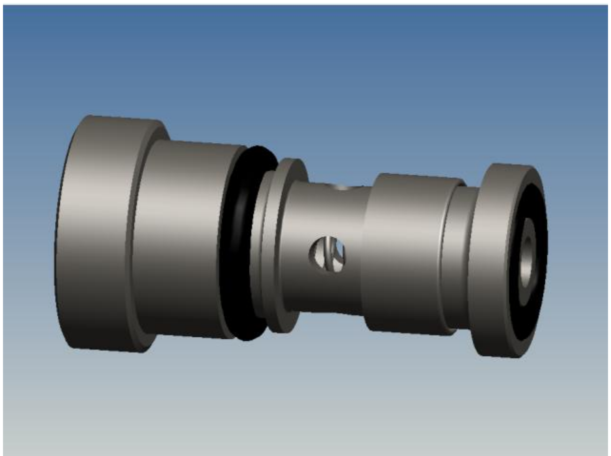

Figure 6.5 The final design of the De-air interval valve.

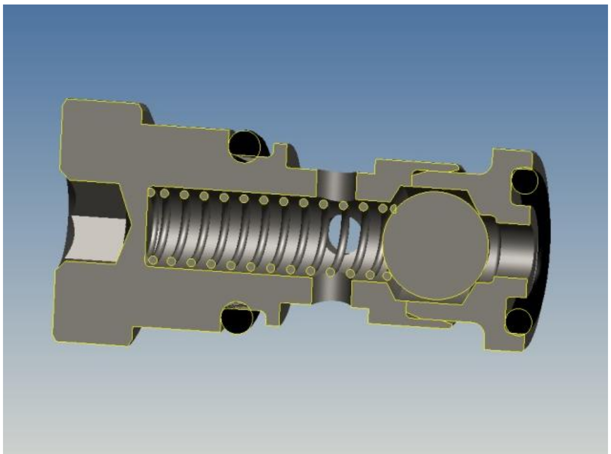

Figure 6.6 A cross section of the De-air interval valve.

6.3 Design 3: Lock valve

The Lock valve has been redesigned, according to figure 6.7, so that the pressurized volume now is located within the valve instead of in a separate chamber. The valve is meant to work in two stages. In the first stage the small volume inside the slide pressurizes and when the pressure continuous to rise the slide will move so that the pressurized volume instead will be connected to the outlet and thereby bleed the system. The second stage is meant to be used at max pressure. When the small spring is fully compressed the slide will be in contact with the spring support plate and be held back by the larger spring. At max pressure the slide will compress the large spring so that the inlet will be connected directly to the outlet. This function is meant to be used during the assembling of the coupling and as a pressure restrictor.

The cylinder and slide will be made in steel in able to acquire the preciseness required. The inlet and the cap will be made in brass. The brass is softer than the steel and this will be an advantage when press fitting the parts together since it is important that the geometry of the cylinder doesn't change during assembly. The final design is illustrated in figure 6.8.

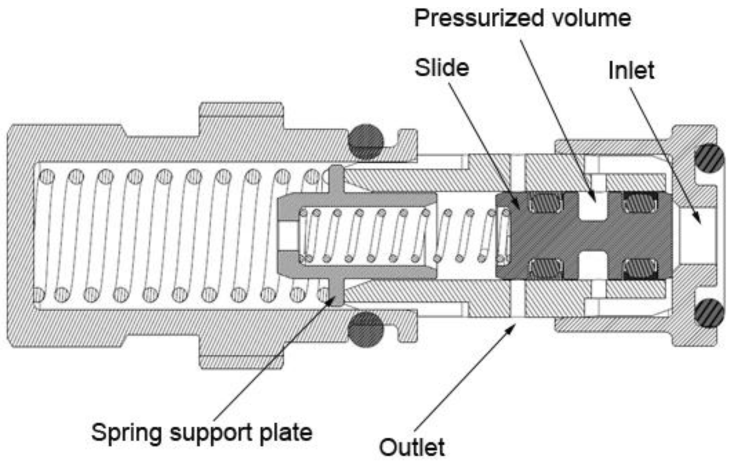

Figure 6.7 The components of the lock valve.

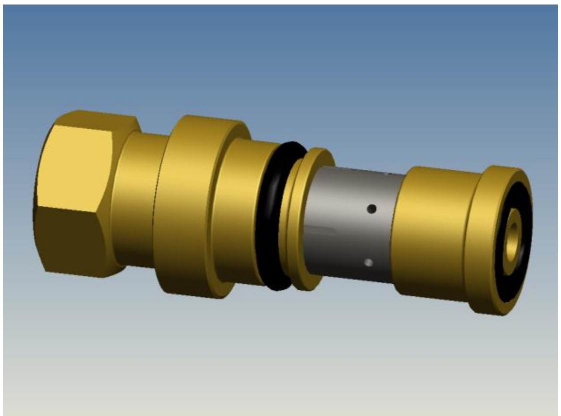

Figure 6.8 The final design of the lock valve.

6.3.1 Slide alternatives

It is crucial for the function of the valve that there is a minimal leakage between the slide and the cylinder, this can be achieved with or without seals. With the use of seals, the gap between the components can be larger since the seals are slightly elastic [13]. Without the seals the inner diameter of cylinder and the outer diameter of the slide need to be very precise and have fine surface finishes. Figure 6.9 presents the final design of the lock valve with the use of seals on the slide and figure 6.10 shows the design without.

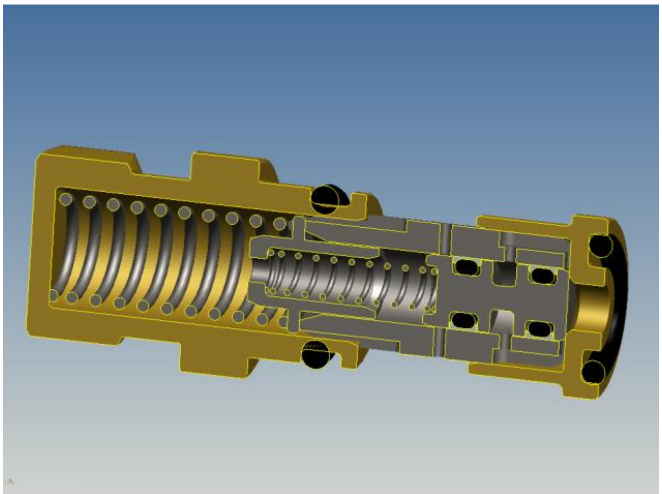

Figure 6.9 Cross section of the design with seals.

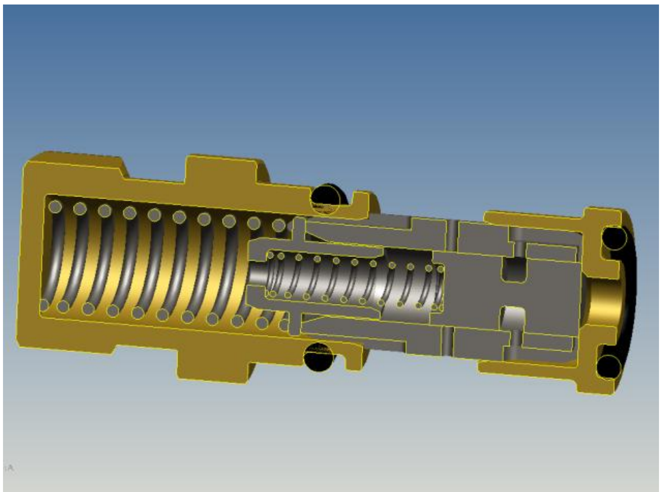

Figure 6.10 Cross section of the design without seals.

The amount of leakage in respect to the gaps width(h_0) and length(L), dynamic viscosity(η), applied pressure(p), the eccentricity(e), radius(r) and speed(v) of the slide can be derived from equation (2) [14, p. 12].

$$q_l = \pi v r h_0 + \frac{\pi r h_0^3 \Delta p}{6\eta L}\left(1 + 1{,}5\left(\frac{e}{h_0}\right)^2\right) \tag{2}$$

With a H7/f6 fit between the slide and cylinder the maximum possible gap is 30ηm, h_0 is defined as the average of h_1 and h_2 i.e. 15ηm [17, pp. 1212, 1215]. The influence of the speed can be disregarded. Insertion of the geometrical parameters, the pressure and the viscosity results in a leakage of 26ml/min. Compared to the pump flow of roughly 800ml/min this leakage can be considered acceptable. The complete calculations are presented in appendix A.

7 Testing

This chapter presents the prototypes with all their internal parts and introduces the rigs used to test them.

7.1 Prototypes

Prototypes are manufactured for the three final designs, they are shown in figure 7.1 together with the original valve.

Figure 7.1 The prototypes of the three final designs. From the left: original valve, simplified overflow valve, de-air interval valve, lock valve.

7.1.1 Simplified overflow valve

Figure 7.2 clearly shows the size difference compared to the current overflow valve. Even with the adapter this solution can be seen as a simplification, having the adapter made in aluminum also makes it significantly lighter.

If the housing for this or future generations could be made so that the adapter won’t be needed, the valve will only have one component that needs to be specially manufactured since the ball and the spring are standard components.

Figure 7.2 The simplified overflow valve compared to the Gen V valve (to the left), the simplified valve with adapter and mounting tool and the Gen V valve disassembled (to the right).

7.1.2 De-air interval valve

This concept is made in two versions shown in figure 7.3. The difference between them is the gap around the ball, one of them has a 0.1mm gap and the other one has 0.25mm gap. The reason why two versions are done is to investigate what effect the gap has on the leakage flow.

Figure 7.3 The two De-air interval valve prototypes before assembling.

7.1.3 Lock valve

Figure 7.4 shows that the Lock valve undoubtedly is the most complex solution. It is also longer than the current valve since the slide has to move a relatively long distance compared to a ball valve but also because it has a larger area subjected to the pressure and therefore requires a large spring to hold it back at high pressures.

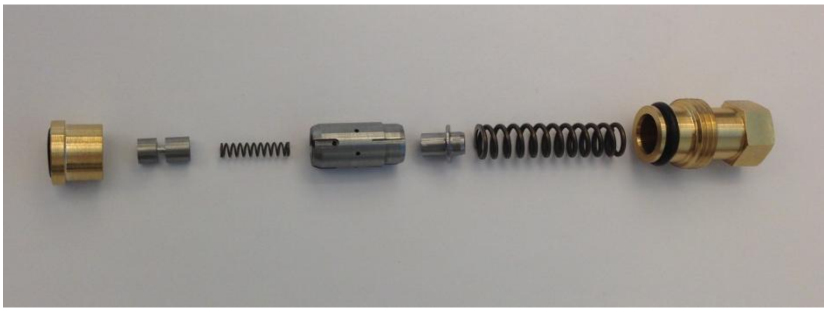

Figure 7.4 The Lock valve with all its components.

7.2 Test setup

Two different rigs are used to validate the function of the prototypes, a pump rig and a modified Gen V coupling mounted on a Volvo rear differential.

7.2.1 Pump rig

A pump rig, shown in figure 7.5, is used to measure the flow rate through the valves for different pressures. The rig is controlled with the software DIAdem, developed by National Instruments, which allows you to adjust the current to the motor driving the pump and measure time, flow rate, pressure and temperature.

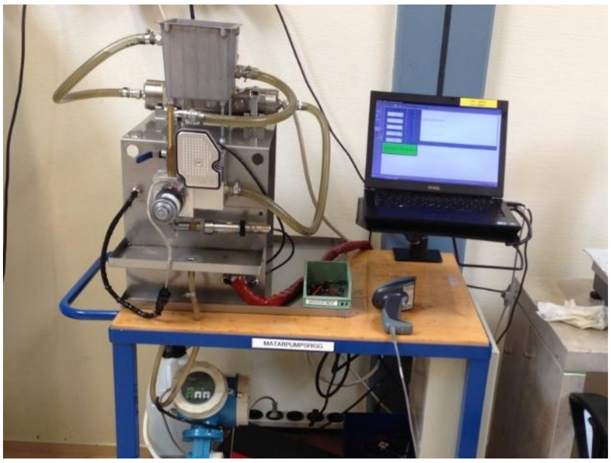

Figure 7.5 The pump rig.

7.2.2 Modified Gen V coupling

A Gen V coupling mounted on a Volvo rear differential was modified. The original return channel was plugged and instead a new outlet was drilled and a nipple was mounted. A transparent hose was connected to the nipple to making the effluent of air and oil visible. The setup is shown in figure 7.6.

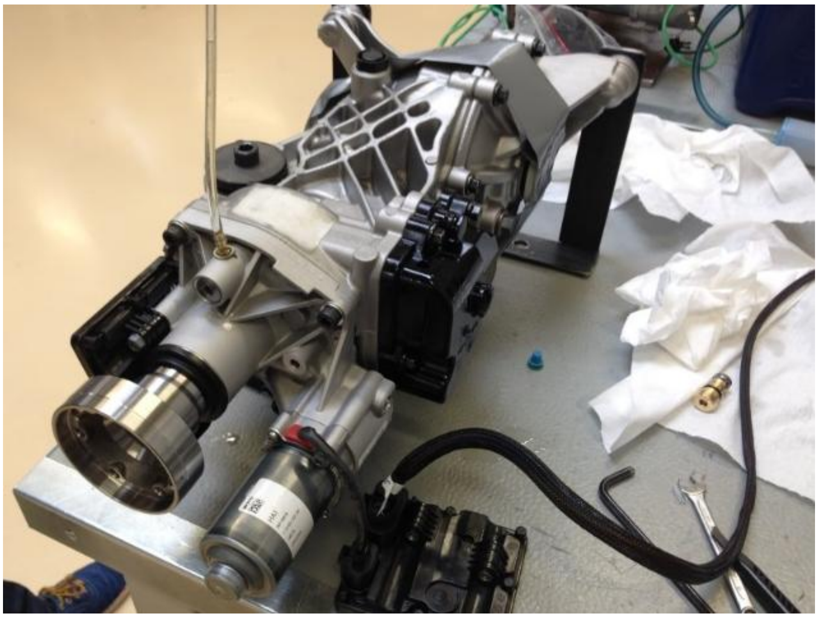

Figure 7.6 The modified Gen V coupling setup.

8 Results

This chapter includes the result from the two rigs used to test the prototypes and a cost estimation of the valves as if they were to be produced in full scale.

8.1 Pump rig results

Each valve is tested in the pump rig to find their opening pressures and to make sure that they aren't leaking when closed. At least three ramp-up cycles are performed on each valve, the graphs for each cycle is presented in appendix C.

8.1.1 Simplified overflow valve

Figure 8.1 shows one of the ramp-up cycles for the simplified overflow valve. The graph shows that the valve effectively limits the pressure at a slightly higher pressure than expected but before the pressure stabilizes there is a short pressure peak. This behavior can also be seen for the Gen V overflow valve, in figure 8.2, but not to same extent as the simplified valve. Another difference that can be seen is that the leakage just before opening and closing is slightly higher for the simplified valve.

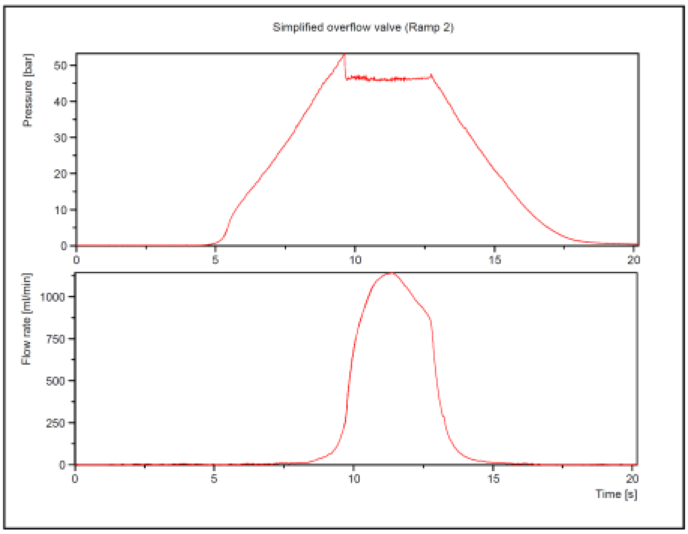

Figure 8.1 Ramp-up cycle for the simplified overflow valve.

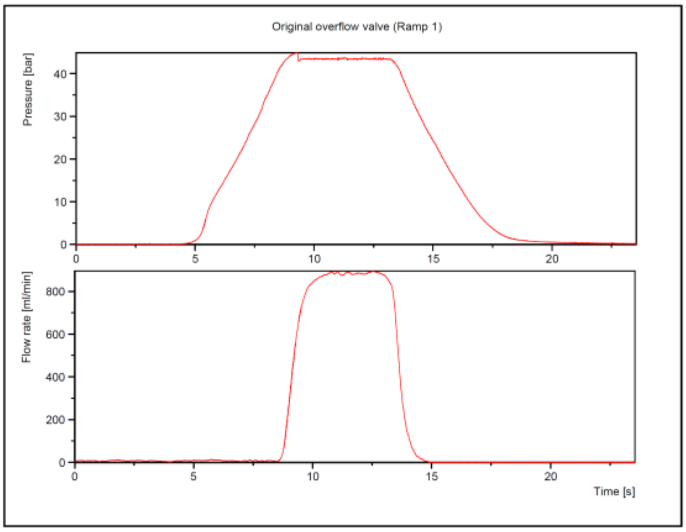

Figure 8.2 Ramp-up cycle for the Gen V valve.

8.1.2 De-air interval valve

In figure 8.3 the graph for the De-air interval valve with the larger gap is shown. The pressure only rose to about 4 bars even when maximum current was sent to the motor. This indicates that the valve didn't close for higher pressures.

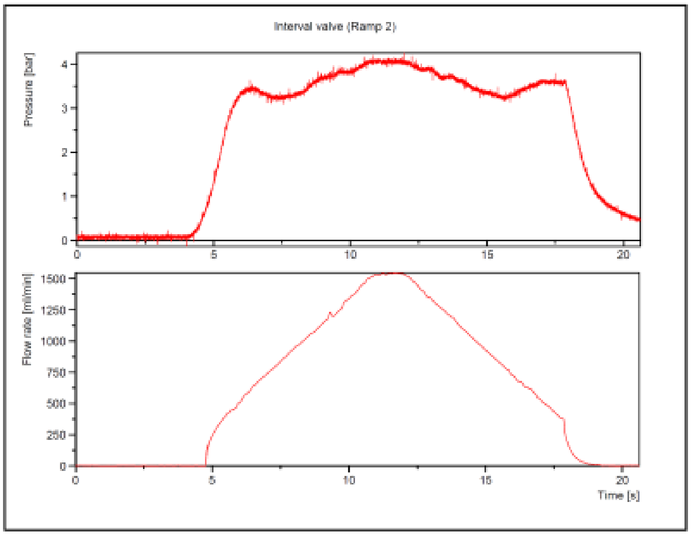

Figure 8.3 Ramp-up cycle for the De-air interval valve with 0.25mm gap.

Figure 8.4 shows the graph for the De-air interval valve with the smaller gap. The graph clearly shows that this valve has a different behavior than the one with the larger gap. The valve doesn't show any signs of leakage for higher pressures but when the pressure falls down to the closing pressure at approximately 3 bars a small leakage occur. No signs of leakage can be seen during pressure build-up when the ball moves from the first seat.

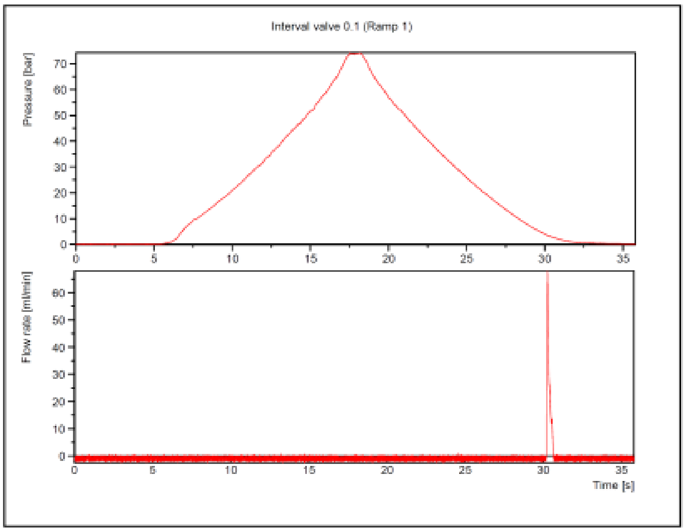

Figure 8.4 Ramp-up cycle for the De-air interval valve with 0.1mm gap.

To investigate how the pressure is affected by the opening of the valve a slower ramp-up cycle is performed, the graph is shown in figure 8.5. A small leakage flow can now be found when the ball moves from the first seat but this doesn't seem to effect the pressure curve. When the ball falls back during pressure drop a higher leakage occurs and a small impact can be seen on the pressure curve. A random pressure cycle was performed to simulate the behavior of the valve during driving, this graph is shown in appendix C. The graph shows a small leakage every time the pressure drops below 3 bars.

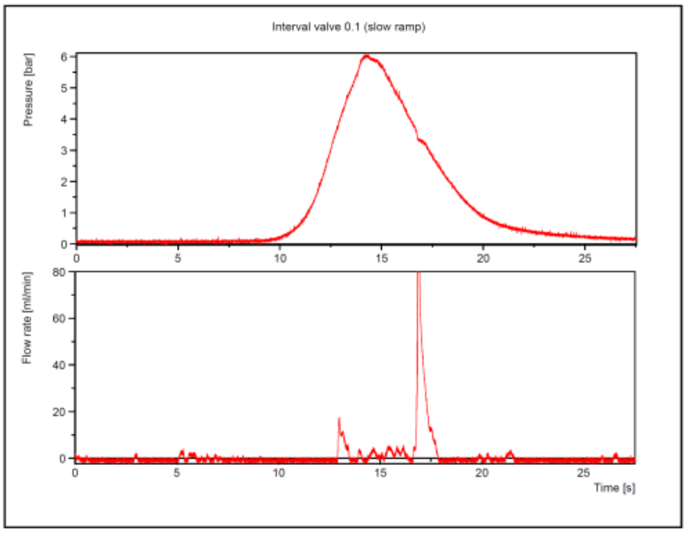

Figure 8.5 Slow ramp-up for the De-air interval valve with 0.1mm gap.

8.1.3 Lock valve

Figure 8.6 shows a pressure ramp-up cycle for the Lock valve. A small leakage can be seen after approximately 4 seconds which could be due to the lock function, but investigating the lock function is difficult in this rig. For higher pressures the valve effectively limits the pressure at about 46 bars.

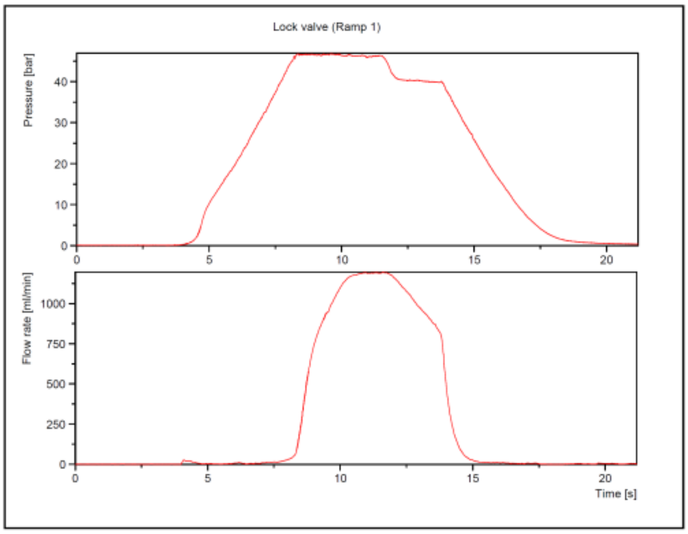

Figure 8.6 Ramp-up cycle for the Lock valve.

Another interesting outcome of this test was that the Lock valve had a significantly lower noise level when limiting the pressure than the Gen V overflow valve.

8.2 Modified Gen V housing

In this rig only the De-air interval valve and the Lock valve was tested to see how long it would take to de-air the coupling. Before running the pressure cycles the piston chamber was drained by removing the pump. After reinstalling the pump the drained oil was poured back in the system and a pressure cycle was performed to investigate how long time it would take to completely de-air the piston chamber.

8.2.1 De-air interval valve

For the De-air interval valve the pressure was altered between 2 and 10bars at 3Hz. The test run was filmed and from the video the time it took to de-air the coupling could be extracted. The time from then the pump first started until when air bubbles no longer could be seen in the transparent hose was less than 10 seconds.

When running the valve in this rig a narrow unstable pressure span was found during pressure build-up.

8.2.2 Lock valve

When testing the Lock valve the pressure was altered between 0-10bars at 1Hz. The tests revealed that the lock function of the valve was a slow process, de-airing took more than 40 seconds due to that the bled off volume at each cycle was small.

8.3 Cost and mass

The mass and the estimated cost of the valves are shown in table 8.1. The costs are estimated in relation to the Gen V valve for full scale production, in collaboration with the purchase department at BorgWarner.

Table 8.1 Mass and estimate cost for the valves.

	Gen V overflow valve	Simplified overflow valve	Interval valve	Lock valve
Mass (g)	31	2	32.5	50
Estimated cost (%)	100	35	98	594

9 Conclusions and Future Work

This chapter includes conclusions of the results and future work regarding what would be interesting to look further into for each valve.

9.1 Conclusion

The objective for this master thesis was to investigate new or alternative solutions to bleed the hydraulic system aiming at cost and weight reduction. The result shows that it is possible to simplify the current solution and that it might be possible to use a different type of bleed valve. To simplify the valve would mainly lead to cost reduction. Changing the type of valve could also reduce the cost, but additionally avoid bleeding at high pressures and flow rate and thereby reducing the sound level. To bleed at a lower pressure would also result in a more frequent bleeding of the system which might be advantageous for some driving conditions.

The simplified overflow valve proved to work as intended even if it didn't performed quite as good as the current overflow valve. The concept showed that the number of parts and the size can be reduced while maintaining the same function if it could be mounted from inside the coupling. This would however mean that it can't be made as a separate component and thereby not be tested before assembling.

For bleeding at a lower pressure the de-air interval valve proved to be a good solution. The concept can be made as a separate component that can be tested separately before assembling as the current valve. The design of the valve body is close to the current and the cost estimation revealed that there are no major possibilities for cost or weight savings. The function was satisfying even if the tests revealed that the valve was instable for a very narrow pressure interval when the pressure was increased slowly. When the ball changed seat the valve emitted a faint clicking sound, much lower than the sound for the Gen V valve.

The lock valve had, as expected, no advantages regarding the cost due to its complexity and narrow tolerances to make the slide fit. It did however limit the pressure at a constant level and the lock function also worked even if the bled off volume was very small. Worth noticing is also that it didn't emit as much noise when opening at max pressure as the Gen V valve or the simplified valve.

9.2 Future work

The simplified overflow valve and the De-air interval valve functioned as intended and are considered as interesting solutions to replace the current valve. Their geometry does however need further consideration to assure that their performance satisfies the specifications.

9.2.1 Simplified overflow valve

The spring preload or inlet area must be adjusted to acquire a more accurate opening pressure at 44 bar. The valve seat also needs to be improved to make sure that there aren't any leakage just before the valve opens. If the valve is to be mounted from the inside further work regarding the redesign of the housing is needed. The expansion process to secure the valve seat didn't work as smooth as desired so some further work considering the angles and the geometry of the tool needs to be done to ease the mounting.

9.2.2 De-air interval valve

The tests showed that the gap around the ball is critical for the function of the valve. The instability of the valve can most likely be eliminated by changing the inner geometry. A CFD analysis where the gap, ball size, spring force, distance between the seats and the area of the in- and outlet can be changed would be a good way to get a better understanding of how the valve works and thereby optimize its geometry.

If the cost of the interval valve is to be lowered, the outer geometry of the valve could be redesigned to be more integrated in the housing in a similar way as the simplified overflow valve.

9.2.3 Lock valve

The cost of the Lock valve will most likely never be competitive with the current valve. If the function however is desired, the geometry of the valve needs to be simplified to the greatest possible extent.

9.3 Reflections

The work flow went along as planned except the time it took to get the prototypes delivered. This was something that was hard to predict since it had to do with how the parts was prioritized at the manufacturer. The planned time schedule and the actual outcome are presented in appendix E.

At the beginning of the project it wasn't stated clearly if prototypes were to be produced but when the opportunity arose and prototypes were evaluated this made the result more substantial and was well received by BorgWarner.

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Appendix A: Leakage calculations

A.1 Equations and explanation of symbols

The leakage flow can be derived from equation (A1) [16]. The parameters are illustrated in figure A1 and described in table A1.

$$q_l = \pi v r h_0 + \frac{\pi r h_0^3 \Delta p}{6 \eta L}\left(1 + 1{,}5\left(\frac{e}{h_0}\right)^2\right) \tag{A1}$$

Table A1 Explanation of parameters.

Parameter	**Name/Explanation**	**Unit**
q_l	Leakage flow	m^3/s
v	Relative velocity	m/s
r	Radius	m
l	Length	m
$\Delta p = p_1 - p_0$	Pressure difference	Pa
e	Eccentricity	m
$h_0 = (h_1+h_2)/2$	Average gap	m
η	Dynamic viscosity	Ns/m^2

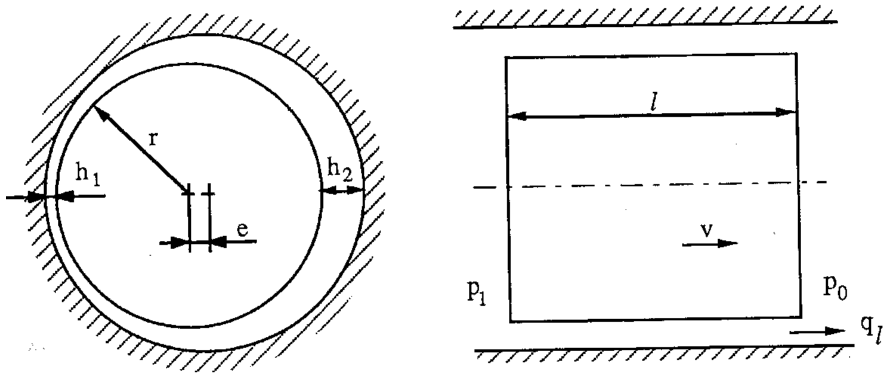


Figure A1 Illustration of the parameters.

A.1.1 Calculations

In this case, since the relative velocity is relatively low, it can be neglected.

Insertion of the values according to table A2 in equation A1 results in a leakage flow of $4.28*10^{-7} m^3/s$ or 26ml/min.

Table A2 Parameter values.

Parameter	Value	Unit
r	3,0E-03	m
h_0	1,5E-05	m
Δp	4,0E+06	Pa
e	1,5E-05	m
η	2,8E-02	m^2/s
L	4,4E-03	m
v	0,0E+00	m/s

$$\frac{\pi * 0.003 * 1.5 * {10^{-5}}^{3} * 4 * 10^{-6}}{6 * 0.028 * 0.0044}\left(1 + 1.5\left(\frac{1.5 * 10^{-5}}{1.5 * 10^{-5}}\right)^{2}\right) = 4.28 * 10^{-7} m^3/s$$

Appendix B: Spring calculations and data

Calculations for the four different springs used in the final designs.

The spring force(F) is related to the pressure(P) and the area(A) subjected to it according to equation (B1) [14].

$$P = \frac{F}{A} \Leftrightarrow F_{Spring} = P * A_{Inlet} \tag{B1}$$

The rate of a spring can be derived according to equation (B2), where k is the spring rate and x the displacement.

$$F = k * x \tag{B2}$$

B.1 Simplified overflow valve

The valve should limit the pressure to 44bar, with the inlet diameter of two millimeter this requires a spring force of 13.8N. The data is shown in table B1.

Table B1 Parameter values for the simplified overflow valve.

P	44	Bar
d	2	mm
$A = \frac{d^2 * \pi}{4}$	3.1	mm^2
F	13.8	N

B.1.1 Spring data for Lesjöfors compression spring 2871

The use of Lesjöfors compression spring 2871 pretensioned to 9.37mm satisfies the specifications. The spring data is shown in table B2.

Table B2 Parameter values for Lesjöfors compression spring 2871

F	18.8	N
L	7.7	mm
L_0	14.1	mm
Wire diameter	0.63	mm
Outer diameter	4.63	mm
Spring rate	2.95	N/mm

B.2 De-air interval valve

The distance between the inlet and outlet seat is one millimeter. The span between the opening pressure and closing pressure is desired to be approximately one bar. The values are shown in table B3.

Table B3 Parameter values for the De-air interval valve.

Parameter	**Value**	**Unit**
P_1	4,2	Bar
P_2	3,3	Bar
d_1	5	mm
d_2	6	mm
$A_1 = \frac{d_1^2 * \pi}{4}$	19.6	mm^2
$A_2 = \frac{d_2^2 * \pi}{4}$	28.3	mm^2
F_1	8.3	N
F_2	9.3	N

With the areas of the seats considered this requires a spring with a rate of approximately one newton per millimeter.

B.2.1 Spring data for Lesjöfors compression spring 2877

With the use of Lesjöfors compression spring 2877, data shown in table B4, the valve will open when the pressure exceeds 4.2bar and close when the pressure falls below 3.3bar.

Table B4 Parameter values for Lesjöfors compression spring 2877.

Parameter	**Value**	**Unit**
F	16.5	N
L	11.2	mm
L_0	27.2	mm
Wire diameter	0.63	mm
Outer diameter	5.63	mm
Spring rate	1.03	N/mm

B.3 Lock valve

This concept required two different springs and due to the limited space and specific forces needed there wasn't any standard springs that fulfilled the requirements.

B.3.1 Lock function

The spring that controls the lock function of the valve is working in the pressure span of two to five bars. The slide needs to move four millimeters in this pressure span in order to connect the pressurized volume to the outlet. The data for this scenario is shown in table B5.

Table B5 Parameter values for the Lock function.

Parameter	**Value**	**Unit**
P_1	2	Bar
P_2	5	Bar
d	6	mm
$A = \frac{d^2 * \pi}{4}$	28.3	mm^2
F_1	5.6	N
F_2	14.2	N

The specified forces and lengths requires a spring rate of 2.14N/mm.

B.3.1.1 Custom spring small

Since the operating lengths, forces and spring rate is very specific there isn't any standard spring that satisfies the requirements. A custom spring is ordered from Lesjöfors according to the spring data shown in table B6.

Table B6 Parameter values for custom spring small.

Parameter	**Value**	**Unit**
F_1	5.6	N
F_2	14.2	N
L_1	14.3	mm
L_2	10.3	mm
L_0	18.4	mm
Wire diameter	0.5	mm
Outer diameter	3.6	mm
Spring rate	2.14	N/mm

B.3.2 Overflow function

The spring operating the overflow function of the valve is designed so that it requires a force of 124.4N to move the slide six millimeters from the position where it is in contact with the support plate. This is achieved at the maximum pressure of 44bar. The data is shown in table B7.

Table B7 Parameter values for the overflow function.

Parameter	**Value**	**Unit**
P	44	Bar
d	6	mm
$A = \frac{d^2 * \pi}{4}$	28.3	mm^2
F	124.4	N

B.3.2.1 Custom spring large

There is no standard spring that fulfills the desired specifications, a custom spring is ordered from Lesjöfors with spring data according to table B8.

Table B8 Parameter values for custom spring large.

Parameter	**Value**	**Unit**
F_1	88.9	N
F_2	124.4	N
L_1	23.5	mm
L_2	17.5	mm
L_0	38.5	mm
Wire diameter	1.3	mm
Outer diameter	9	mm
Spring rate	5.92	N/mm

Appendix C: Test Results

Test results gathered from DIAdem extracted from the pump rig. The graphs shows flow rate and pressure relative to time.

C.1 Gen V overflow valve

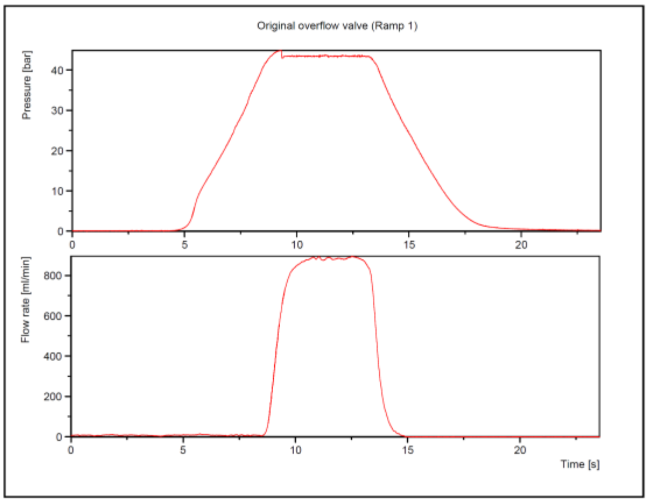


Figure C1 Gen V overflow valve ramp-up 1.

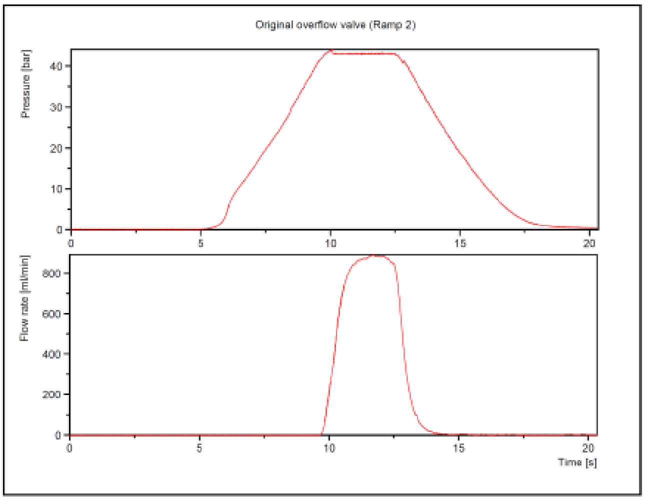


Figure C2 Gen V overflow valve ramp-up 2.

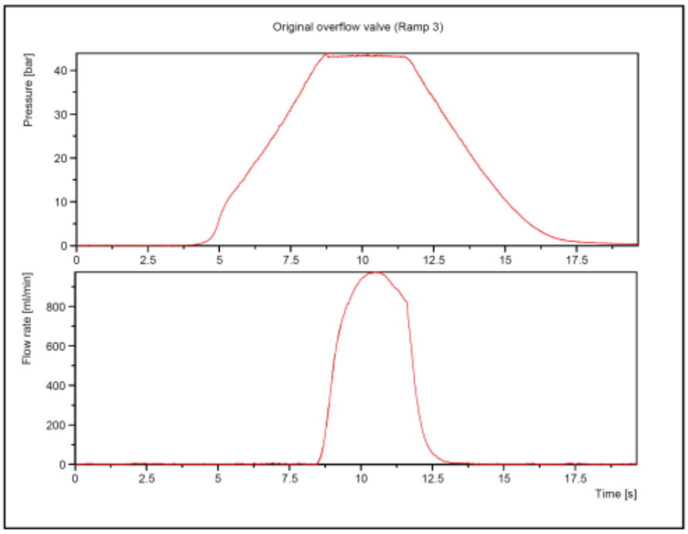


Figure C3 Gen V overflow valve ramp-up 3.

C.2 Simplified overflow valve

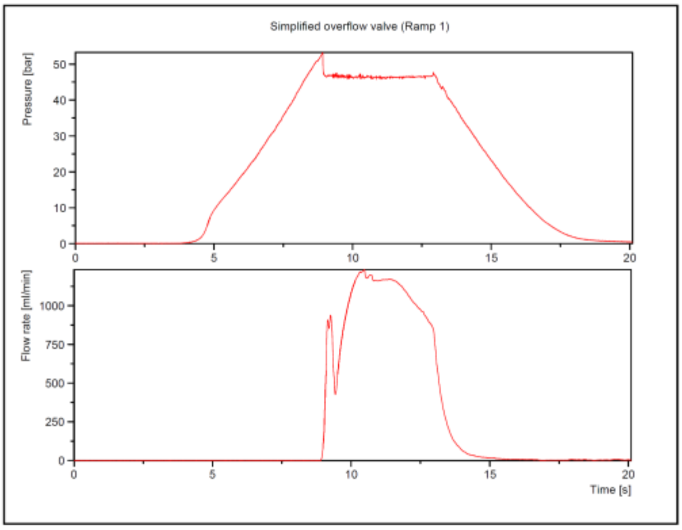


Figure C4 Simplified overflow valve ramp-up 1.

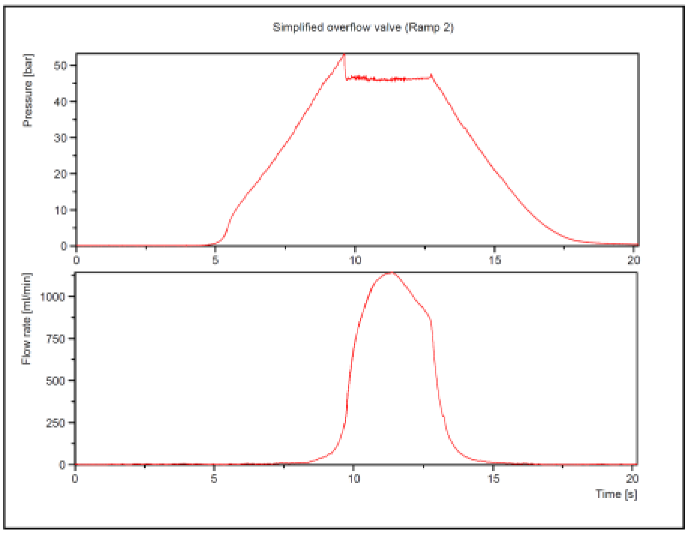


Figure C5 Simplified overflow valve ramp-up 2.

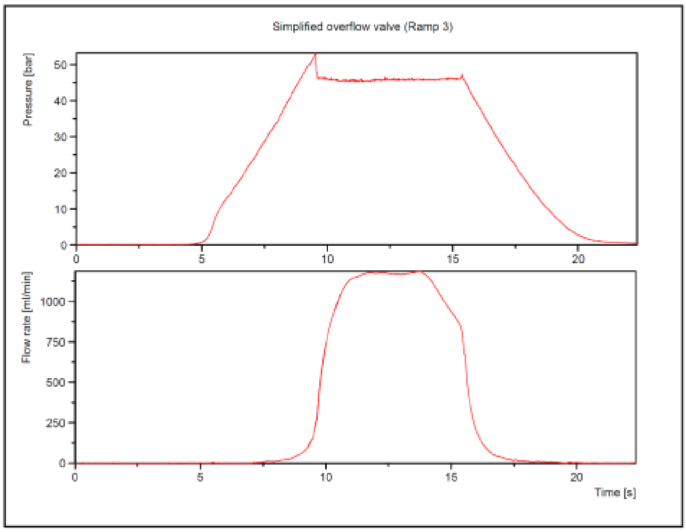


Figure C6 Simplified overflow valve ramp-up 3.

C.3 De-air interval valve

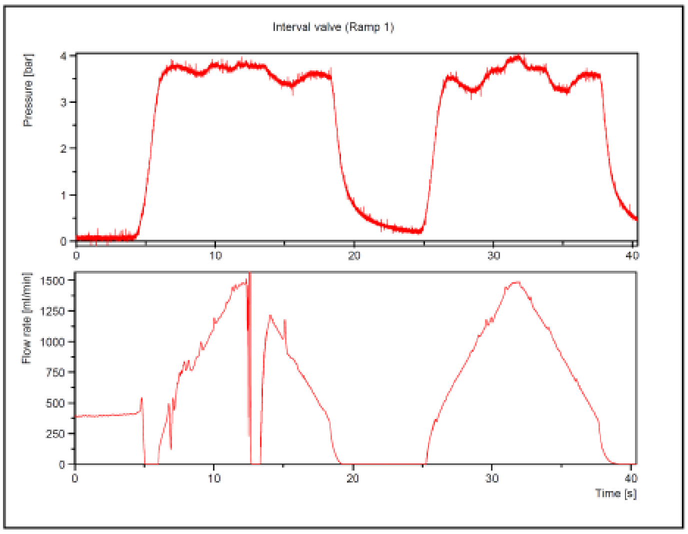


Figure C7 De-air interval valve (gap 0.25) ramp-up 1.

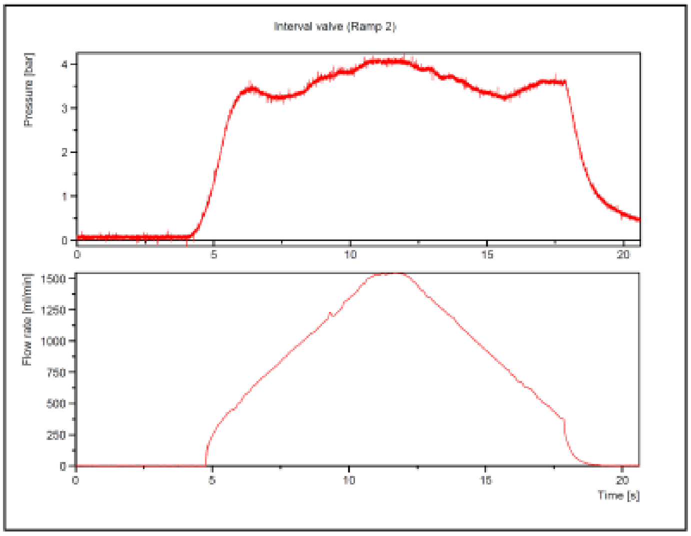


Figure C8 De-air interval valve (gap 0.25) ramp-up 2.

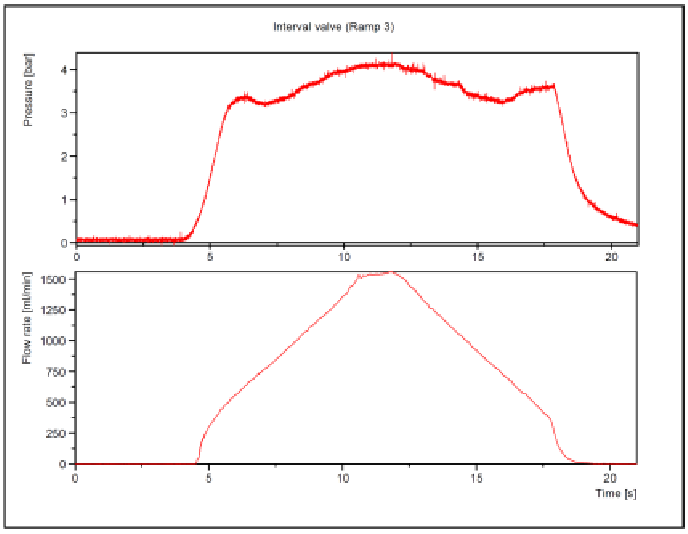


Figure C9 De-air interval valve (gap 0.25) ramp-up 3.

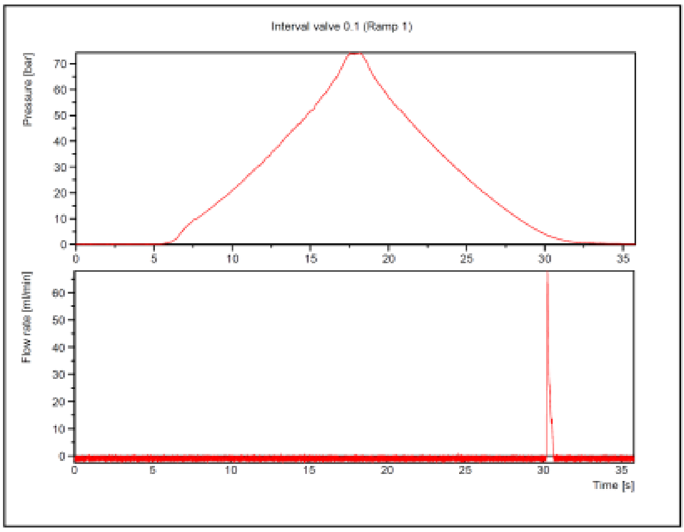


Figure C10 De-air interval valve (gap 0.1) ramp-up 1.

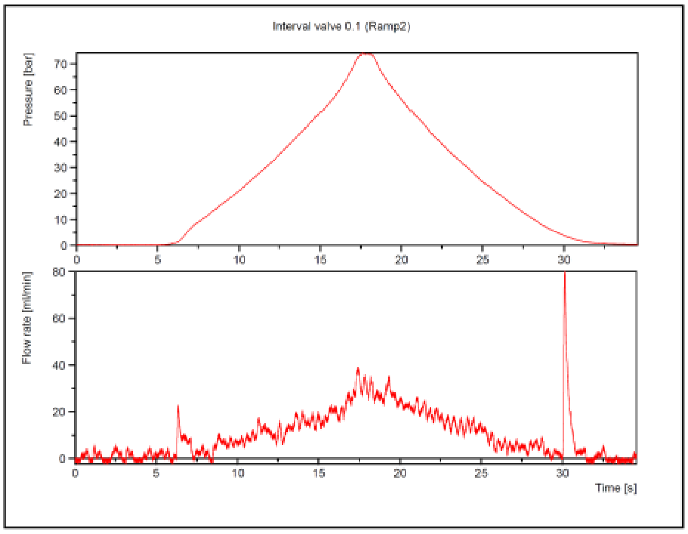


Figure C11 De-air interval valve (gap 0.1) ramp-up 2.

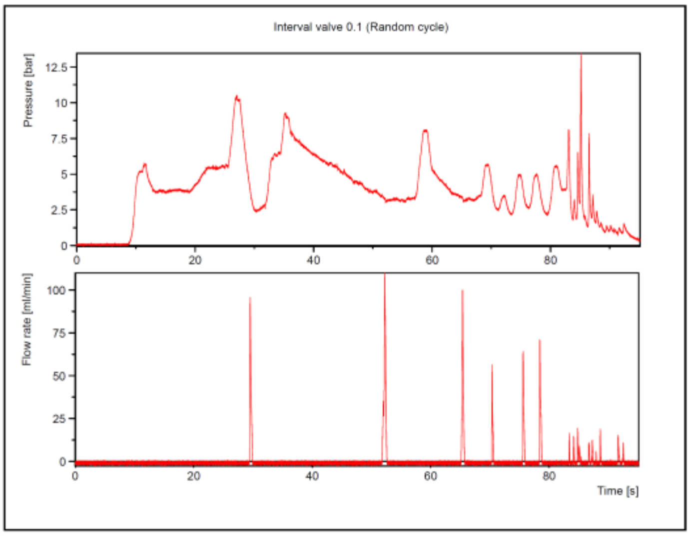


Figure C12 De-air interval valve (gap 0.1) random cycle.

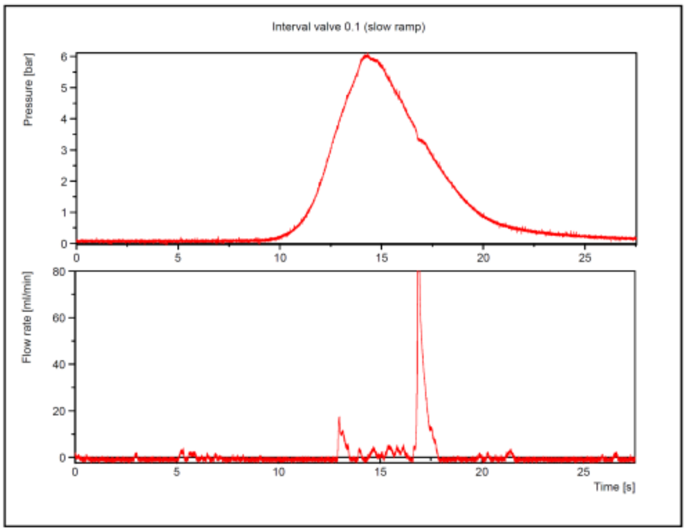


Figure C13 De-air interval valve (gap 0.1) slow ramp-up.

C.4 Lock valve

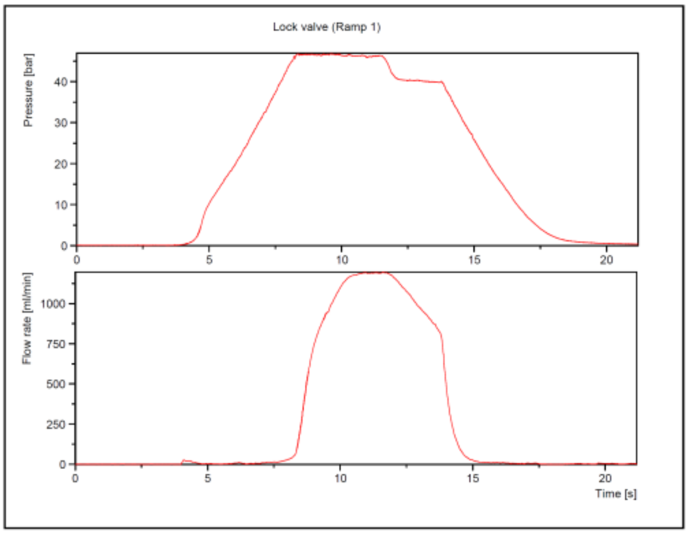


Figure C14 Lock valve ramp-up 1.

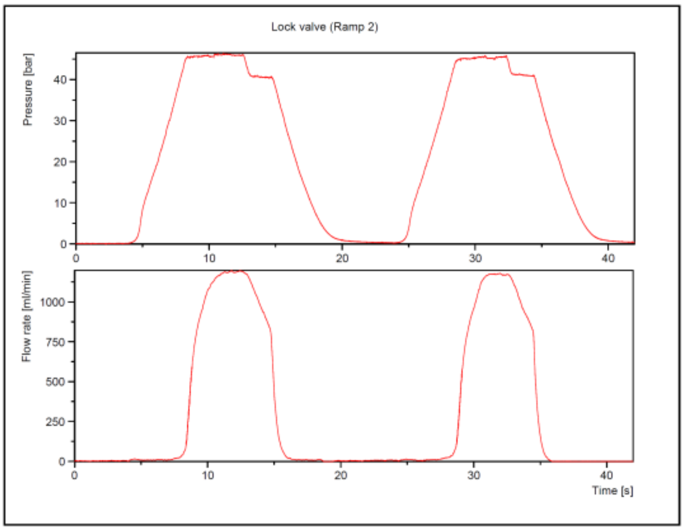


Figure C15 Lock valve ramp-up 2.

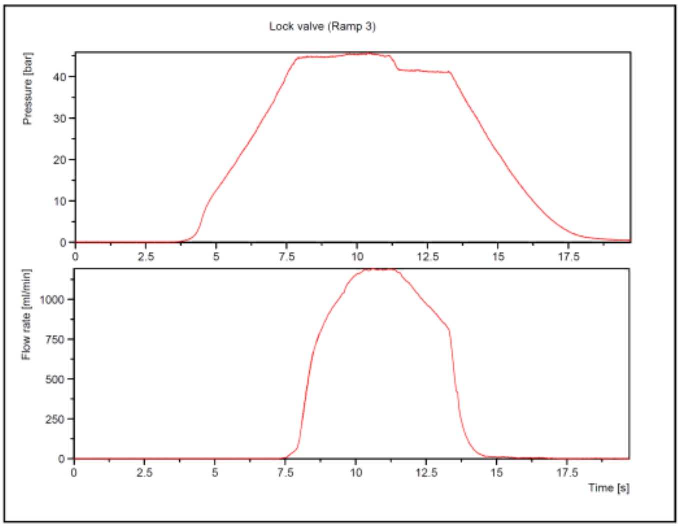
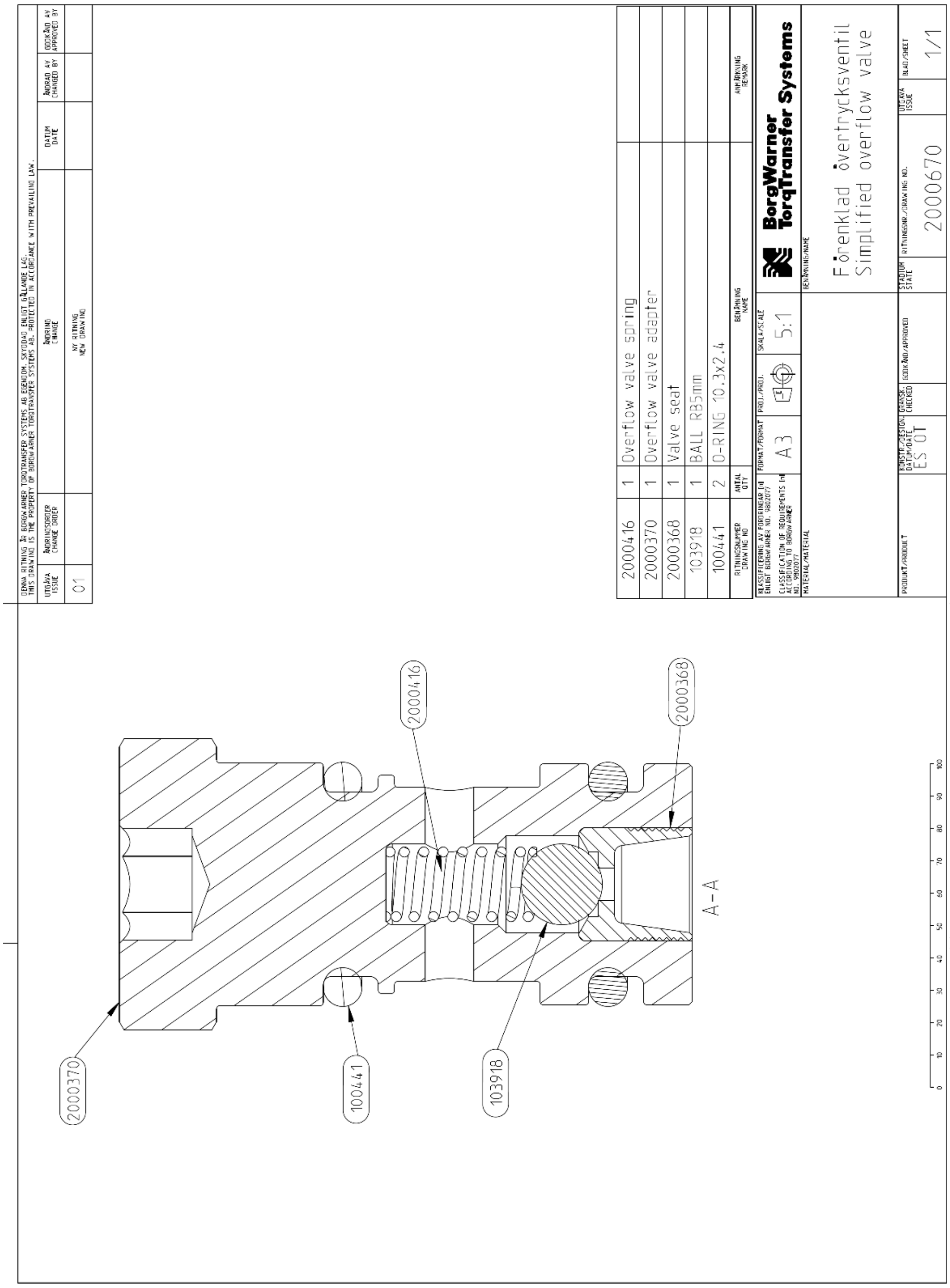


Figure C16 Lock valve ramp-up 3.

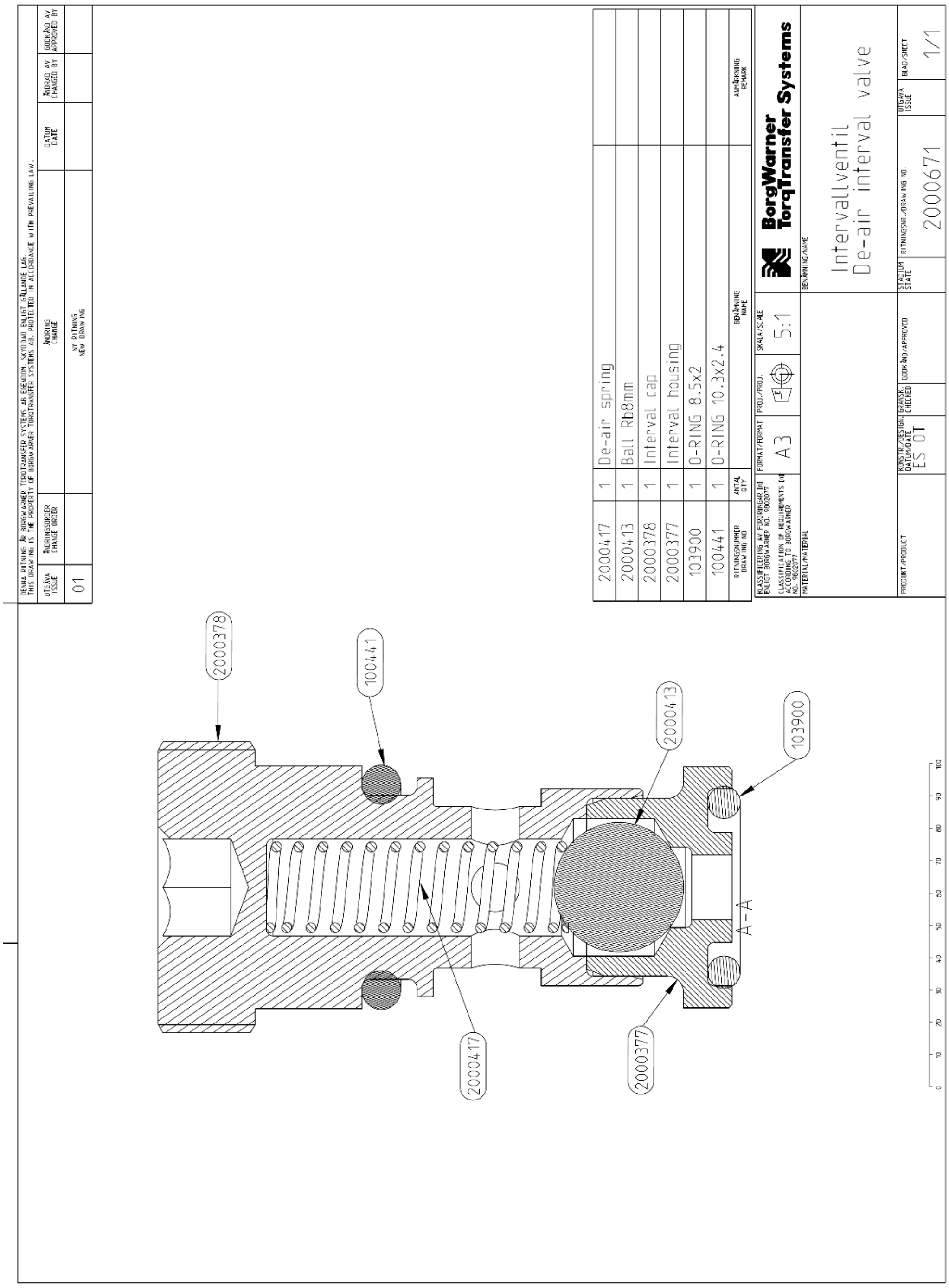
Appendix D: Assembly Drawings

Assembly drawings of the final designs.

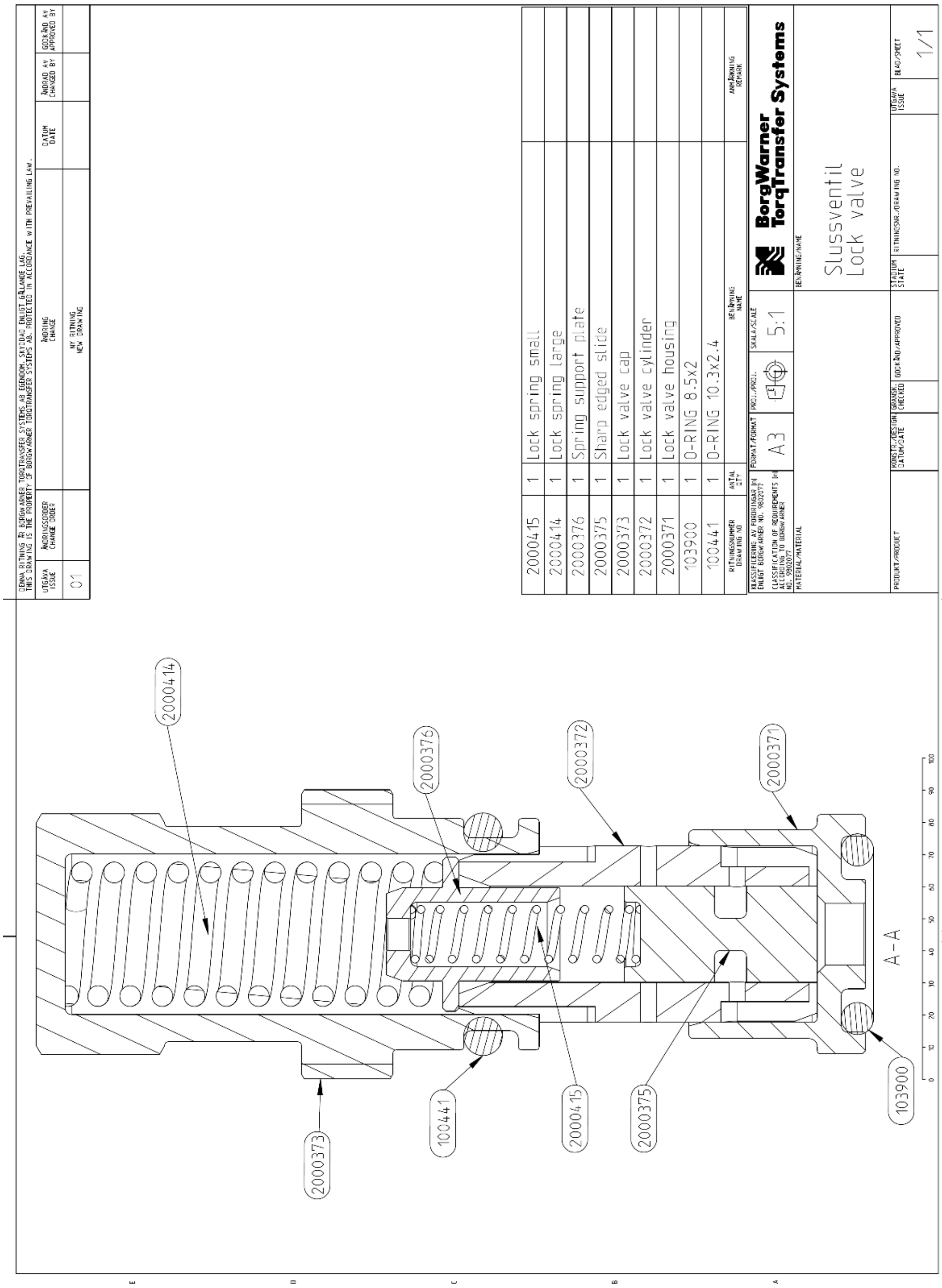
D.1 Simplified overflow valve



D.2 De-air interval valve



D.3 Lock valve



Appendix E: Work Distribution and Time Schedule

The work throughout this thesis was distributed evenly. The writing was done on a shared desk due to lack of space at the office, which naturally led to that both of us was included in all steps of the project. During the concept generation some work was done individually but the concepts were then discussed and developed together and in cooperation with our supervisor at BorgWarner.

The planned time schedule and the actual outcome is presented in figure E1 and E2.

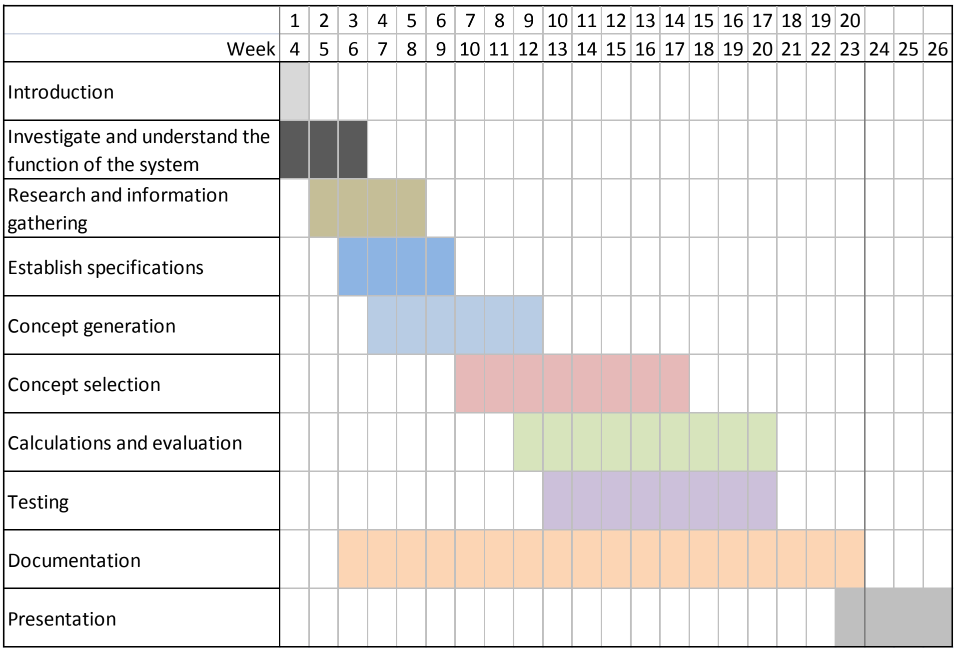


Figure E1 Planned time schedule

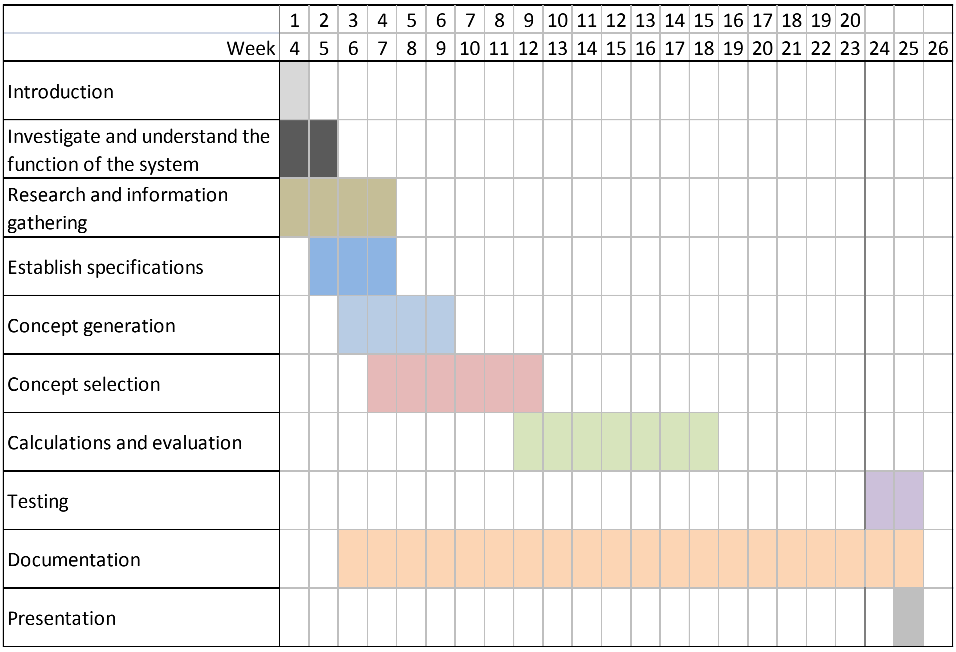


Figure E2 Time schedule outcome