University of Southern Queensland
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Disposable stormwater sampling device for water quality hazard detection

A dissertation submitted by
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ABSTRACT

Flow-weighted stormwater sampling is typically performed by large passive sampling devices or by automatic sampling equipment. While effective these systems often require significant effort to deploy and automatic samplers in particular can be expensive preventing widespread deployment over a catchment. This study aims to develop a proof of concept prototype sampling device capable of being installed in urban pit drains. The device is to be small and simple enough for widespread deployment over urban environments to allow for the detection of localized water pollution hazards.

A compact flow splitting sampling device is designed and a prototype constructed for the purpose of performance testing under controlled conditions. The device performs well proving to be capable of flow splitting accuracy in the order of 3%. The stormwater sampling device is also tested for other performance characteristics. A subsystem of the device is capable of indicating the duration of a flow event accurate to around 2%. The device also proves to be adequately capable of protecting samples from contamination and sampling suspended solids.

The sampling device developed ultimately proves to be capable of satisfactory collection of flow-weighted stormwater samples. Design details for the device along with recommended future modifications are presented. It is expected that future work would see the device tested in the field to evaluate infield performance and reliability.

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ENG4111/ENG4112 Research Project

LIMITATIONS OF USE

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CERTIFICATION OF DISSERTATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Bryan F Triaca

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Signature:_________________

Date:_______________

ACKNOWLEDGEMENTS

I would like to start by thanking my supervisor Dr Ian Brodie for providing the initial idea for this project and his guidance and support in seeing it to completion.

I would also like to thank my employer Collier & Miller for providing me with the time and flexible working conditions I needed to complete my degree and this dissertation.

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1. INTRODUCTION

Stormwater sampling equipment and procedures are frequently required for the purpose of obtaining representative stormwater samples that may be analysed in a laboratory. Such testing when properly conducted enables scientist, engineers and relevant authorities to produce reliable stormwater quality data that can guide future actions in stormwater catchment management.

The simplest form of stormwater sample collection is the grab sample where by a sample jar is simply filled by hand from catchment runoff during a rainfall event. This procedure is adequate in many cases where single samples representing a single moment in time are considered adequate. The grab sampling procedure does however have some significant limitations. Grab sampling requires skilled personnel be onsite during rainfall events in order to catch samples. This is in many cases impractical and also potentially dangerous depending on the sampling location. Further to this the composition of the samples will frequently not be representative of the average stormwater pollutant concentration throughout the rainfall event. Finally if multiple samples are required from various locations it may not be possible for the available personnel to attend all sampling sites before the rain has passed and the runoff water drains away.

In order to overcome the shortfalls of manual grab sampling procedures many autonomous sampling devices have been developed. Broadly these include automatic samplers that frequently use a peristaltic pump to collect samples and passive samplers that are non-powered. Automatic samplers offer reliable and accurate time or flow weighted sampling and can collect many samples in a number of bottles during a sustained rainfall event. The primary limitation of automatic samplers is however there high cost making them unsuitable for widespread deployment and also making vandalism a concern in populated areas. (Harmel et al. 2006)

There are various passive sampling device designs that have been developed for the purpose of collecting runoff samples. These devices are often effective but can be time consuming to construct and deploy.

The focus of this project is to create and test a new compact stormwater sampling device capable of being installed in an urban pit drain or similar location where runoff water falls vertically. It is hoped that the design concepts developed will provide a stormwater sampling solution that is cost effective and easy to use making devices based on such concepts suitable for wide spread deployment particularly in urban environments. Such devices could be spread across a catchment area and the results obtained from the analysis of collected samples could be used to identify catchment areas with unusually high pollution levels requiring further investigation.

1.1 Report structure

This reports focuses on the design construction and testing of a stormwater sampling device capable of being installed in an urban pit drain with the aim of developing the design to a proof of concept level. A summary of chapters is presented to aid in navigation of the report.

Chapter 2. Idea development

Existing sampling designs and sampling modes are considered.

Chapter 3. Project Objectives

Feasibility and consequences of the project are considered. The primary performance requirements of the sampling device are established.

Chapter 4. Sampling device design

Details of the components of the stormwater sampling device are presented.

Chapter 5. Flow Simulation Equipment

Details regarding the flow simulation performance requirements and design are presented along with the operating procedure.

Chapter 6. Performance Testing Procedures

Experimental procedures for testing the various performance parameters of the stormwater sampling device are presented.

Chapter 7. Results

Results from performance testing are presented and analysed.

Chapter 8. Discussion

Discussion of the adequacy of the stormwater sampling devices performance.

Chapter 9. Future design possibilities

A part by part review of the sampling device components with recommendations for future designs.

Chapter 10. Conclusion

Chapter 11. References

2. IDEA DEVELOPMENT

2.1 EXISTING WORK IN THE FIELD

The literature review presented in APPENDIX B revealed only one short report with similar goals to those set for this project. In the report by Dowling and Mar an attempt is made to make a flow weighted stormwater sampling device capable of collecting a representative flow-weighted stormwater sample. The device described is installed in a pipe culvert. Stormwater enters the device through a 0.84mm diameter needle orifice. The theoretical foundation of the device is that as the flow through the culvert increases the water level will rise above the level of the needle orifice providing greater head pressure to force a sample through the orifice. Testing of the device revealed it to be inadequate in terms of collecting a sample that is flow weighted due to there being a non-linear relationship between culvert flow and orifice collection rate. (Dowling, Mar 1996)

Conventional passive sampler designs are summarized by bent et al. (2001) and tested by Brodie and Porter. The broad categories of conventional designs as presented by Brodie and Porter include:

- Gravity flow samplers (Figure 2-1)
- Rotational flow samplers (Figure 2-2)
- Siphon flow samplers (Figure 2-3)
- Flow splitting samplers (Figure 2-4)
- Direct sieving samplers

(Bent et al. 2001), (Brodie, Porter 2004)

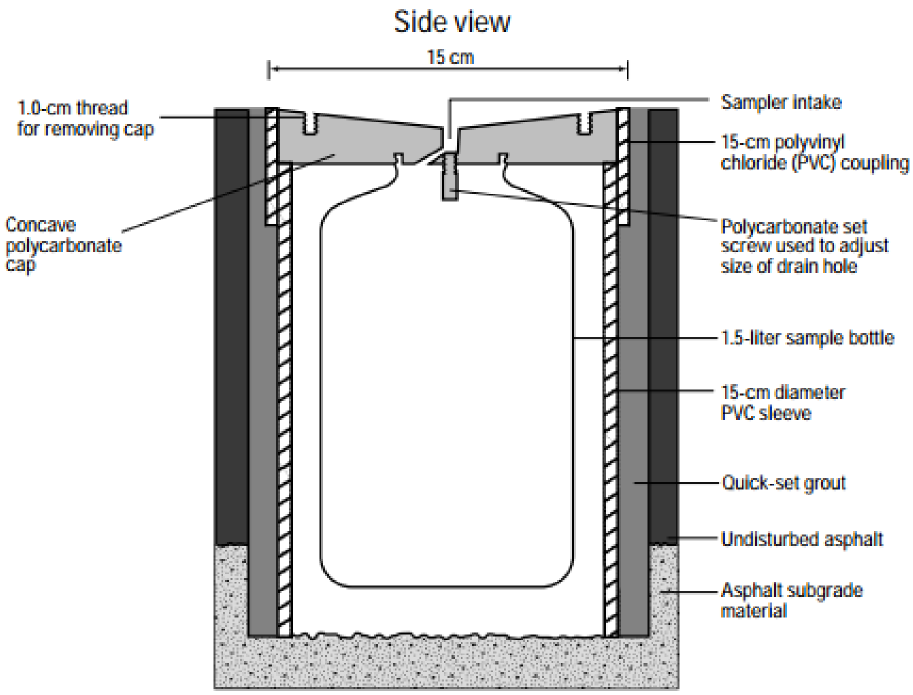


Figure 2-1 Gravity Flow sampler (Waschbusch, 1999)

Figure 2-2 Commercially available Coshocton wheel sampler, a type of rotational flow sampler (Open Channel Flow 2013)

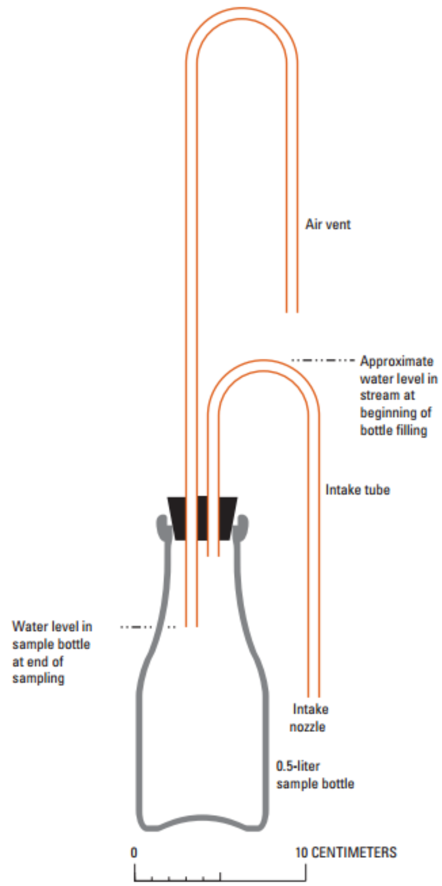


Figure 2-3 U-59A siphon sampler developed by the USGS in the 1950's (Diehl 2008, p1)

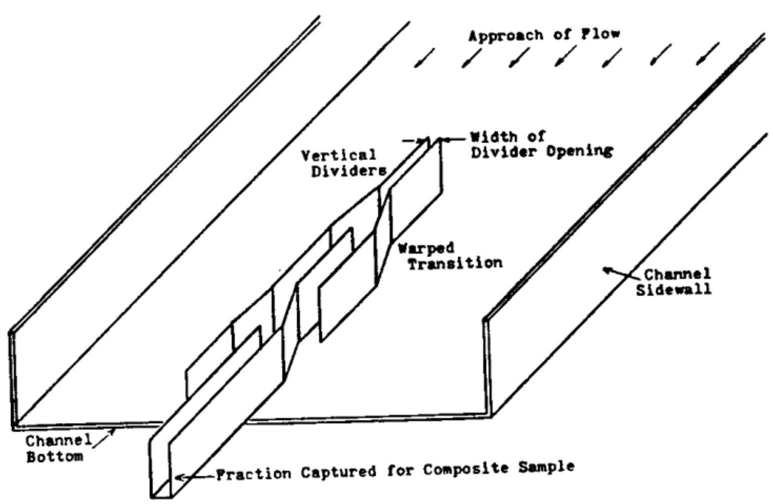


Figure 2-4 Flow splitting sampler (Clark & Mar 1980)

2.2 SAMPLE CAPTURING MODES

In order to gain an insight into the total quantity of pollutants being transported by stormwater runoff from a catchment it is necessary to be able to relate the concentration of pollutants to the stormwater discharge rate over the duration of the storm event. For this reason it is necessary to take multiple samples or a continuous sample over the duration of a storm event. Further to this samples may be collected as discrete samples or as composite sample.

When collecting discrete samples it is necessary to catch many samples and keep note of the time and discharge rate correlating to their time of capture. Composite samples consist of a single large sample collected over the duration of the event.

The frequency with which the samples are collected maybe in accordance with one of three sampling schemes: flow-weighted, time-weighted or user defined. (Weiss et al 2010)

2.2.1 Flow-weighted sampling

Flow weighted sampling for passive devices typically involves separating a constant fraction of the stormwater discharge which is stored to create a composite sample. The sample has pollutant concentration representing the mean concentration for the entire discharge volume. The volume of the collected sample can also be used to estimate the total discharge volume from the catchment. With this data the total mass of pollutant transported by the flow event can be calculated.

2.2.2 Time-weighted sampling

Time weighed sampling involves collecting discrete samples at pre-determined time intervals. It is necessary to be able to correlate the time and discharge rate corresponding to each sample so that the data can be later integrated to find the total pollutant discharge from the catchment. Time-weighted composite samples can also be collected although are only capable of accurately indicating average pollutant concentrations when sampling from constant flowrates.

2.2.3 User defined sampling

User defined sampling frequency may be used when taking manual grab samples or programmable automatic samplers. Samples are taken when certain conditions are met such as when flow velocity reaches a certain threshold.

(Weiss et al 2010)

2.3 Design direction

Investigating existing passive stormwater sampling equipment no existing designs are found that are readily adaptable for use in a pit drain where space is limited and water falls vertically as opposed to through a channel or pipe as is often the case in road side or agricultural field situations. It is decided to develop new concepts capable of capturing flow-weighted samples in the operating environment imposed by an urban pit drain. Chapter 4 details the concepts that are developed for testing.

3. Project Objectives

3.1 Objectives Overview

Broadly the objectives of this project are to develop and test concepts for a low cost stormwater sampling device and to report the findings. This is achieved by way of designing, constructing and testing a prototype.

3.2 Project feasibility

Review of the currently available literature suggests that there has been limited work conducted in effort to develop a compact, effective and low cost flow-weighted stormwater sampling device. Any progress towards developing and testing new concepts applicable to such devices will be of value given the current lack of working concepts.

Research of the existing passive sampler designs reveals several effective sampling methods though none that fulfil the desired specifications. Success of larger scale passive sampler designs bodes well for the viability of a scaled down system though challenges are to be expected.

Existing flow-weighted, passive stormwater sampling designs such as the Coshocton wheel sampler while effective tend to require a significant flow rate to operate and also require a significant amount of space and sometimes minor earthworks to install. In urban environments such as sealed carparks or streets such devices become impractical. Automatic samplers can frequently be deployed successfully in such environments, the disadvantage of automatic samplers is the cost of the sampler itself.

It is intended that the sampling device developed in this study will allow for true flow-weighted sampling with a low cost passive device in urban environments unsuited to existing passive devices. Owing to the low cost and readily deployable nature of such a device it would be possible to install many such devices in small catchments over an urban landscape to allow for the detection of localized pollution hazards.

3.3 Outcomes and benefits

This project aims to produce and test a proof of concept prototype stormwater sampling device capable of achieving the performance criteria set out in 3.4. The final prototype is not refined to a production ready state but is rather intended to provide a foundation for future development. Even though the project somewhat focuses on the production and testing of a physical prototype the outcomes and benefits of the project will be the information and experience gained that will contribute to the knowledge base of stormwater sampler design. The outcomes achieved by this project are.

- Development of new mechanisms and or adaptations of existing mechanisms from current passive stormwater sampler designs used to achieve the performance goal of a compact low cost sampling device.
- Quantifiable results describing the performance of the tested mechanisms. Results of practical testing reveal the strengths and weaknesses of the mechanisms tested. Based on the results generated it is possible to provide recommendations to direct future research in the development of similar mechanisms.

The information gained from this project has the potential to help advance the field of stormwater monitoring by helping to provide an additional tool for the cost effective collection of weighted stormwater samples.

3.4 Design Requirements

Core to the projects objectives are the features and functions that the prototype device is intended to have/perform. A review of the literature and practical consideration yielded six desirable qualities.

- Ability to capture a sample at a controlled rate over time.
- Ability to prevent contamination of a captured sample.
- Ability to capture a representative amount of suspended solids in the sample.
- Ability to indicate the duration of flow event.
- Low cost.
- Easy installation.

(Bent et al. 2001), (Brodie, Porter 2004), (Dowling, Mar 1996), (Harmel et al. 2006), (Weiss et al 2010)

3.4.1 Ability to capture a sample at a controlled rate over time

The primary function of the sampling device developed is to capture a stormwater sample over time. It is necessary to capture a sample over the duration of a storm event in order to gauge the total mass of pollutants that are transported away from the catchment area and into waterways during a storm event.

The major challenge in the design of passive flow-weighted samplers is reliably separating a small and constant fraction of the flow to be stored. Existing passive samplers such as the flow splitter and Coshocton sampler must handle all or at least a predictable portion of the entire water flow from the catchment for their mechanisms to accurately separate a fraction of the flow for sampling.

The requirement of handling the entire flow volume entering a drain pit significantly limits the stormwater flow volume that a flow weighted device can handle. The device that has been developed so far is expected to handle small flow rates as might be encounter in a small urban watershed during modest rainfall. A device capable of sampling from a higher flow volume would need to either be simply bigger or be supplied a flow that is split off from the main stormwater flow.

3.4.2 Ability to indicate the duration of flow event

This idea was suggested as a means to have the device provide some sort of indication of the duration of the sampling time. Such information could provide a means by which to compare the duration of a rain event to the actual device sampling time and determine average flow rates.

3.4.3 Ability to prevent contamination

Samples may become compromised if anything other than the stormwater should enter the collection vessel. Prior to sample collection it must be ensured that debris as well as insects cannot easily find their way into the device. Ideally the sampling devices would only be deployed a short time before an anticipated rain event to minimize the time in which contamination could occur.

After a sample has been collected it will need to be protected from contamination or dilution from further water flow. It will be necessary to collect samples soon after a rain event in order to have them preserved according to standard procedures, and sent to a lab for analysis. This quick removal from the sampling site allows minimal time for contamination but it is still desirable to have the sample sealed after capture.

3.4.4 Ability to capture a representative amount of suspended solids in the sample

An important stormwater quality parameter often measured is the quantity of suspended solids (TSS) present in the runoff. Unlike dissolved pollutants however suspended solids particles can settle out of a flow relatively easily. This is particularly true for larger particles. Brodie and Porter highlight the significance of specifying an upper limit to the particle size that a stormwater sampler should be expected to reliably sample and ultimately chose 500 µm for their work in developing a flow splitter design.

In the case of a pit mounted sampler the device will be subjected to whatever flows into the drain. (Brodie, Porter 2004)

3.4.5 Low cost

The cost of stormwater sampling can the possible scope of stormwater monitoring strategies (Harmel et al 2006). Of particular relevance to this project is the cost of purchasing and using sampling equipment. Automatic sampling devices generally cost thousands of dollars making wide spread deployment cost prohibitive. Likewise true flow-weighted passive sampling devices are often time consuming to install. One goal of this project is to produce a low cost solution to the collection stormwater samples that can provide preliminary pollutant data. This information can then be used to identify problem areas in a catchment area that require more detailed study using more sophisticated sampling strategies.

3.4.6 Easy installation

The need for the devices to be easy to install ties into the economic considerations of stormwater monitoring. The less time required for personnel to deploy and then retrieve sampling devices the lower will be the total cost of the stormwater monitoring program. The device developed focuses more on other performance requirements. Easy installation is expected to arise from the device being small and lightweight.

3.5 CONSEQUENTIAL EFFECTS OF THE PROJECT

The project is intended to produce results that may eventually be used to improve the effectiveness of stormwater sampling activities. By providing users with a cost effective means to take many flow-weighted water samples from across a catchment better decisions may be made in developing plans to combat water pollution from urban catchments.

It is not anticipated that this technology will pose a significate safety hazard to users. Deploying the devices will involve personnel working roadside and opening pit drains, but these hazards are easily minimized by observing standard safety procedures that the likes of council engineers or environmental scientists would already have well established.

It is anticipated that a commercially available version of the stormwater sampling device would be primarily manufactured from plastics derived from oil. The most likely polymers would be polyethylene or polypropylene. These materials are non-renewable but are reasonably recyclable.

4. SAMPLING DEVICE DESIGN

The performance requirements identified is section 3.4 present significant design challenges. The requirement for the device to be low cost eliminates the possibility of using electronics and pumps to measure flow rates and capture samples. The requirement to catch a flow-weighted sample as opposed to a time weighted sample eliminates the possibility of using a simple restricting orifice to catch a sample of manageable size.

To address the performance requirements it is chosen to pursue passive flow splitter design. A scaled down rotational flow splitting design similar to a Coshocton sampler was considered although it was expected that the system would not scale well down to the dimensions required and that the added complexity would defeat the desired low cost nature of the sampling device (United Stated department of Agriculture 2005).

Figure 4-1 presents the basic mechanism of the Coshocton wheel sampler. It was considered that a similar scaled down mechanism could be utilized for the purpose of producing a compact flow weighted device. In such a device incoming flow would be captured in an inlet reservoir and then directed towards the wheel at and appropriate angel. The concept was ultimately abandoned in favour of a flow splitting design due to concerns regarding the devices ability to operate with low flow volumes without stalling.

Additional to the sampler's primary function of capturing a flow weighted water sample it also has the ability to indicate the duration of a flow event. This function is achieved by a subsystem that essentially captures a small filtered time-weighted sample. As this sample is time-weighted its volume is proportional to the time over which it was collected.

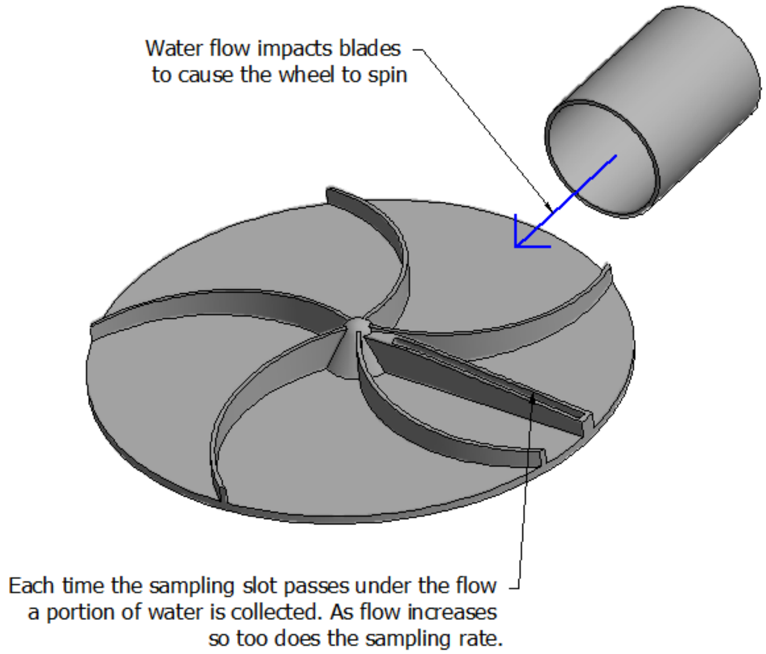


Figure 4-1 Simplified representation of Coshocton wheel sampler

4.1 Primary components

The stormwater sampling device consists of six primary components as can be seen in Figure 4-2. In addition to these six components is the flow duration indicator as a separate unit as can be seen in Figure 4-3.

The system is designed to be adjustable to allow for different sampling rates and for fine tuning to optimize performance.

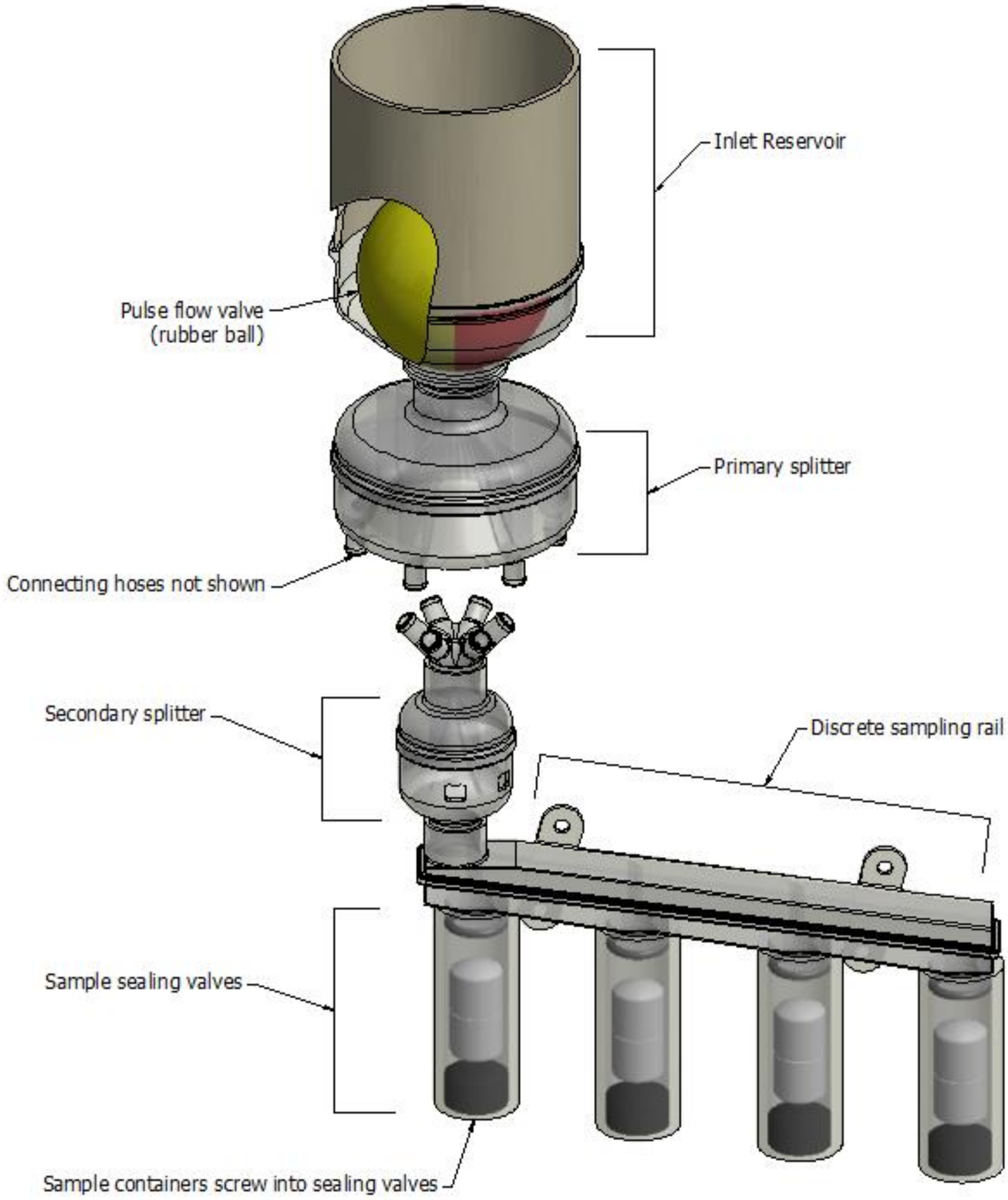


Figure 4-2 Stormwater sampler primary components

Figure 4-3 Flow duration indicator

4.1.1 Inlet reservoir

The inlet reservoir contains incoming water and directs it towards the primary flow splitter. The reservoir acts as a buffer to protect against water loss during momentary flow surges as well as housing the pulse flow valve. The inlet is designed with a top lip height 170mm above the throat of the primary splitter. When the splitter is handling high flow rates water can build up in the inlet reservoir increasing the head pressure at the flow splitter throat allowing water to be forced through the splitter throat faster. If required the inlet reservoir height can be further raised by fitting a length of PVC pipe.

At the base of the inlet reservoir is a male tapered fitting that fits into the throat of the primary splitter. The taper angle is 8° making it semi-locking allowing for easy assembly and disassembly during testing. A commercial version of the flow splitter would likely use a threaded connection between the upper reservoir and primary splitter affording a more secure connection and allowing the system to support the weight of a suspended sample bottle below.

4.1.2 Pulse flow valve

Proper operation of the primary flow splitter requires that the splitter throat be completely filled by the water flow so that the flow engages all of the splitter veins equally. Achieving this becomes a problem with small flow rates which tend to dribble down one side of the splitter resulting in wildly inaccurate splitting.

To allow the sampling device to accurately split small flow rates whilst still being able to handle larger flow rates a valve is used to block the splitter throat allowing water to accumulate in the intake reservoir. When enough water has accumulated in the inlet reservoir the valve suddenly releases a surge of water that can be accurately split. When the intake reservoir is emptied again the valve locks back into position stopping flow to the primary splitter.

The original design for the pulse valve consisted of a 3D printed valve float which sealed on an O-ring in the bottom of the upper reservoir as seen in Figure 4-4. The float is held down on the O-ring by its own weight and also by a pair of magnets only releasing when the buoyancy force is strong enough to overpower the magnetic couple. Unfortunately in practice as the water level rose in the upper reservoir the float would pry up off the seal causing it to leak. Various magnet configurations were tested to fix the problem to no avail. It is possible that the mechanism would work better if the sealing surface of the float was spherical instead of conical.

As an alternate method to achieve the intermittent flow characteristic required, several hollow rubber balls were trialled to replace the 3D printed valve float. A soft 50mm ball achieved excellent sealing against the O-ring but would never release allowing the water to overflow out of the inlet reservoir. A firmer 60mm ball never sealed at all unless held down manually. Finally a 93mm diameter ball was found that caused the desired flow behaviour. The balls diameter is such that it seals on the conical section of the intake reservoir. Unfortunately the seal between the ball and the conical surface sometimes leaks depending on the orientation of the ball. Because the ball is made of two halves of rubber it is slightly out of round. Figure 4-5 shows the ball arrangement.

The rubber ball valve dose not save up as much water volume as the original design was intended to, this creates some difficulty is achieving accurate flow splitting as the smaller pulse of water dose not as easily flood the throat of the flow splitter. To fix this a flow restricting bush is inserted to allow the smaller volume to properly fill the splitter throat, this dose however come at the cost of limiting the maximum flow the device can handle. The bush can be seen in Figure 4-5.

Despite the leaky nature of the valve it does work well enough for the proof of concept testing in this report, although it does set a minimum flow requirement for the tests. It is expected that the sealing performance of this design could be significantly improved if a ball was purposely manufactured to be more spherical than the bounce ball used. Having the ball seal on an edge or O-ring rather than on the tangent of the conical surface may also help.

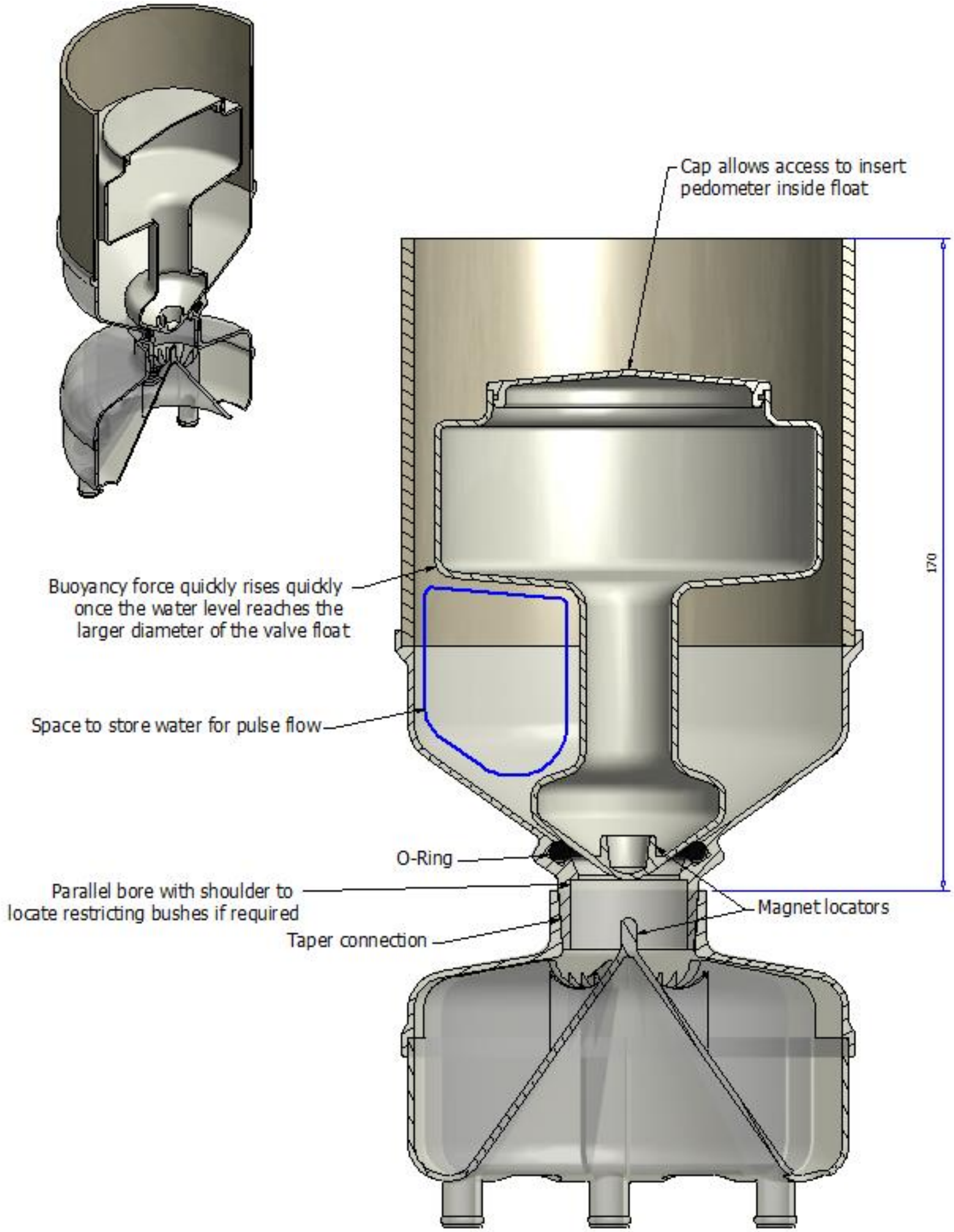


Figure 4-4 Cross section of Inlet reservoir, original pulse flow valve and primary splitter

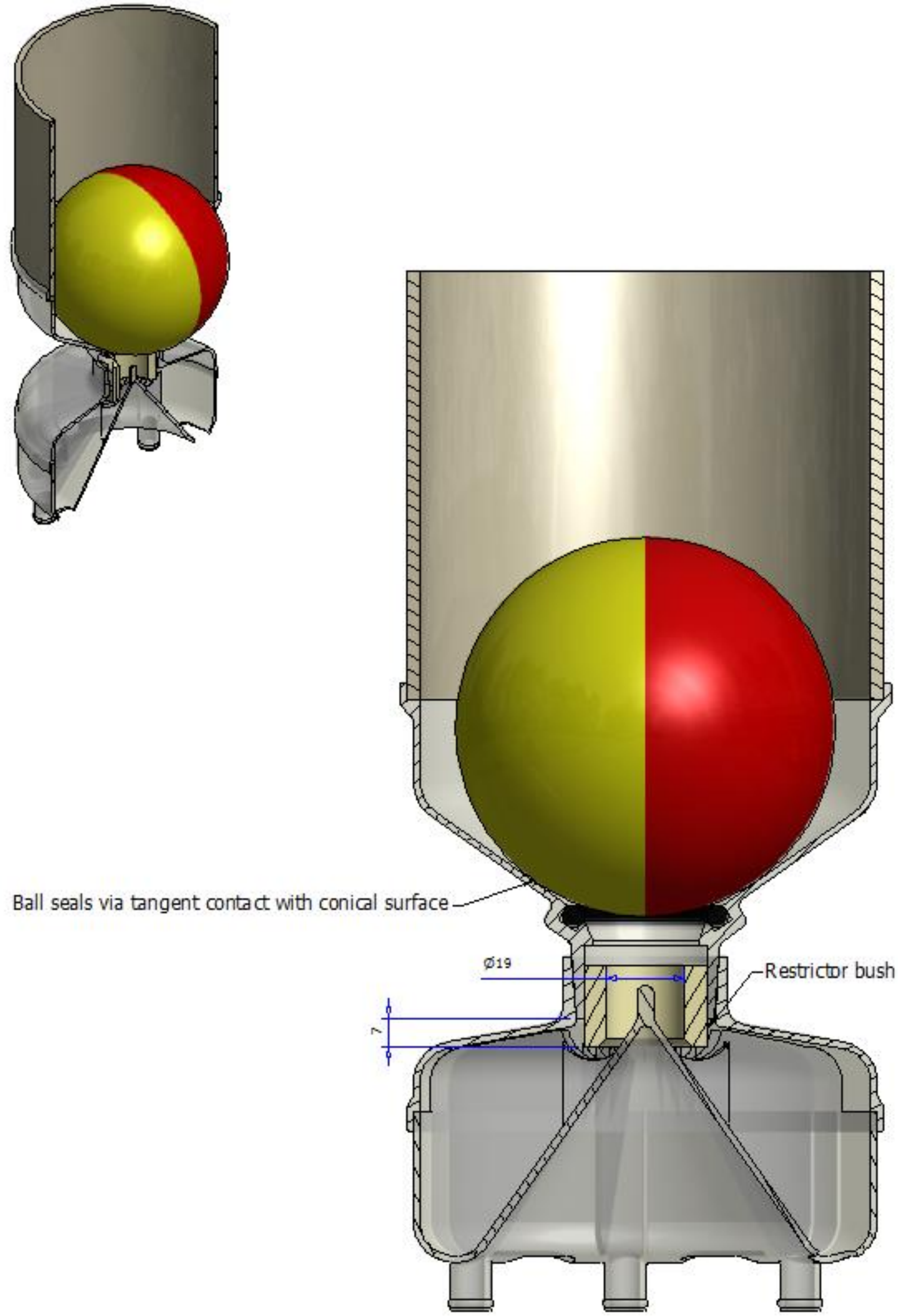


Figure 4-5 Cross section of Inlet reservoir, 93mm rubber ball and primary splitter with 19mm restrictor bush fitted

4.1.3 Primary flow splitter

The primary flow splitter takes incoming flow from the inlet reservoir and splits it 30 ways over 30 veins as shown in Figure 4-6. Although the veins create 30 flow paths for the split water 24 of them merge into dump ports which quickly release the water. Six of the flow paths lead to sample outlet ports, 10mm vinyl hoses are connected to the outlet ports. The fraction of water to be sampled is determined by how many of the ports are connected to either a sample bottle or the secondary splitter.

Due to the internal complexity of the primary flow splitter it was necessary to print the part in two parts as seen in Figure 4-6, otherwise the splitter would have been filled with difficult to remove support material.

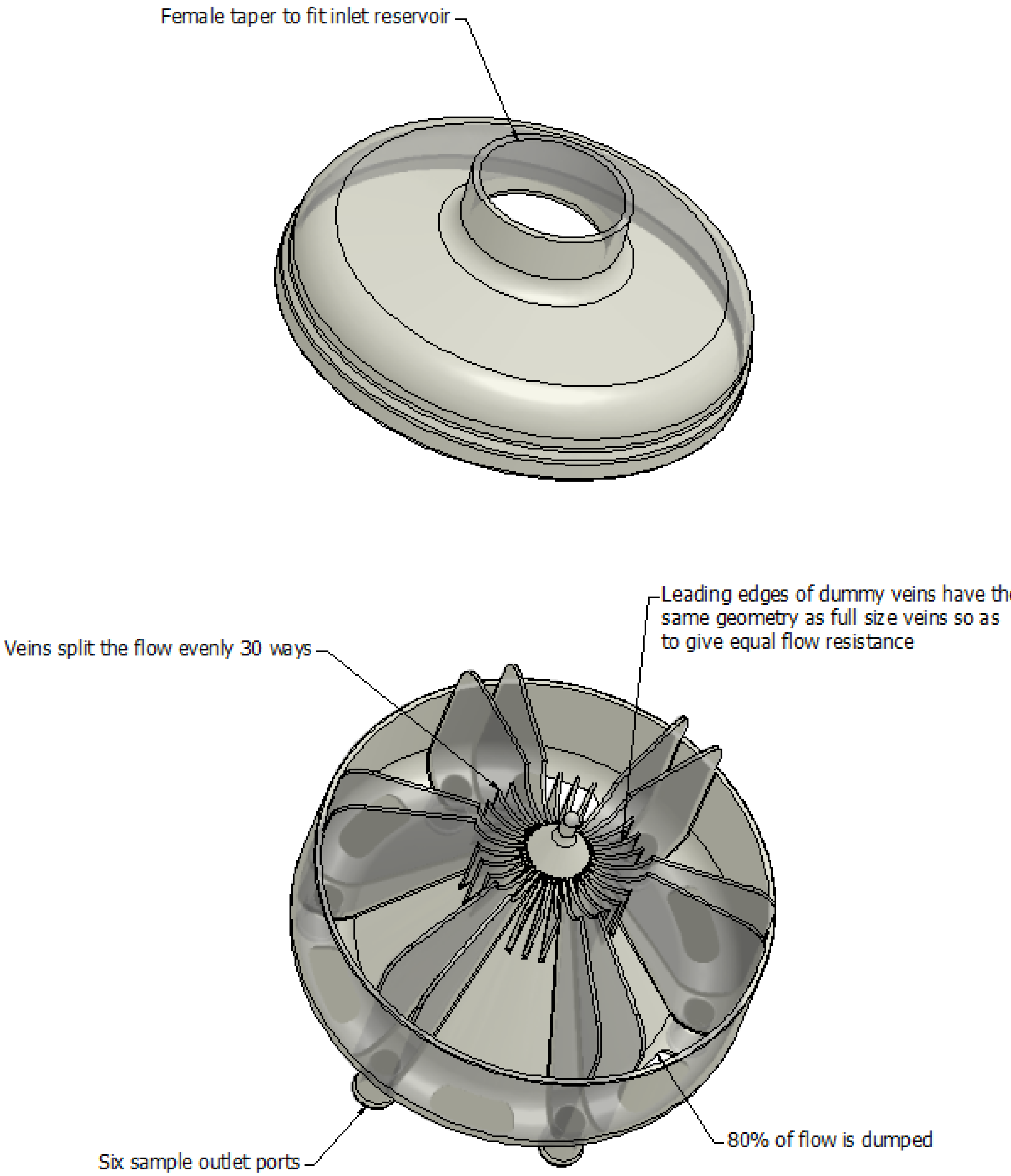


Figure 4-6 Primary flow splitter shown in two pieces

4.1.4 Secondary flow splitter

The secondary flow splitter as seen in Figure 4-7 is used to further split the flow from the primary splitter by a factor of five allowing for a theoretical minimum sampling rate of 0.667%. Unlike the primary splitter the secondary does not use hose connections for the outlet ports. Instead the sample flow is directed into a cavity underneath the splitting veins and then onto the outlet.

Like the primary splitter the secondary splitter was 3D printed, again due to complicated geometry it was necessary to construct the splitter in segments to allow the printing support material to be removed.

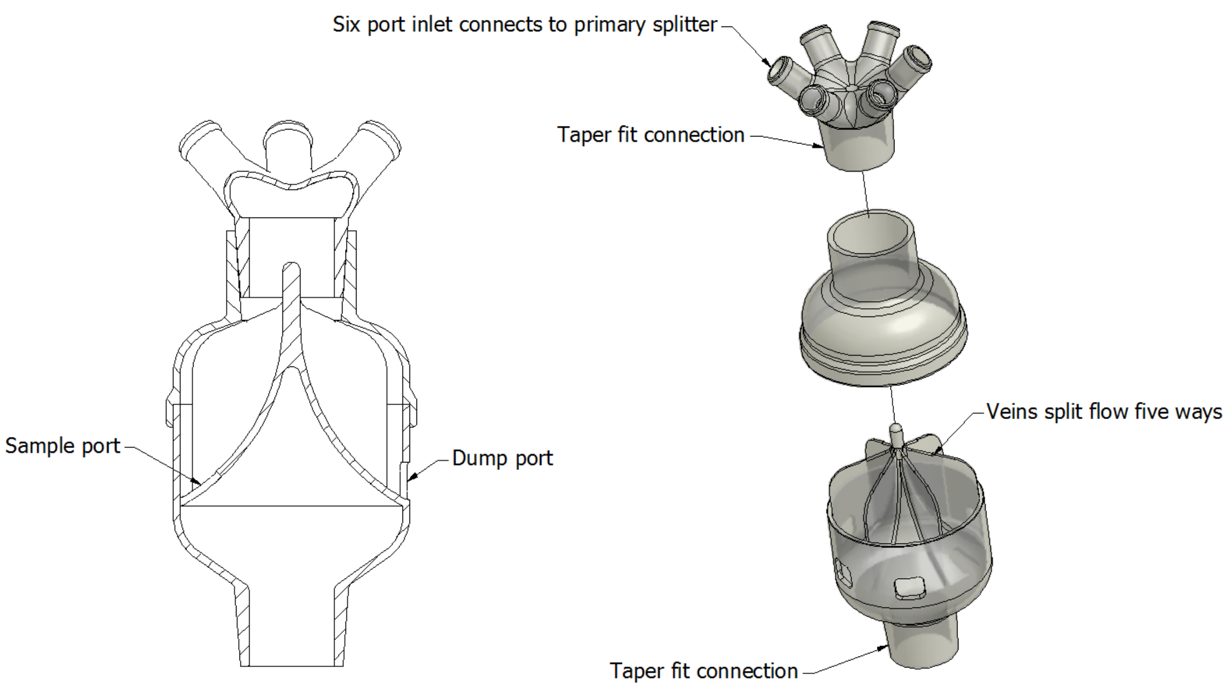


Figure 4-7 Secondary flow splitter

4.1.5 Discrete sampling rail

The stormwater sampling device provides the ability to catch multiple discrete samples throughout the duration of a flow event via an attachment that carries four sample bottles. Water entering the rail is directed over ports leading to the sample sealing valves, as seen in Figure 4-8. As the flow rates entering the rail are slow the water is unable to jump the port and so flows down through the sealing valve and into the sample bottle. Once the one sample bottle is full the sealing valve float locks into position and additional flow is then able to flow over the sample port and onto the next.

As with other components it was necessary to print the component in two halves to clear the support material. To aid with mounting the prototype rail for testing, tabs were added to allow the rail to be fastened in position.

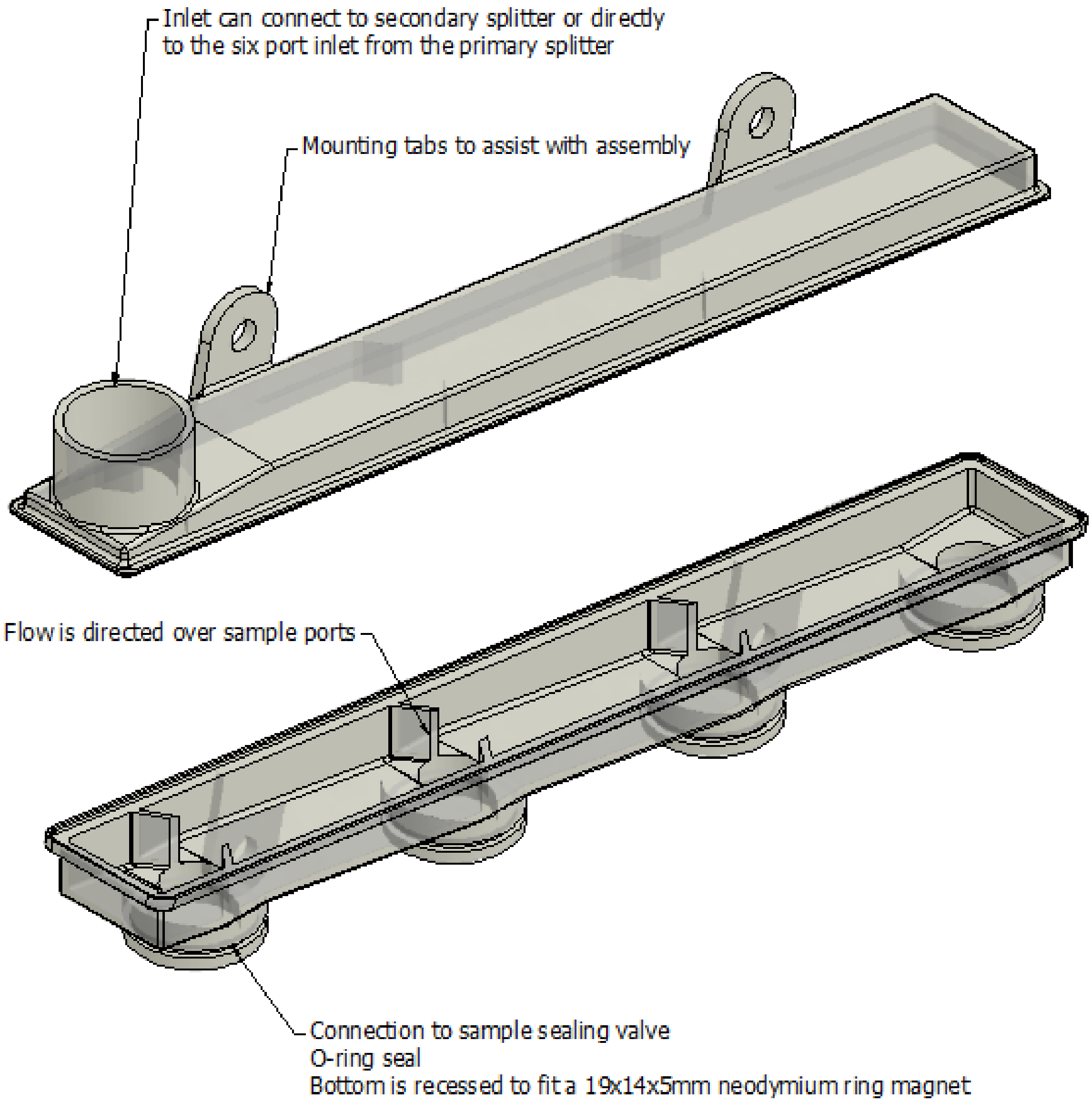


Figure 4-8 Discrete sampling rail

4.1.6 Sample sealing valve

The sample sealing valve seen in Figure 4-9 acts to positively seal the each sample container once completely filled. This is done to prevent sample contamination from continuing flow.

The main tube is 40x5mm acrylic, the acrylic has good optical properties allowing clear observation of the valve's operation during testing. The float is made from two 15mm PVC caps fitted on a short section of PVC pipe, a 19x10x1.5 ring magnet is trapped between the pipe section and the top cap. When the sample bottle is full the water level in the acrylic tube rises lifting the float until the magnet in the float couples with the magnet in the discrete sampling rail. The 22x4 O-ring is trapped between the float and rail magnet creating a positive seal.

For the prototype valve a PET bottle cap with a 16mm hole drill through the top is pressed into the bottom of the acrylic tube creating a sealed attachment point for the sample bottle. The sample bottles used for the purpose of prototyping are 750mm PET beer bottles, these are used as they are cheap and readily available.

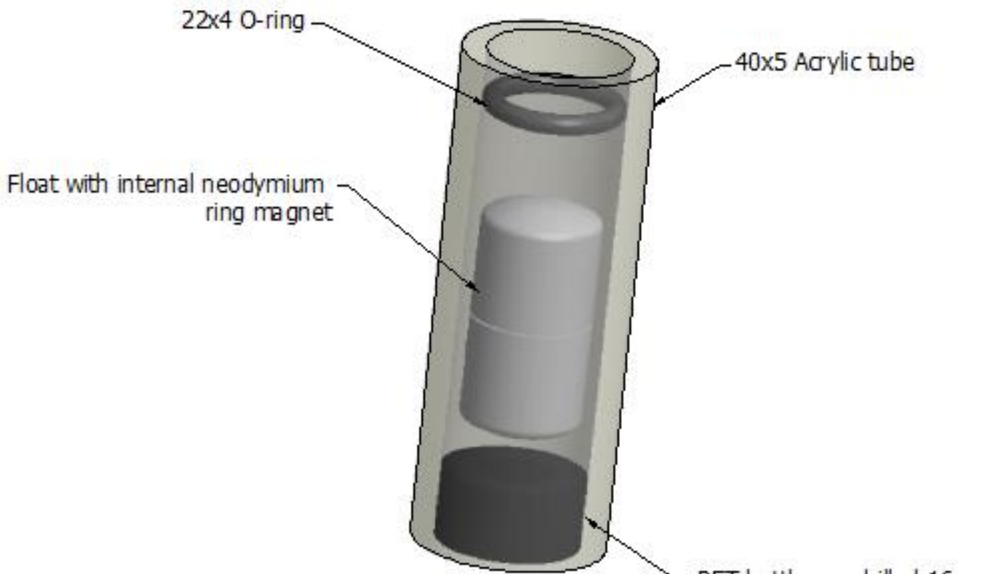


Figure 4-9 Sample sealing valve

4.1.7 Flow duration indicator

During the design stage of this project it was intended that indicating the duration of flow would be achieved by installing a pedometer inside the original float valve design as depicted in Figure 4-4. With this design an upper reservoir and float valve would be required in addition to those used for flow-weighted splitting. The reservoir and float valves used to indicate flow duration would be supplied with a constant flow rate which would cause the float to cycle at a constant rate. The pedometer installed in the float would then read a number of steps proportional to the duration of flow as the float cycled between the locked position and releasing. The benefit of this system would be that there would be no need to capture and measure a time weighted sample as the flow duration would be simply calculated from the pedometer reading.

As was discussed in section 4.1.2 the original float valve design failed to cycle and was eventually abandoned in favour of a rubber ball float. While the rubber ball does cycle it is poorly suited to carrying the pedometer and so the original flow duration indication method is also abandoned.

As a mechanism for indicating the flow duration was still required a new concept was developed to perform the task. The flow duration indicator as depicted in Figure 4-3 and Figure 4-10 was designed to reliably catch as small a time-weighted sample as possible. As this sample is time weighted its volume is proportional to the time over which it is captured.

4.1.7.1 Flow duration indicator components

- The intake at the top is made from a 90 to 50mm PVC reducer fitting holes around the perimeter allow water to escape quickly once the device is full thus maintaining constant heat pressure regardless of the incoming flowrate.
- A fibre filter made from a scouring pad is trapped between the white acetal spacer and the intake. The filter prevents particles from clogging the outlet needle.
- A spacer is machined from acetal to adapt the acrylic tube to the PVC fitting
- A acrylic tube as used in the sample sealing valves allows visibility into the device
- A PET cap is pressed into the acrylic tube to allow fitment of a sample bottle
- A 16 gauge needle is fitted through the PET cap to provide a restricted outlet. The end of the needle is squashed for further restriction
- Two breather hoses are fitted. The first ventilates the space under the filter as the filter prevents air from escaping when wet. The second ventilates the sample bottle. The breathers are 4mm silicone hose.

Figure 4-10 Flow duration indicator

5. FLOW SIMULATION EQUIPMENT

5.1 CONSTANT HEAD SUPPLY SYSTEM DESIGN REQUIREMENTS

Testing procedures for the stormwater sampling device require the delivery of known quantities of water at know flow rates. Further to these performance requirements are a host of other desired features to make the testing equipment safe, environmentally friendly and easy to use. These features include:

- Ability to recycle water for multiple test runs.
- Ability to easily determine quantity of water released in a test run.
- Ability to control flow rate.
- Ability to supply constant flow rate over duration of a test.
- Ability to easily and safely reset the test system.
- Ability to supply at least 150 L of water per test run.
- Ability to store test water when system is not in use.

The design developed to address these needs consists of a large Mariotte's bottle upper reservoir to supply a constant head of water which is drained into a lower reservoir. A crane scale suspends the upper reservoir allowing its weight to be recorded before and after a test run.

The layout used for the constant head supply system is presented in Figure 5-1.

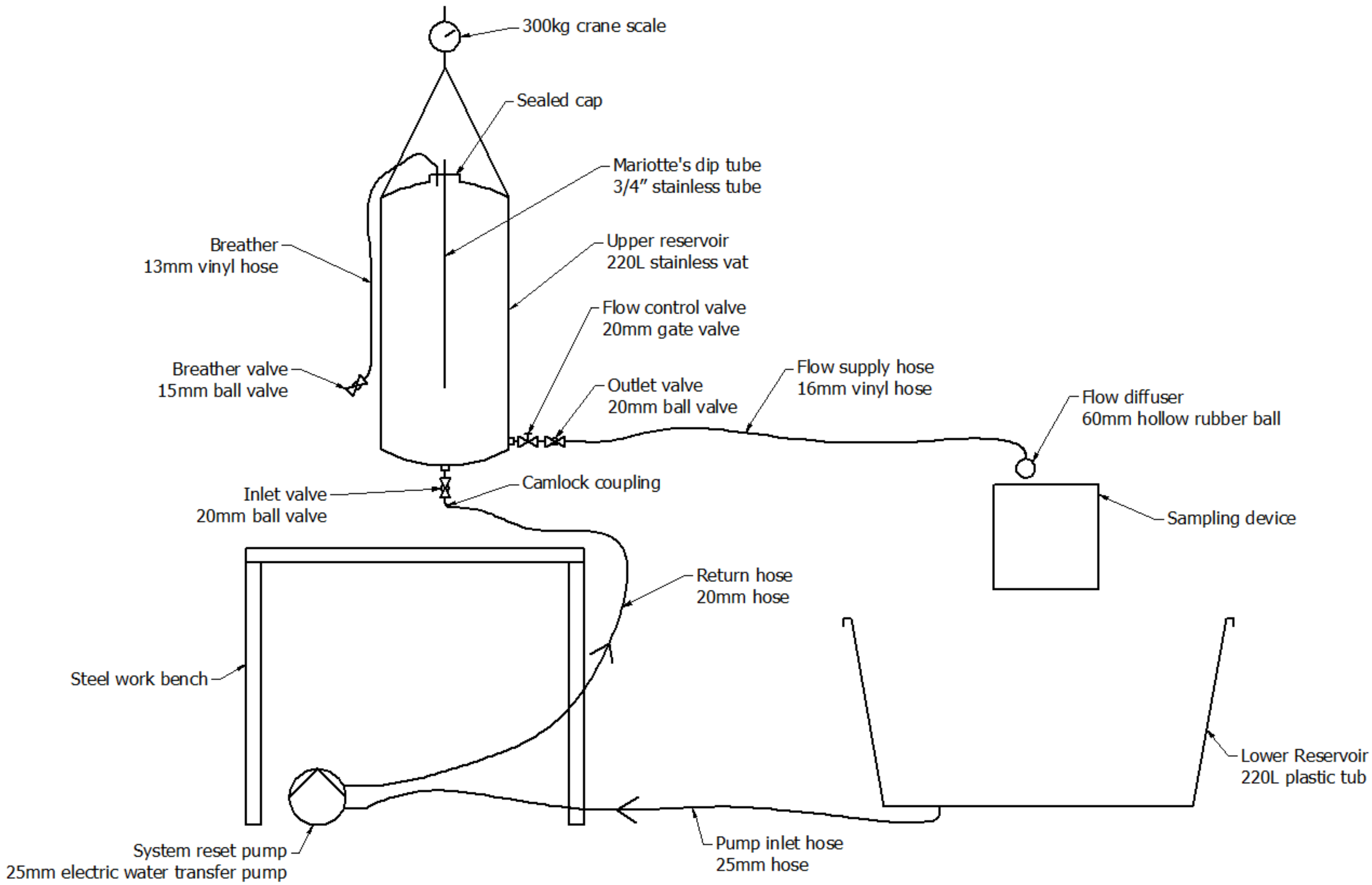


Figure 5-1 Constant head supply system layout

5.2 DESIGN FEATURES

5.2.1 Constant flow rate

Delivery of a constant flow rate of water is facilitated by using a Mariotte's bottle type arrangement to produce a constant head supply that can be controlled by a valve. The upper reservoir is a disused 220L stainless wine vat. The vat conveniently was already fitted with two threaded ports that could act as inlet and outlet points doing away with the need to fill the vat from the top. The sturdy stainless construction ensures that the walls won't collapse under the negative pressures produced by the Mariotte's bottle arrangement.

Figure 5-2 shows the Mariotte's dip tube assembly. The stainless dip tube is sealed to the cap with O-rings, a copper T fitting at the bottom of the tube prevents water from the pump from being shot up the tube by the while the system is being reset. A breather tube with ball valve is fitted so that the upper reservoir can be vented during reset, else the pumped water would be forced up and out of the dip tube. The length of the breather tube allows the ball valve to be accessed from the ground.

Flow out of the upper reservoir is controlled by two valves in series. A 20mm gate valve provides an easily adjustable flow restriction to the outlet thus controlling the flow rate. A 20mm ball valve is used to quickly start and stop the flow as required. This setup allows the gate valve position to be maintained between test runs as there is no need to close the gate valve to stop flow.

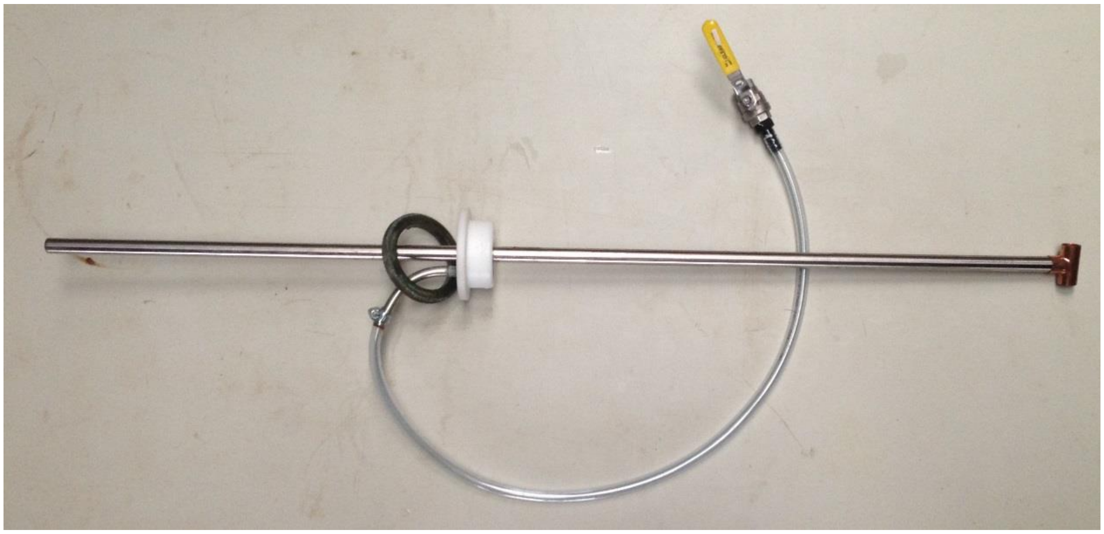


Figure 5-2 Mariotte's dip tube with breather

5.2.2 Ability to measure quantity of water discharged

During testing it is necessary to be able to accurately determine the quantity of water that has been passed through the flow sampling device. To achieve this the upper reservoir is suspended by a crane scale which makes it easy to weigh the upper reservoir before, during and after a test run allowing the mass of water discharged to be determined. As the crane scale is well of the ground it is necessary to use a ladder to reach it safely. An overhead block and tackle is used to lift the crane scale and upper reservoir. Rigging consists of lifting chain and D-shackles.

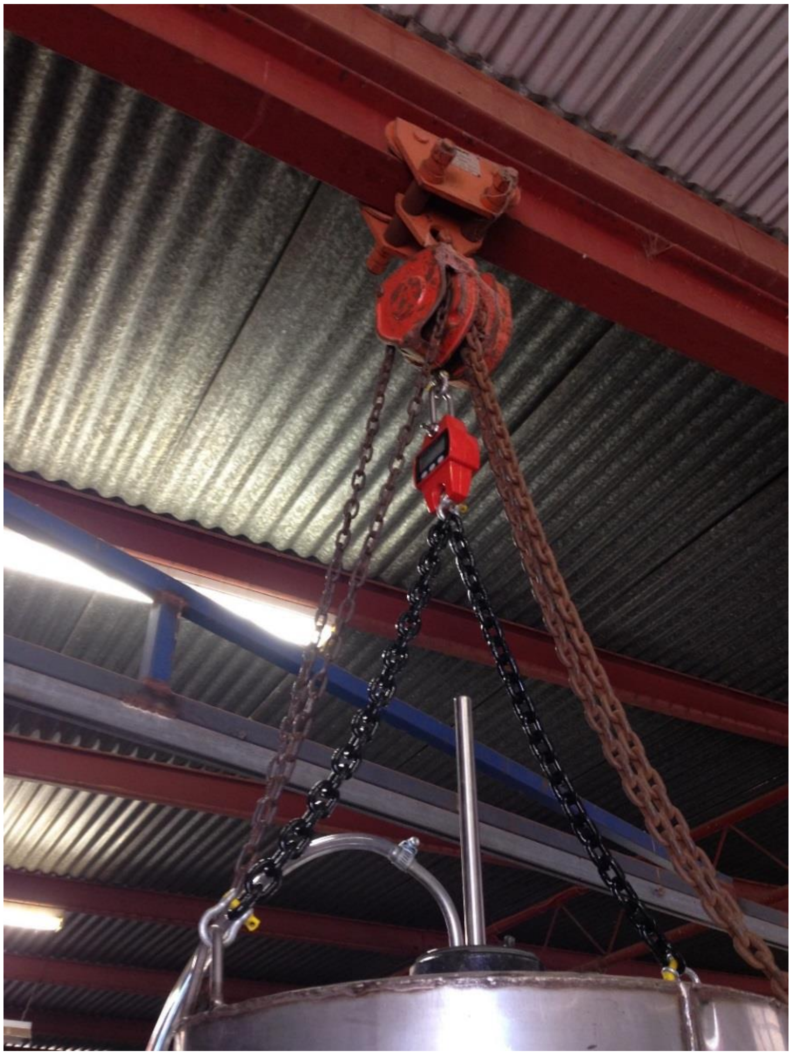


Figure 5-3 Crane scale rigged in position

5.2.3 Water recycling / reset system

Several thousand litres of flow are required for testing, as disposing of this water after a single use would be wasteful and inconvenient the system is designed to have the ability to reuse test water. As flow testing precedes water that is not captured by the sampling device falls into the lower reservoir, a 220L plastic tub. A 25mm electric transfer pump is used to pump water from the lower reservoir to the upper reservoir. The hose connecting the pump to the upper reservoir is fitted with a camlock coupling so that it can be easily removed from the upper reservoir, this is done so the weight of the hose does not affect the crane scale reading. The system is intended to be easy and safe to reset as there are many test runs to perform.

5.3 CONSTANT HEAD SUPPLY SYSTEM OPERATING PROCEDURES

5.3.1 Resetting the system

Before the system can be used for a test run the test water must be pumped from the lower reservoir into the upper reservoir and then the system needs to be primed ready for testing. Priming is necessary to evacuate water from the dip tube, else the outlet flow will be too fast when the test is first started.

Resetting Procedure:

1. Connect the camlock coupling on the return hose to the inlet of the upper reservoir, open the inlet ball valve.
2. Open the breather ball valve.
3. Start the pump and wait until the lower reservoir is emptied.
4. Close the inlet ball valve and then turn off the pump
5. Close the breather ball valve.
6. Prime the system by opening the inlet valve again allowing water to back flow through the pump, leave open until bubbling can be heard from the dip tube.
7. Close the inlet valve and uncouple the inlet hose, rest the inlet hose in the lower reservoir such that water cannot flow out of it.
8. The system is primed and ready for the next test run, a reading can now be recorded from the crane scale.

5.3.2 Setting the flow rate

It is necessary to set the flow rate to suit the specific test being performed, this is achieved by allowing the system to flow for a measured amount of time and measuring the amount of water that leaves the upper reservoir in this time. By having the crane scale turned on it is possible to watch the upper reservoir mass drop in real time.

The outlet ball valve must be fully open as in testing. Flow adjustments are made using the gate valve. Once the desired flow rate is achieved the ball valve is closed preserving the gate valve setting. If necessary reset the system.

5.3.3 Testing runs

With the system set and primed starting a test run only requires opening the outlet ball valve. Before starting a test run there are a few things to double check:

Pre-run check list

1. System is primed, breather is closed
2. Outlet hose is disconnected
3. Upper reservoir mass is recorded
4. Sampling device is ready with sample container fitted
5. Stop watch is ready to record time

While the test is running regular bubbling is heard from the dip tube as air is pulled down into the reservoir, lack of bubbling indicates a problem, either there is a sealing problem or the upper reservoir water level is too low.

To end the flow simply close the outlet ball valve and stop the stop watch.

5.3.4 Overnight storage

As there are several days' worth of tests to do it is desirable to leave the system set up overnight. Water is least likely to leak from the system if stored in the upper reservoir, keeping water in the upper reservoir also leaves the system ready to run the next morning.

It is necessary to lower the upper reservoir onto its stand to relieve the load on the crane scale. The manufacture advises against leaving the scale loaded for long periods of time.

6. PERFORMANCE TESTING PROCEDURES

6.1 MAXIMUM AND MINIMUM FLOWRATES THAT CAN BE SAMPLED

The stormwater sampling device can only sample flowrates that fall within a finite range. The maximum flow rate is limited by the speed at which water can flow through the device's sampling mechanisms. If the maximum flow rate is exceeded the intake reservoir of the sampling device will overflow losing an unaccounted for fraction of the flow. The minimum flowrate is related to the device's ability to seal the intake reservoir and save water for a flow pulse. In the prototype a floating hollow rubber ball is used to seal the top reservoir, this works reasonably well but some leakage does occur. If a leak proof seal could be achieved then there would be no minimum flow rate requirement. It is necessary to quantify maximum and minimum flow rates to describe the device's performance and to specify flow rates for other experiments.

6.1.1 Aim

To quantify maximum and minimum flow rates that the sampling device can operate between.

6.1.2 Safety

1. Use ladder to reach crane scale
2. Keep transfer pump electrical connections dry
3. Wear closed footwear

6.1.3 Equipment

1. Constant head supply system
2. Stormwater sampler
3. Crane scale
4. Stop watch
5. Ladder

6.1.4 Method

1. Set sampling device with one hose connected to the primary splitter and the secondary splitter installed, there is no need to set a sample collecting container.
2. Set the constant head supply system as described in its operation instructions.
3. Start the flow by fully opening the outlet ball valve on the constant head supply.
4. Slowly open or close the flow control gate valve on the constant head supply to adjust the flow rate to an equilibrium point where the sampling device is nearly overflowing. Aim to have the water in the sampling device inlet reservoir 10mm away from the top edge.
5. Shut off the flow using the ball valve. After the sampling device has fully drained restart the flow and check if the water level in the sampler inlet reservoir returns to the same level. Do this at least five times to confirm repeatability.
6. Measure the flow rate by allowing the constant head supply to run flow for 10 minutes, weigh the constant head supply before and after the run to determine the flow rate.
7. Reset the constant head supply by pumping the test water back into the top reservoir.
8. Start the flow by fully opening the outlet ball valve on the constant head supply.
9. Adjust the flow control gate valve to only allow a very small flow into the sampling device. At this very small flow rate the desired pulse flow cycle caused by the floating ball is not expected as the small flow of water will leak past the ball at the same rate that it enters the sampler inlet reservoir.
10. Increase the flow rate until the float ball is seen to reliably cycle.
11. Measure the flow rate by allowing the constant head supply to run flow for 10 minutes, weigh the constant head supply before and after the run to determine the flow rate.

6.2 CONSISTENCY OF SAMPLE COLLECTION RATE

The stormwater sampling device has been designed such that it will capture a constant fraction of any flow that is passed through it. It is this function that defines the sampler as a flow-weighted sampling device. In order to verify and characterize the devices performance in this key area practical testing is required.

6.2.1 Aim

To quantify the fraction of flow collected by the sampler under differing flow rates and with a range of sampler settings.

6.2.2 Hypothesis

The performance of the sampling device may be affected by flow rate.

6.2.3 Safety

1. Use ladder to reach crane scale
2. Keep transfer pump electrical connections dry
3. Wear closed footwear

6.2.4 Equipment

1. Constant head supply system
2. Stormwater sampler
3. Crane scale
4. Digital weight scales
5. Stop watch
6. Ladder

6.2.5 Method

Multiple tests need to be run for differing settings. Three different flow rates will be tested along with four different flow splitting configurations making for a total of 12 unique tests. Each test will be run three times making a total of 36 test runs.

Flow rates to be tested:

The three flow rates to be tested are 5.5L/min, 3.5L/min and 1.8L/min these flow rates cover the range over which the device operates reliably neither overflowing nor inadequately cycling the pulse flow valve.

Splitting configurations to be tested:

1. One hose connected to the primary splitter and the secondary splitter is used. Theoretical flow splitting ratio = (1/30)x(1/5) = 1/150, 0.667%
2. Three hoses connected to the primary splitter and the secondary splitter is used. Theoretical flow splitting ratio = (3/30)x(1/5) = 1/50, 2%
3. One hose connected to the primary splitter and the secondary splitter is not used. Theoretical flow splitting ratio = 1/30, 3.33%
4. Three hoses connected to the primary splitter and the secondary splitter is not used. Theoretical flow splitting ratio = 1/10, 10%

For each test run:

1. Set stormwater sampler in required configuration.
2. Set the constant head supply system as described in its operation instructions.
3. Set flow rate using procedure set out in the constant head supply system instructions.
4. Reset constant head supply system.
5. Record the weight registered on the crane scale.
6. Start the test by simultaneously opening the outlet ball valve and starting the stopwatch.
7. Record any relevant observations regarding the function of the testing equipment and sampling device.
8. Let the test run until the crane scale registers 100kg less than at test start. Stop the test buy simultaneously closing the outlet ball valve and stopping the stop watch.
9. Record the final reading on the crane scale.
10. Record the time taken for the test to run.
11. Remove the sample collection bottle and weigh the contents.
12. Reset the system for the next test.

6.3 ABILITY OF THE DEVICE TO INDICATE SAMPLE COLLECTION TIME

The flow duration indicator is a separate component of the sampling device prototype that essentially catches a small time-weighted sample of water. As the volume of this sample is related to the flow duration and not the flow rate the duration of the runoff event can be determined from the volume of the captured sample.

6.3.1 Aim

To quantify the flow duration indicators sample collection rate and consistency of sample collection rate over a range of runoff flow rates.

6.3.2 Hypothesis

There may be some variation in sample collection rates between test runs, there may be a relationship between flow rate and sample collection rate.

6.3.3 Safety

1. Use ladder to reach crane scale
2. Keep transfer pump electrical connections dry
3. Wear closed footwear

6.3.4 Equipment

1. Constant head supply system
2. Flow duration indicator
3. Crane scale
4. Stop watch
5. Ladder
6. Digital weight scales

6.3.5 Method

To test the flow duration indicator two test runs will be performed at four different flow rates for a total of eight tests. Preliminary testing of the device while it was being made indicates that it will take approximately 30 minutes to perform each test.

For each test run:

1. Set flow duration indicator in position with an empty sample bottle attached.
2. Set the constant head supply system as described in its operation instructions.
3. Set flow rate using procedure set out in the constant head supply system instructions.
4. Reset constant head supply system.
5. Record the weight registered on the crane scale.
6. Start the test by simultaneously opening the outlet ball valve and starting the stopwatch.
7. Record any relevant observations regarding the function of the testing equipment and flow duration indicator.
8. Let the test run until the sample bottle is full. Stop the test buy simultaneously closing the outlet ball valve and stopping the stop watch.
9. Record the final reading on the crane scale.
10. Record the time taken for the test to run.
11. Remove the sample collection bottle and weigh the contents.
12. Reset the system for the next test.

6.4 ABILITY TO PROTECT SAMPLE FROM CONTAMINATION

The sampling device has four sampling outlet ports which allow four samples to be collected sequentially. As each sample container is filled the magnetic sealing valves snap shut to prevent the collected samples from being contaminated by continuing flow. To validate this system a copper trace will be added to the test water after the sealing valves have been activated. The valves ability to exclude the copper dosed water will be tested.

6.4.1 Aim

To validate the magnetic sample sealing valves ability to prevent sample contamination and quantify any degree of contamination that does occur.

6.4.2 Hypothesis

The sealing valves will prevent any significant contamination.

6.4.3 Safety

1. Use ladder to reach crane scale
2. Keep transfer pump electrical connections dry
3. Wear closed footwear
4. Avoid direct contact with copper dosed water

6.4.4 Equipment

1. Constant head supply system
2. Stormwater sampler
3. Crane scale
4. Stop watch
5. Ladder
6. Copper sulphate
7. Photometer Kit
8. Coppercol reagent tablets

6.4.5 Method

1. Set the sampler splitting configuration to have all six hoses connected to the primary splitter, do not use the secondly splitter. This will cause the maximum flow to be applied over the sealing valves.
2. Fill four 750mm test bottles with RO water and fit to the sampler with the sealing valves in the open position. Check RO water copper concentration with photometer to ensure it is zero.
3. Pour additional RO water into the sampler until all four sealing valves snap shut.
4. Dose the test water to a rate of 45mg/L free copper, this will require around 18g copper sulphate per 100L of water. Agitate well and allow an hour for the solution to stabilize. Check concentration with photometer using standard procedure.
5. Pump test water into upper reservoir of the flow simulator, close reservoir breather and disconnect inlet hose.
6. Record crane scale reading.
7. Test free copper concentration of test water with photometer just before starting the test.
8. Start flow through sampler at 5L/sec flow rate. Start stop watch.
9. Visually inspect sealing valves for leakage.
10. Allow the test to run until 150L of test water has passed through the system. Stop the stop watch and take a final measurement of the test water free copper concentration.
11. Rinse the exterior of the sample bottles to prevent contamination from copper dosed droplets of water during removal.
12. Remove sample bottles.
13. Agitate samples and test for free copper immediately, record readings.
14. Dispose of copper dosed test water by incorporating into the next copper treatment of on farm aquaculture ponds.

6.5 Ability to capture a representative amount of suspended solids in the sample

An important stormwater quality parameter that is often measured is the total suspended solids. Due to the nature of many sampler designs suspended solids are often underrepresented in captured samples as the solids settle out before they make it to the sample container. Alternately the nature of the sampling devices pickup point may lead to a biased sample. (Bent et al. 2001 p13) The sampling device in this study handles the entire water flow and the symmetrical nature of the splitting system should result in no TSS bias, testing will confirm this performance parameter.

The constant head supply system used in other experiments is not used in this experiment as it is poorly suited to handling suspended solids which would be expected to settle out in the upper reservoir. Instead actual runoff water is pumped from an on farm drainage ditch during a rainfall event and delivered to the sampling device.

6.5.1 Aim

To assess the sampling devices ability to capture a water sample with an unbiased TSS concentration.

6.5.2 Hypothesis

The device is expected to capture samples with unbiased quantities of TSS.

6.5.3 Safety

1. Fuel transfer pump before starting the experiment to avoid having to refuel after the engine heats up.
2. Be cautious of hot engine parts
3. Wear closed footwear

6.5.4 Equipment

1. Bottom reservoir from constant head supply system
2. Stormwater sampler
3. Stop watch
4. 1” engine driven water transfer pump
5. Tape measure
6. Photometer kit
7. Clean shovel

6.5.5 Method

This experiment must be conducted during a rainfall event so that the chosen drainage ditch is flowing. The ditch used is the sole drainage point for 12 hectares of citrus so only modest rainfall is required to produce adequate flow. When rainfall ends it typically takes several hours for the flow in the ditch to stop allowing time for testing.

For this test the lower reservoir of the constant head supply system is located outside near the drainage ditch. The sampling device remains attached to the lower reservoir as in other experiments.

The gate valve from the constant head supply system is fitted to the outlet of the 1” transfer pump. The flow supply tube is fitted to the gate valve. The suction hose from the transfer pump is submerged in the drainage ditch.

For this experiment the sampling device is set up with one hose connected to the secondary splitter for a theoretical sampling rate of 3.33%.

For each test run:

1. Start the transfer pump and set the flow rate by adjusting the gate valve. As the required flow rates are well below the pumps capacity the pump is run at idle.
2. Turn off the transfer pump and drain any water in the lower reservoir, wash out any sediment.
3. Set the sampling device and sample capture container.
4. Restart the transfer pump and start the stopwatch.
5. Allow the test to run for 30 minutes or until the lower reservoir is nearly full.
6. Observe the test while it is running, look for any deposits of solids settling in the sampling device
7. Turn off the transfer pump and stop the stop watch.
8. Use the tape measure to measure the depth of water in the lower reservoir, use this to calculate the approximate volume of water passed through the sampling device.
9. Use the shovel to vigorously agitate the water captured in the lower reservoir in order to re-suspend any solids that have settled out, immediately capture a sample of the agitated water.
10. Use the photometer to test the turbidity of the water via the standard procedure in the manual. This involves first filtering a sample to use to blank the photometer to allow for any colour in the water that may attenuate light. Testing needs to be done on both the water captured in the lower reservoir and the sample captured so that the turbidity may be compared.

7. RESULTS

Testing of the storm water sampling device was conducted under controlled conditions according to the experimental procedures of chapter 6. The full set of experimental data can be found in APPENDIX C.

7.1 MAXIMUM AND MINIMUM FLOWRATES THAT CAN BE SAMPLED

Before proceeding with other experiments it was necessary to determine the operational limits of the device in terms of the maximum and minimum flow rates that could be handled.

The minimum flow rate was that which would cause the pulse flow valve to cycle reliably. The rubber ball used as a valve was manufactured from two halves bonded together, around the seam of the ball a small discontinuity of the surface can be felt. This defect in no way harms the balls designed purpose as a bouncy ball but when used as a valve the surface discontinuity can cause leakage. It is observed that during operation if the ball lands with the seam of the ball not touching the sealing surface between the ball and the inlet reservoir a near perfect seal is formed. If however the seam does cross the sealing surface leakage will occur. As the ball acting as a valve cycles it rolls when floating causing the sealing position for each cycle to be random

During testing the valve was seen to cycle with as little as 0.8L/min flow rate, at this low rate the valve would occasionally land in a position that would cause an increased leakage rate and the valve would cease to cycle. In order to eliminate this behaviour it was necessary to increase the flowrate to the range of 1.5 to 1.8L/min, then the valve would never stall. The maximum flow rate the device can handle is simply the maximum flow rate that will not cause the upper reservoir to overflow. During testing this limit was found to be at around 6L/min.

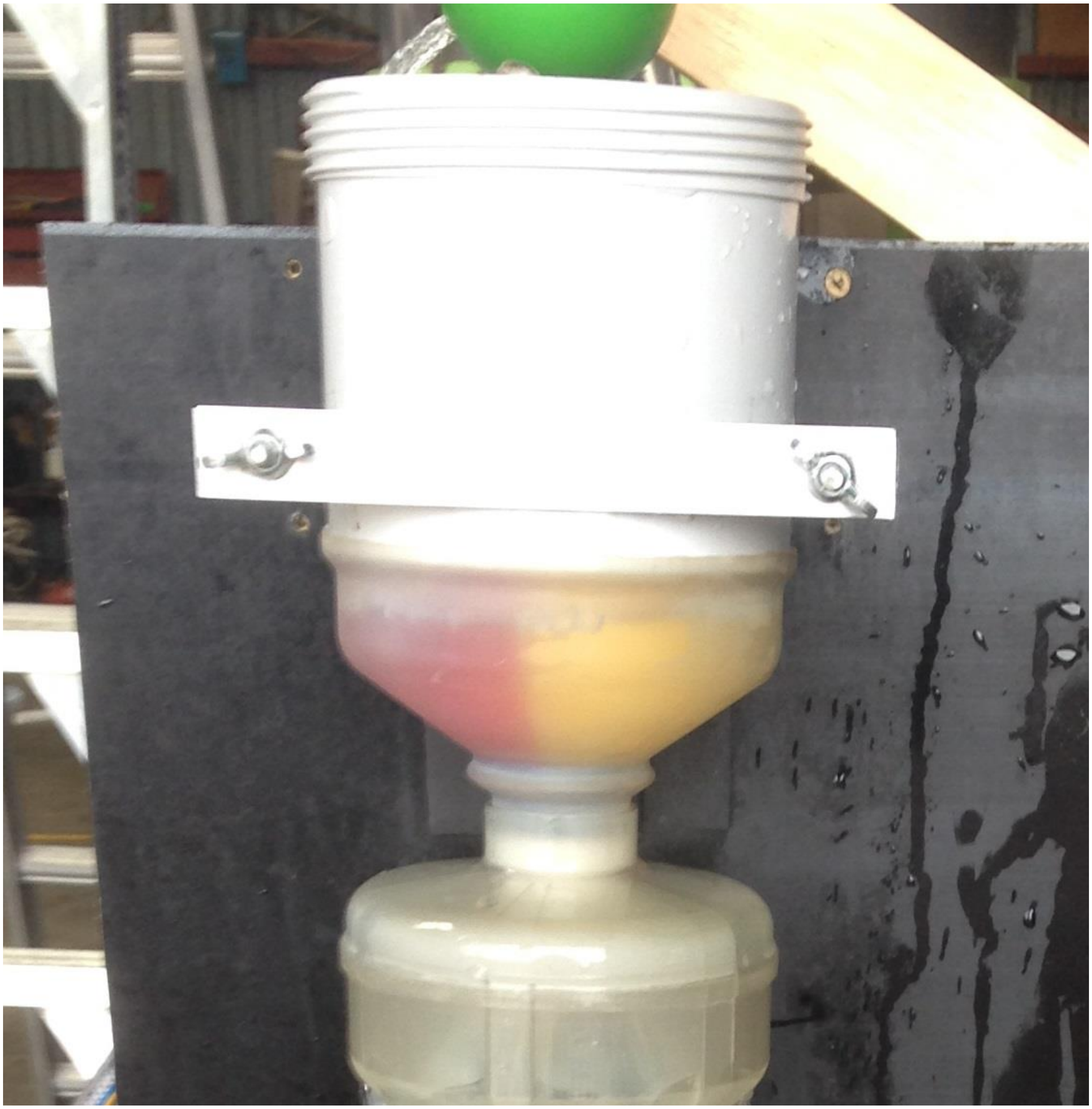


Figure 7-1 Ball shown in position that would cause leakage

7.2 CONSISTENCY OF SAMPLE COLLECTION RATE

The consistency of the sample collection rate is a primary performance measure of a flow-weighted sampling device. Accuracy of flow splitting was tested according to the procedures of section 6.2 with varied configurations of the system. Half of the tests performed made use of both the primary flow splitter and the secondary flow splitter, while the other half only used the primary splitter.

The error of the flow splitting is expressed as the percentage difference of the volume of water collected in the sample container verses the theoretical volume that should have been collected.

Figure 7-2 shows the stormwater sampling device being tested for flow splitting accuracy.

Figure 7-2 Flow splitting testing

7.2.1 Flow splitting error with only primary splitter in use

Testing of the primary flow splitter indicates that the primary flow splitter is capable of reasonably accurate flow splitting. Testing was conducted for two splitter configurations, one with only one hose connected to the primary splitter and the other with three hoses connected. Results for flow splitting accuracy are presented in Figure 7-3 and Figure 7-4.

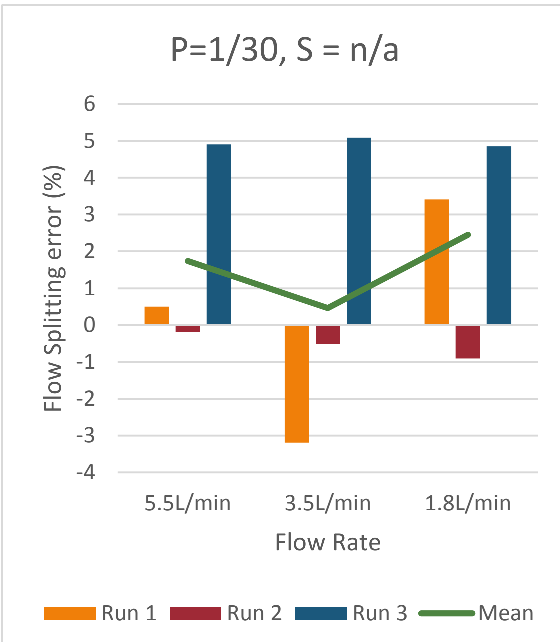


Figure 7-3 Flow splitting error for one sample port connected to the primary flow splitter, secondary flow splitter not in use, theoretical sampling rate = 3.33%

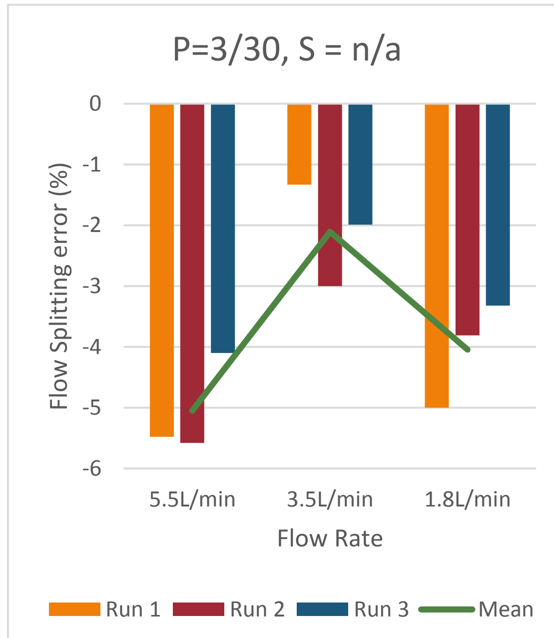


Figure 7-4 Flow splitting error for three sample ports connected to the primary flow splitter, secondary flow splitter not in use, theoretical sampling rate = 10%

Inspecting the results of Figure 7-3 and Figure 7-4 it is seen that the device is capable of capturing moderately accurate sample volumes. The maximum error recorded for the primary splitter was -5.58%, this level of accuracy should suffice for most stormwater monitoring routines.

7.2.2 Flow splitting error with primary and secondary flow splitters in use

The sting of the sampling device using the primary and secondary flow splitters yielded erratic results which appear to be caused by insufficient flow passing through the secondary flow splitter. Just as for testing the primary splitter testing was conducted for two splitter configurations, one with only one hose connected to the primary splitter and the other with three hoses connected. Results for flow splitting accuracy for the combined primary and secondary splitter arrangement are presented in Figure 7-5 and Figure 7-6.

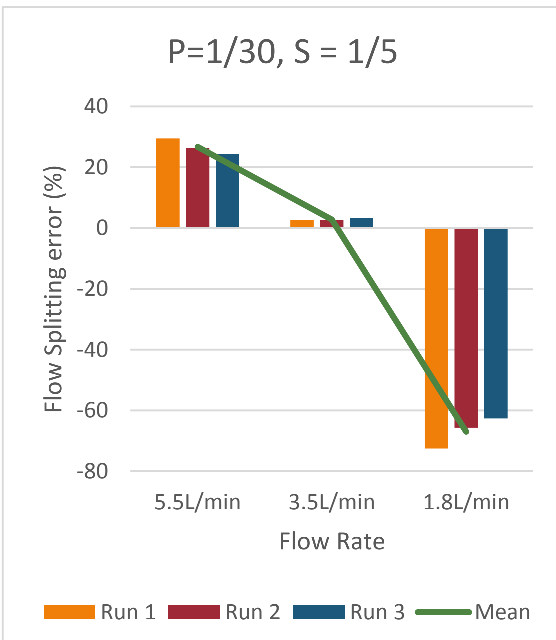


Figure 7-5 Flow splitting error for one sample port connected to the primary flow splitter, secondary flow splitter is in use, theoretical sampling rate = 0.667%

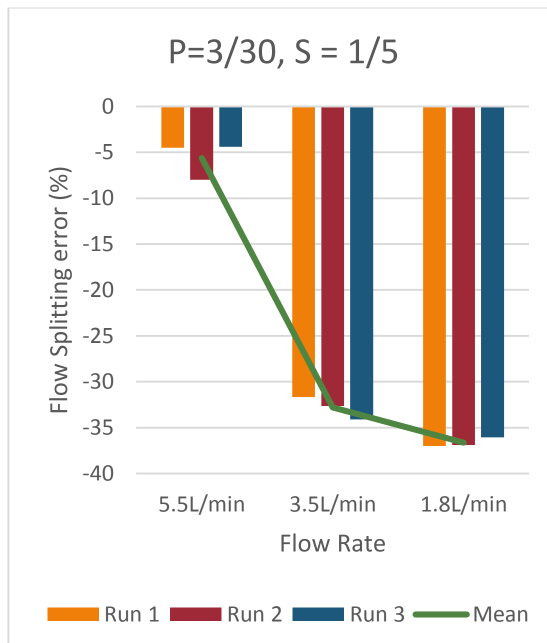


Figure 7-6 Flow splitting error for three sample ports connected to the primary flow splitter, secondary flow splitter is in use, theoretical sampling rate = 2%

From Figure 7-5 and Figure 7-6 it is seen that the flow splitting accuracy was unacceptably inaccurate when the secondary splitter was used. The poor splitting accuracy is attributed to the secondary splitter being unable to split the small flow rates coming from the primary splitter. During testing it was observed that as a pulse of water passed through the primary splitter it would be restricted and drawn out, exiting the splitter as a small flow rate with the duration of the pulse exiting being longer that the duration of the pulse entering. This meant that the secondary splitter was supplied with long flow pulses of reduced flow rate that were more difficult to split than shorter pulses of larger flow rates would have been. It was not possible to see the flow entering the throat of the secondary splitter although it is expected that small flow rates tended to not fill the throat instead draining down one side of the splitter leading to inaccurate splitting.

Inspecting the flow splitting error of Figure 7-5 and Figure 7-6 it is seen that the sampling error between the three consecutive runs of each flow setting / splitter configuration combination tent to be quite consistent.

During testing each splitter configuration was tested for a single flow rate before resetting the equipment for a different flow rate. This was done as changing flow rates is time consuming compared to changing the splitter configuration. This meant that the sampling device would be disassembles and reassembled between testing different flow rates on the same configuration. This reassembly between testing different flow rates has the effect of randomizing which side of the throat the flow is biased towards leading to somewhat random splitting action. The splitting error is consistent between runs of the same flowrate as there is no disturbance to the sampler between runs. This erratic behaviour demonstrated that the secondary flow splitter is ineffective as its performance is highly dependent on uncontrollable factors of its assembly before use.

Table 7-1 Summary of splitter performance based on absolute values of flow splitting error.

	Primary splitter only	**Primary and secondary splitters**
Maximum Error (%)	5.580	72.550
Minimum Error (%)	0.190	2.600
Median Error (%)	3.365	30.550
Mean Error (%)	3.177	28.589
Standard deviation (%)	1.800	21.508

The performance of the sampling device with and without the secondary flow splitter is summarized in Table 7-1. It is seen that the primary splitter alone appears to be impressively accurate although further testing would be beneficial to improve the certainty of the results. Results for the secondary splitter are somewhat meaningless beyond indicating that it is ineffective.

7.3 Ability of the Device to Indicate Sample Collection Time

The flow duration indicator described in section 4.1.7 performs the roll of indicating flow duration by catching a time-weighted water sample the volume of which is proportional to the duration of the flow event. As this sample is not intended to be used for multiple pollutant or TSS tests where significant sample volume may be required it is desirable to make it as small as possible for convenience of handling.

Accuracy of the duration indicator is defined as the consistency of sample collection rate over multiple test runs at varying flow rates. Figure 7-7 shows the sampling rate for each test run along with the mean sampling rate for each flow rate tested. In Figure 7-8 the deviation of the mean sampling rate vs the overall mean sampling rate is plotted. It can be seen that the sampling rate is reasonably constant over the range of flows tested with maximum deviation of 1.6% from the overall mean sampling rate occurring with the flow rate of 0.6L/min.

During testing as the flow rate entering the flow duration indicator was increased it was observed that the water level in the inlet reservoir would rise as more water was forced to overflow through the spill holes. The upward trend in sample collection rate with increased flow rates is attributed to this increase in head height. This was not unanticipated and the slight dependency of sample collection rate on flow rate is deemed acceptable, although it may be worth attempting to further improve the design in future.

Figure 7-9 shows the flow duration indicator being tested with water overflowing through the spill holes.

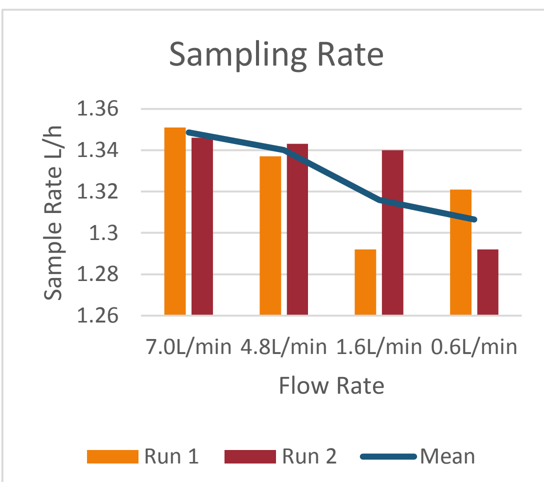


Figure 7-7 Time-weighted sample capture rates for the flow duration indicator

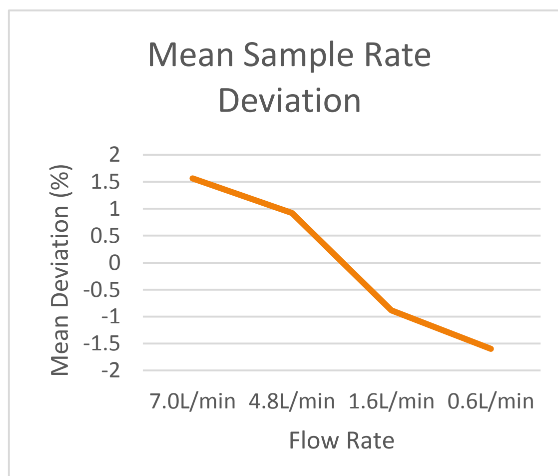


Figure 7-8 Deviation of the mean sample collection rate of each tested flow rate from the overall mean sample collection rate

Figure 7-9 flow duration indicator being tested with a 1.6L/min flow rate

The mean sampling rate of the flow duration was found to be 1.328L/h. With this figure the duration of a flow event is easily calculated using the equation:

$$Flow\ duration(h) = sample\ volume(L)/1.382$$

Table 7-2 summarizes significant statistics for the flow duration indicators performance.

Table 7-2 flow duration indicator sampling rate statistics

Maximum Sampling Rate (L/h)	1.351
Minimum Sampling Rate (L/h)	1.292
Median Sampling Rate (L/h)	1.339
Mean Sampling Rate (L/h)	1.328
Standard deviation (L/h)	0.022

7.4 ABILITY TO PROTECT SAMPLE FROM CONTAMINATION

The sampling device has been designed with magnetic sample sealing valves that seal the sample bottles once full in order to protect the samples from contamination. Testing was conducted in accordance with the procedures of section 6.4, results data can be found in APPENDIX C.

7.4.1 Contamination detection limit

The detection limit of the equipment used during testing is calculated so that the minimum detectable volume of sample contamination can be quantified. The detection limit equation is;

$$DL = \frac{V_s \times DL_p}{C}$$

Where

DL is the minimum volume of leakage into the test bottle that can be detected

V_s is the volume of the test bottle = 0.75L

DL_p = is the detection limit of the photometer = 0.02mg/L

C is the concentration of free copper in the test water = 0.46mg/L (measured concentration)

Applying the formula the detection limit for the test is found to be 0.326mL.

7.4.2 Results

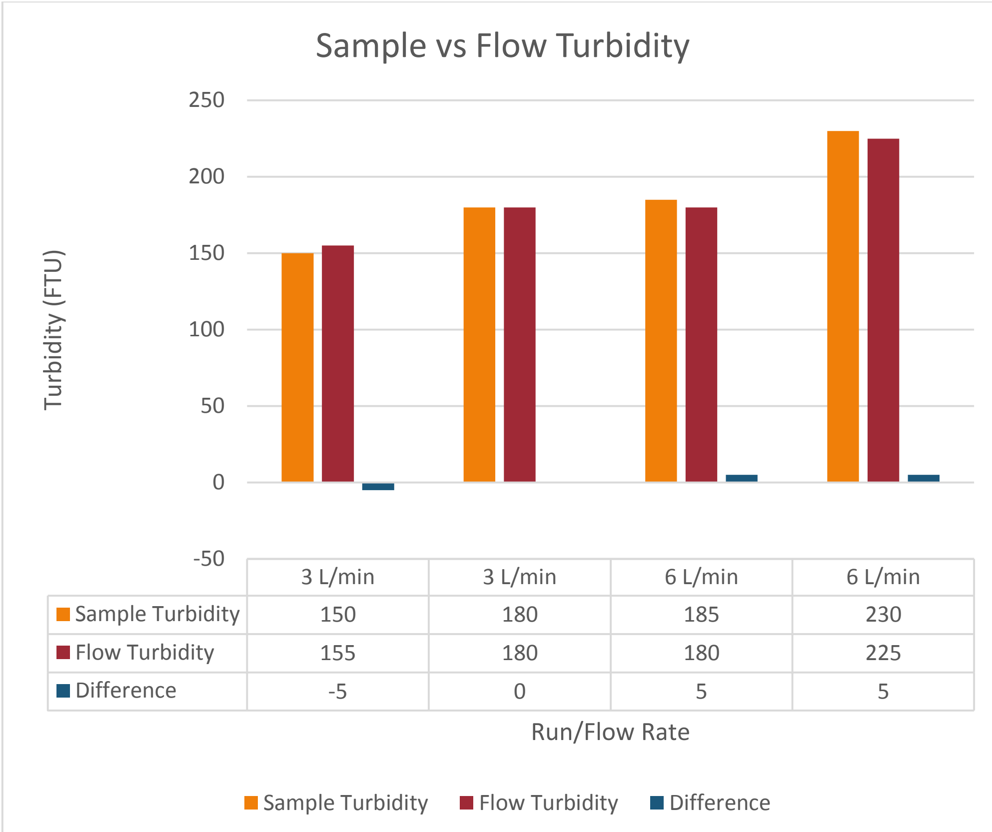
The test was run according to section 6.4 with two test runs over all four valves making for eight data points. In all tests there was no detectable free copper in the test bottles. The clear acrylic tube used to construct the sample sealing valves allows clear view of the inside of the valve during testing. Visually inspecting the sealing valves during the test there was no leakage of the valves observed.

7.5 ABILITY TO CAPTURE A REPRESENTATIVE AMOUNT OF SUSPENDED SOLIDS

Determining the sampling device's ability to capture suspended solids relied on a combination of visual observations during testing along with measurements of turbidity of captured samples compared to the turbidity of the larger test water volume. Experiments were conducted in accordance with the procedures of section 6.5, results data can be found in APPENDIX C.

Figure 7-10 summarizes the turbidity measurements for the four test runs performed along with the difference between the sample turbidity and flow turbidity. The maximum difference recorded is 5 FTU. It is noted that the resolution of the photometer used to measure the turbidity is 5 FTU so the results do not confirm that there is any bias in the devices ability to capture TSS.

During and after test runs special care was taken to inspect the sampling device for any accumulation of solids. No solids were seen to accumulate in the device indicating that they were all passed through finally ending up the sample bottle or being ejected from the system. Water dumped from the sampling device was captured in the lower reservoir of the flow simulation equipment, when this reservoir was drained after each test solid particles were observed to have settled to the bottom. Similar particles were seen in the test bottles. It is taken then that the system was subjected to rapidly settling suspended solids and was able to pass them without any accumulation.



	3 L/min	3 L/min	6 L/min	6 L/min
Sample Turbidity	150	180	185	230
Flow Turbidity	155	180	180	225
Difference	-5	0	5	5

Figure 7-10 Measured turbidity of samples and flow water

8. DISCUSSION

8.1 FLOW HANDLING CAPACITY

The stormwater sampling device was found to be capable of splitting a maximum flow rate of 6L/min before overflowing. The somewhat limited flowrate capacity stems from the primary splitter being restricted in order to improve splitting performance on small pulse flow volumes supplied by the pulse flow valve. Table 8-1 presents the maximum catchment areas that can be sampled for different intensities of rainfall. It is seen that the maximum catchment area becomes very limited when sampling intense rainfall events. Future design iterations of this sampling device will need to address the flow capacity limitation encountered in this design.

Table 8-1 Maximum catchment area that can be sampled vs rainfall intensity

Rainfall intensity	**Maximum catchment area (sampler capacity = 6 L/min)**
5mm/h	72 m^2
10mm/h	36 m^2
20mm/h	18 m^2
40mm/h	9 m^2

The minimum flow rate that the device can reliably sample is imposed by the leakage of the pulse flow valve and was found to be in the range of 1.5 to 1.8L/min. Reducing the minimum flow rate capacity is a matter of improving the pulse flow valve performance. As the flow restrictor that limits the maximum flow capacity was also made necessary by the sub-optimal pulse flow valve performance it is concluded that improving the pulse flow valve performance is key to future success of this design.

The testing procedure specified in section 6.1 and used for the determination of maximum and minimum flow rates was by nature brief and was not intended to produce results of high statistical significance. Rather the test was intended provide reasonably operational ranges to allow for specification of flow rate used in subsequent testing. Future works aimed at expanding the operational range of a similar stormwater sampling device will need focus more heavily on testing methods that characterize maximum and minimum flow conditions.

8.2 CONSISTENCY OF SAMPLE COLLECTION RATE

Controlled testing of the device has revealed mixed results with the primary splitter achieving consistently accurate results while the secondary splitter performed erratically. Sampling accuracy required for any stormwater monitoring program is ultimately depended on the nature of the study. While increased precision is always desirable it is necessary to consider the cost of autonomous stormwater sampling hardware and the practicalities of deployment.

Brodie (2005) reports the consistency of the sampling rates of two passive stormwater sampling devices, a flow splitter and an orifice and weir device. In Brodie's paper the flow splitter is reported split flow at a mean rate of 1:179.4 ±3.0 placing 68% within 1.7% of the mean flow sampling rate. The orifice and weir device fared less well with a mean flow sampling rate of 153.2±24.5 making for 68% of samples being within 16% of the mean.

The sampling device developed in this project when configured using the primary splitter only and sampling from one outlet port (theoretical sampling ratio 1:30) produced an actual mean sampling ratio of 1:29.6±0.84. With this 68% of samples achieve a sampling ratio within 2.85% of the mean. The mean error from the theoretical sampling ratio is 2.6 %.

With the sampling device configured to sample from three outlet ports (theoretical sampling ratio 1:10) the actual mean sampling ratio was 1:10.4±0.15. With this 68% of samples achieve a sampling ratio within 1.45% of the mean. Although the mean error from the theoretical sampling ratio is 3.7%.

From these results it is seen that the flow splitter developed by Brodie and the device developed in this projects are capable of similar levels of sampling accuracy in terms of consistency of sampling ratio. It is noted that other papers do not generally report sampling accuracy in terms of sample collection rate consistency.

Ackerman et al. (2009) compared event mean concentrations (EMCs) of TSS, fecal coliform and copper generated by various sampling methods to true EMCs in order to evaluate the performance of sampling devices and procedures. This approach represents a method which attempts to describe the real world performance of sampling devices as in most stormwater sampling programs it is the accuracy of EMCs that are of primary concern.

A future refined version of the sampling device in this study would eventually need to be subjected to testing similar to that done by Ackerman et al. in order to validate performance beyond simple flow splitting accuracy. Such extensive testing is not warranted for the current design as it is only developed to a proof of concept level.

8.3 Indication of Sample Collection Time

The original idea for the flow duration indicator was to install a pedometer in the original pulse flow valve design as pictured in Figure 8-1. With this system a small constant flow rate would have been supplied to the inlet reservoir causing the valve to cycle at a constant rate. The pedometer would then have counted each cycle with the number of cycles recorded being directly proportional to the flow duration. For testing purposes the same inlet reservoir and pulse flow valve would have been used for both flow duration testing and flow splitting testing in order to save parts. In the field two separate units would need to be used to allow both tasks to be performed simultaneously.

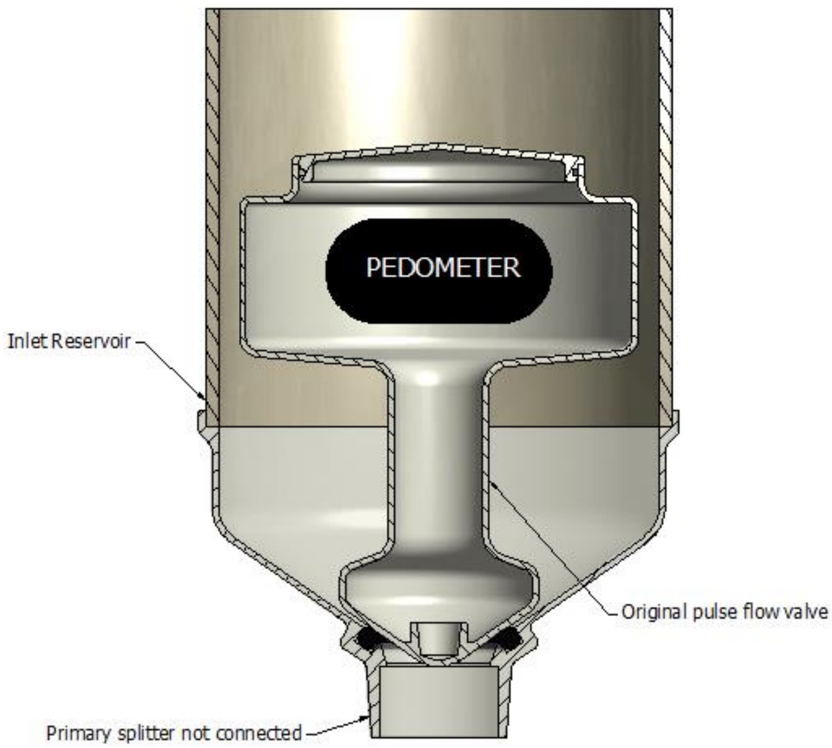


Figure 8-1 Original flow duration indicator design

As was discussed in section 4.1.2 the original pulse flow valve design failed to cycle and was ultimately replaced by a rubber ball. The rubber ball allows for flow splitting operations to be performed as planned but cannot be fitted with the pedometer.

The benefit of the original flow duration mechanism is that it doesn't require storing a sample. Without needing to store sample the device could potentially measure the duration of very long flow events, also personnel using the device would not have to collect and measure a sample, rather just recording the pedometer reading.

As the original design became unworkable the flow duration indicator presented in section 4.1.7 was developed working on the principle of a time-weighted sampling device. The device worked well during testing yielding a sampling rate of 1.328±0.022 L/h, with this the device would be expected to indicate flow duration accurate to 1.7%, 68% of the time.

The flow duration indicator sampling rate dose have a slight undesirable dependency on the supplied flow rate with a 7L/min flow rate being sampled at a 3% greater rate than a 0.6L/min flow rate. This small dependency is not unreasonable but cold potential be reduced or eliminated in future designs.

8.4 SAMPLE PROTECTION

The stormwater sampling device developed in this project protects collected samples via the sample sealing valves described in section 4.1.6. The sample sealing valves provide a magnetically energized sealing action that creates a positive seal.

The stormwater sampling device requires improved sample sealing performance over other designs due to the operation of the discrete sampling rail. As the first bottle attached to the rail finishes filling the sealing valve locks into position sealing the bottle. Water then continues to flow over the valve and onto the next bottle. If the sealing action were not positive then it would be possible for the first sample to become contaminated with water meant for the second.

During testing there was no leakage of the sample sealing valves detected using the methods described in section 6.4 nor was there any leakage observed visually.

In addition to protecting the sample from contamination from water flow the sealing valves also protect the samples from insects and spiders that may be active after a rainfall event.

Free copper from copper sulphate dissolved in the test water was used as a trace in this experiment as it was readily available and farm aquaculture activities provided a convenient method to recycle to copper used. Future experiments may make use of specialty trace chemicals such as those developed by the CSIRO (CSIRO 2013)

8.5 SAMPLING OF SUSPENDED SOLIDS

Collection of stormwater samples with representative concentrations of total suspended solids is often an important performance criteria for stormwater sampling devices. Many sampling devices both passive and automatic are prone to sampling biased TSS due to the tendency for suspended particles to drop out of suspension when flow rates are reduced along with the non-uniform distribution of particles through a flow cross-section. (Bent et al. 2001 p.13)

The flow splitter design developed aims to overcome these challenges by indiscriminately splitting the entire flow into 30 equal portions (only six of which are available for capture).

Testing of the devices ability to handle suspended solid was conducted according to the procedures of section 6.5 using sample turbidity as a proxy for suspended solids concentration. Results presented in section 7.5 reveal that there was no significant difference in turbidity of collected samples compared to the total water volume. In addition to this there was no observed accumulation of solids in the sampling device.

With these results it seen that there are no immediately obvious deficiencies in the device's ability to sample suspended solids. The true adequacy of the design in this regard cannot however be confirmed without additional testing. For future testing it is proposed that the total suspended solids be measured directly using the conventional method of vacuum filtering the water sample and weighing the mass of the solids collected (Department of Ecology State of Washington n.d). This method will give true

TSS results and thus could be trusted to characterize the performance of the sampling device.

In this study turbid water was pumped directly from a drainage ditch for the purpose of testing. In future testing it is suggested to supply the sampling device with a water flow containing controlled concentration and particle size distribution of suspended solids. Brodie (2005) describes such a method by which a soil slurry was sieved through 500µm screen to remove coarse particles and then through a 63µm screen to retain medium particles. Grading the particle size ensures that the device being tested is subjected medium and large particles that are typically difficult to sample thus providing true test of performance.

8.6 TESTING EQUIPMENT

While the focus of this study is centred on the design and testing of the stormwater sampling device another significant part of the work undertaken has been in the design and construction of flow supply equipment. The equipment was designed to allow for easy and safe setting of the system, which had to be performed may times through the testing phase of the project.

During testing of the sampling device the flow supply equipment performed as intended. The crane scale provided convenient and continuous measurement of water leaving the upper reservoir of the testing system. The system reset pump was capable or pumping out the lower reservoir back to the upper reservoir in a few minutes with minimal effort. The ease of use of the system greatly help in completing tests is a safe and timely manner.

9. FUTURE DESIGN POSSIBILITIES

The stormwater sampling device developed and tested in this study has satisfied all performance requirements that were established to varying degrees of success. In this section future design possibilities for each component are discussed.

9.1 PULSE FLOW VALVE / INLET RESERVOIR

Failure of the original pulse flow valve had the effect of limiting the device's flow maximum handling capacity as it became necessary to restrict the primary splitter throat in order to accurately split the small flow pulses from the rubber ball type valve. The rubber ball also leaked considerably thus imposing a minimum flow rate that would cause the valve to cycle properly.

There are four possible courses of action regarding the pulse flow valve, the inlet reservoir is also considered at this point as the two parts must be compatible.

- Refine the original pulse flow valve design.
- Refine the rubber ball design.
- Investigate new pulse flow valve design.
- Do away with the pulse flow valve altogether.

9.1.1 Refine the original pulse flow valve design

Failure of the original pulse flow valve design shown in Figure 4-4 was attributed to rapid leakage that developed when the buoyancy force on the valve in the rising inlet reservoir water became great enough to tilt the valve sideways slightly causing a gap to form between the O-ring and conical sealing surface of the pulse flow valve. It is noted that no leakage of the valve was apparent before the valve was tilted to the side.

To remedy this it is recommended to make the sealing surface on the valve spherical to reduce it sensitivity to angular misalignment. Also the top diameter of the valve should be fitted with bearing points to reduce the degree to which it can tip. The inlet reservoir for this design would go unchanged. Figure 9-1 demonstrates these proposed modifications.

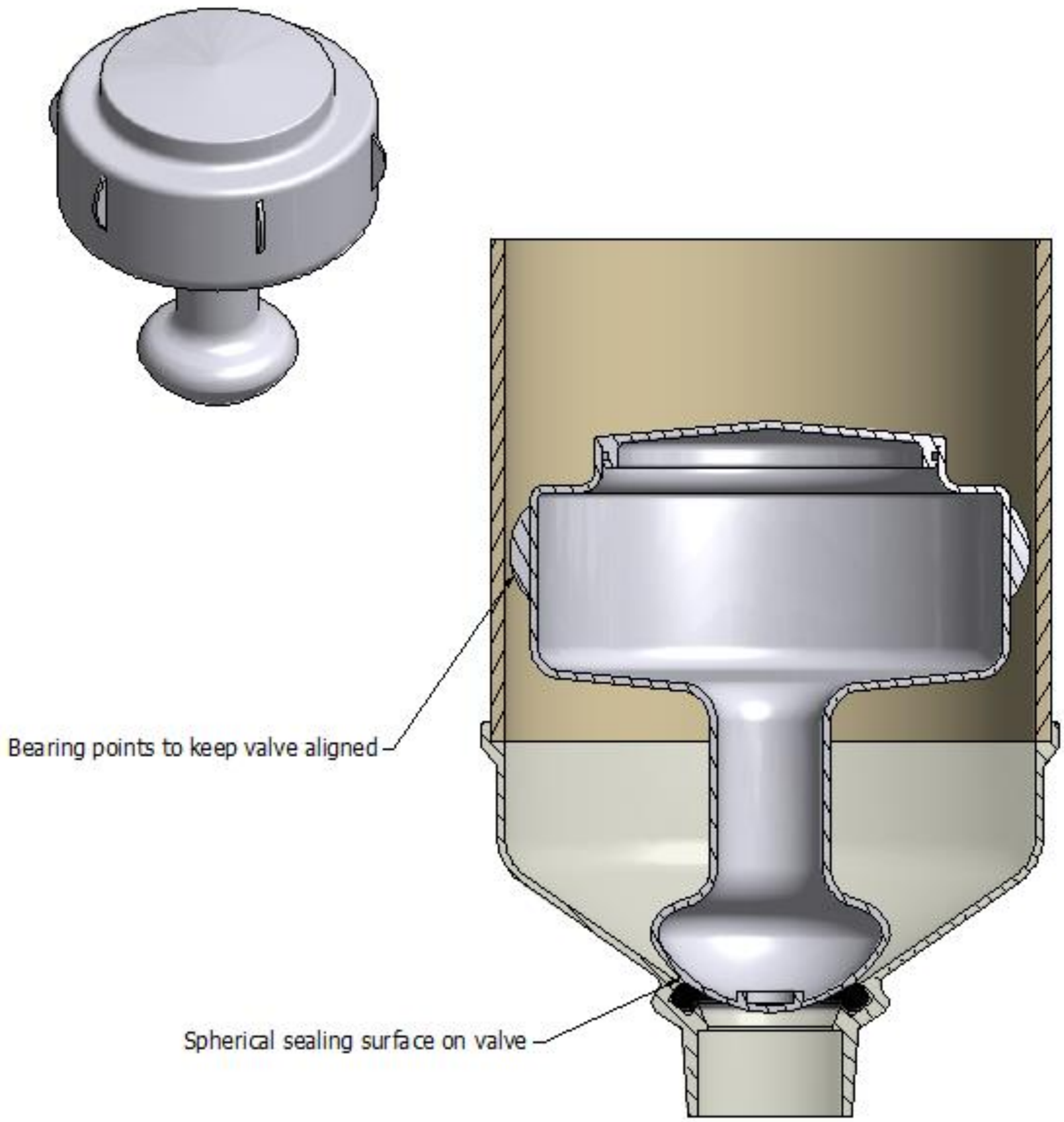


Figure 9-1 Possible refinement of the original pulse flow valve design

9.1.2 Refinement of the rubber ball design

The rubber ball design that was ultimately used for testing suffered two significant shortcomings. The volume of the pulse flow was not as large as the original valve design would have been, and the valve leaked. To increase the volume of the pulse flow the diameter of the inlet reservoir could be increased, this way a certain height of water in the inlet reservoir would correspond to a larger volume without increasing the buoyancy force on the ball. The sealing performance of the ball used was compromised by surface imperfections at the seam of the two rubber halves. A rounder, smoother and perhaps softer ball would be expected to seal better.

9.1.3 Investigate new pulse flow valve design

There are methods of creating a pulse flow other than a floating valve design. The operation of many digital rain gauges relies on slowly saving up a volume of water from rainfall and then dumping it suddenly. Such systems could be appropriated for use in the sampling device. Figure 9-2 shows a tipping bucket rain gauge, such a design could be scaled up for use as a pulse flow valve. Such a design would likely increase the bulk and complexity of the stormwater sampling device but could provide more reliable sealing than the float based designs. The tipping bucket arrangement would only have to be made big enough to supply an adequate pulse flow volume. In the event the device is sampling large flow rate it would not matter is the tipping bucket mechanism were overwhelmed as the flow would be able to surge around it and onto the primary splitter.

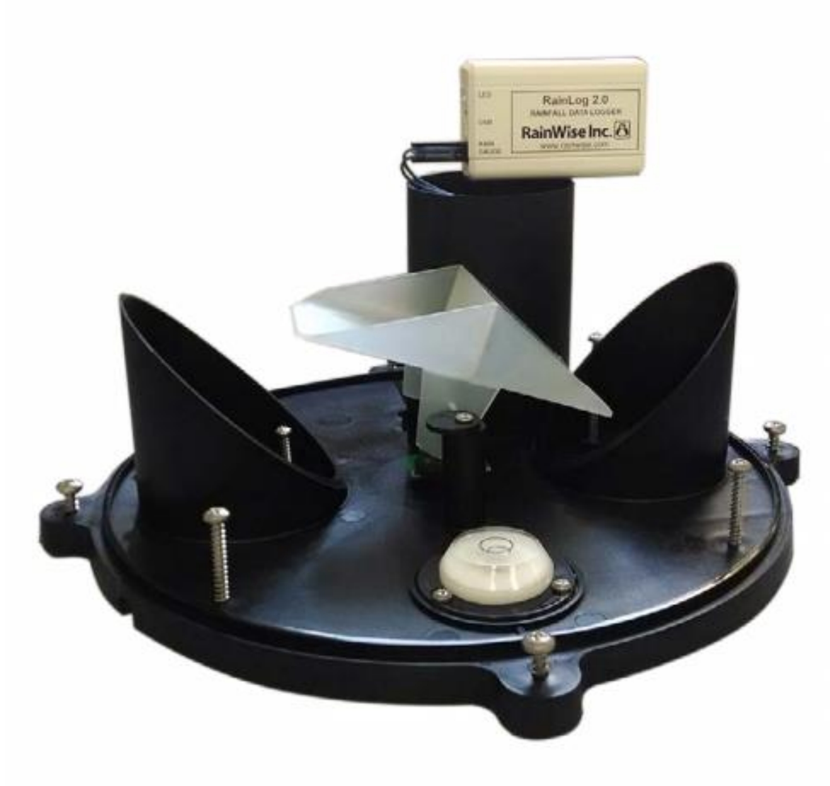


Figure 9-2 Tipping bucket rain gauge made by RainWise inc.

(Rain Measurement and Recording n.d)

9.1.4 Do away with the pulse flow valve altogether

In many flow events it is not necessary to have a sampling device capable of accurately splitting small flow. In such cases it may be preferable to completely do away with the pulse flow valve system and simply let the flow enter the sampling device unrestricted. If the flow rate to be sample can be estimated before an event the sampling device could be tuned for optimal performance with the primary splitter throat being restricted for sampling of modest flows using a restricting bush. For large flow the primary splitter throat can be left unrestricted to maximize capacity. Such measures simplify the sampler design but limit the device's operating range.

9.2 Primary flow splitter / Secondary flow splitter

The primary flow splitter that was developed and tested performed well with the results of flow splitting testing revealing accurate splitting performance. For future designs it may be beneficial to attempt to further increase the splitting ratio of the primary splitter, especially considering the failure of the secondary splitter. The primary splitter in this study split the flow 30 ways and had six sampling ports. The sampling rates available then had a minimum of 3.33% and a maximum of 20%. Sampling at a rate of 20% is not likely to ever be required and in most cases it would be desirable to sample at a rate even less than 3.33%, this is why the secondary flow splitter was originally designed.

There are two possibilities for development of the splitter used in this study:

9.2.1 Discard the secondary splitter and reduce the sampling rate of the primary splitter.

It is possible to design the primary flow splitter with additional vanes in order to split the flow more ways thus reducing the minimum sampling rate, in this case the secondary splitter could be done away with thus reducing the number of parts in the sampling device. As more splitting vanes are added the primary splitter internal will become crowded and the devices ability to pass particles may be compromised.

9.2.2 Place the secondary splitter before the primary splitter

It may be possible to split the flow before it enters the primary splitter, a pre-splitter could split the flow into halves or thirds before the primary splitter divides the flow many ways.

9.3 Discrete sampling rail

During testing it was observed that the discrete sampling rail always filled the sample bottles sequentially as intended. The sampling rail is bulky however with all the sample bottles being aligned causing a significant increase in the width of the sampling device. This arrangement is convenient for prototype work as it allows a good view of the rail and sample sealing valves during testing. For future designs the rail could be formed in a coil shape to make the design more compact and likely stronger. In many stormwater sampling programs it is not necessary to capture discrete samples, in such cases the sampling rail could be removed to simplify the system.

9.4 Sample sealing valves

The sample sealing valves proved effective allowing no leakage once locked in position. Future work on the sealing valves should focus on making the valves more compact and reducing the volume of water retained in the valve body after sealing. Excess water in the valve body does not fit into the sample bottle and is lost when the bottles are collected, this means a small volume of sample water is lost between each discrete sample.

The sample sealing valves uses neodymium magnets to energize the sealing action. As neodymium is a relatively expensive and limited resource it would be beneficial to make the valves work with cheap alnico magnets.

9.5 FLOW DURATION INDICATOR

As described in section 8.3 the original flow duration indicator was intended to use a pedometer to count cycles of a pulse flow valve providing flow duration information as a digital number of steps recorded by the pedometer. Owing the failure of the original pulse flow valve it was necessary to develop a new flow duration indicator. The alternate design is detailed in section 4.1.7. This design requires the capture of a time weighted sample of water which while it did prove accurate is inconvenient. The sampling rate for the device was 1.328L/h meaning long lasting flows would require the collection of large samples to indicate flow duration.

The device was however cheap and easy to make, and could be used on many other types of passive stormwater sampling devices.

If it is sought to develop a flow duration indicator that does not require the capture of a physical sample then a digital rain gauge as was shown in Figure 9-2 could provide a convenient solution. If a digital rain gauge were supplied with a small, constant flow rate then the “rain fall” recorded by the rain gauge would be proportional to the flow duration. The cost of this solution would be dependent on the quality of rain gauge used.

Another electronic solution to flow duration indication would be measure the conductivity across a pair of electrodes inside the sampling device. When water flows through the device conductivity would be detected across the electrodes, when the device is dry the conductivity is broken. A simple data logger could record the time for which conductivity is detected. This method of indicating flow duration would be more compact and likely more accurate than the other methods discussed. If a commercial version of the stormwater sampling device were made such electronics would likely prove very cheap due to their simple nature.

9.6 ADDITIONAL RECOMMENDATIONS

9.6.1 Parts Integration

In addition to the recommendations already made further development of the stormwater sampling device should attempt to compact and simplify the device in order to reduce production cost and make the device easier to deploy in the field. The simplest possible version of the device would consist of an intake reservoir connected to a primary flow splitter and a sample bottle connected directly to the splitter.

9.6.2 Intake screen

During testing of the sampling device water was supplied directly from the flow supply equipment to the intake reservoir of the sampler. In the field it would be necessary to screen incoming water to remove large contaminants like grass, fibre or gravel. Future work will need to evaluate the device’s trash handling ability and develop a system that can screen incoming flow to the necessary quality. The screen would need to be course enough to allow suspended solids through for sampling.

9.6.3 Field deployment rigging

In the field the stormwater sampling device is intended to be install in a pit drain or similar locations where flow to be sampled is falling. A practicality of field deployment will be the development of equipment and methods to securely fix the sampling device wherever it is to be deployed. Future design iterations of the device may include attachment points for field rigging.

10. CONCLUSION

This project was conducted with the aim develop a low cost flow-weighted stormwater sampling device suitable for widespread deployment in urban environments up to a proof of concept level. Review of literature revealed no commercially available or conceptual designs suited to the task so it was decided to pursue new design concepts for development and validation.

Design features for the storm water sampling device were presented in detail in chapter 4 with the most significant design innovation being the primary flow splitter. The primary flow splitter makes use of radially arranged vanes to split flow evenly 30 ways. Testing of the storm water sampler revealed the primary flow splitter to be capable of flow splitting accuracy in the order of 3%.

A significant limitation of the sampling device developed is the limited flow handling capacity of around 6L/min. Future design possibilities for the pulse flow valve and inlet reservoir are presented in chapter 9 that aim to improve this aspect of the design.

The experimental procedures detailed in chapter 6 worked well for validating the various performance parameters of the stormwater sampling device. As is mentioned in section 8.5 the testing procedure for assessing the device's ability to sample suspended solids could be improved by measuring total suspended solids of captured samples directly rather than using sample turbidity as a proxy.

The project as a whole has been successful with the stormwater sampling device developed performing well for all performance requirements, except for the limited flow handling capacity. It is expected that future refinement of the designs presented could further increase the performance of the device leading to eventual field deployment in actual stormwater monitoring programs.

10.1 FURTHER WORK

This project has been successful in developing a low cost passive stormwater sampling device capable of capturing flow weighted samples. The design has been developed to a proof of concept level and further work is required to further develop to design towards service in stormwater monitoring programs. There are three main areas for future work.

- Design refinement.
- Further performance testing under controlled conditions.
- Field testing.

10.1.1 Design refinement

Future design possibilities have been covered in detail in chapter 9. Effort should be especially devoted to increasing the flow capacity of the device and preparing the device for field deployment.

10.1.2 Further performance testing under controlled conditions

Any modifications made to the design should be tested under controlled conditions using procedures similar to those presented in this report. Then the benefits of any modifications can be quantified.

10.1.3 Field testing and development

The primary aim of future work should be to develop the design towards field deployment. The device will need to be field tested in a range of environments and then modified and retested as necessary to optimize infield performance and reliability.

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APPENDIX A - PROJECT SPECIFICATION

University of Southern Queensland

Faculty of Engineering and Surveying

ENG4111/ENG4112 Research project

Project Specification

FOR: Bryan Triaca.

TOPIC: Disposable stormwater sampling device for water quality hazard detection.

SUPERVISOR: Dr Ian Brodie.

PROJECT AIM: To design, build and test a low cost, passive stormwater sampling device capable of autonomously capturing flow-weighted stormwater sample. The device is to be developed to a proof of concept level. Testing will be under controlled conditions, not in field.

PROGRAMME:

1) Research current stormwater sampling methods and equipment to establish desirable performance criteria for mechanisms to be designed.
2) Design a prototype sampling device capable of meeting performance requirements.
3) Construct prototype.
4) Test prototype using flow simulation equipment to determine if the design concepts used in the prototype satisfactorily fulfil the design requirements.
5) Analyse testing results to develop an objective performance results and quantify the effect of any modifications to the device or it operating conditions.
6) Make recommendations of further work beyond proof of concept

As Time permits:

7) Have water samples tested for TSS to evaluate the devices ability to catch representative quantities of TSS.

APPENDIX B - LITERATURE REVIEW

A review of available literature revealed little information directly applicable to the design and testing of a compact flow-weighted stormwater sampling device with Dowling & Mar (1996) providing the only example of a similar project although their device was intended to fit in a culvert as opposed to a pit drain as in this project. Other sources however do provide valuable information regarding the general requirements and challenges of stormwater sampling. Presented below is a selection of works by others that are relevant to the project.

Clark, S.E., Siu, C.Y.S., Pitt, R., Roenning, C.D. & Treese, D.P. 2009, "Peristaltic pump autosamplers for solids measurement in stormwater runoff", *Water Environment Research,* vol. 81, no. 2, pp. 192-200, viewed 15-9-2014, Scopus

This paper discusses experiments conducted to assess the performance of automated water sampling devices that contain peristaltic pumps, including procedures, difficulties and results.

The paper is useful as it provides information on existing water sampling systems and their benefits and shortcomings. The quality of the experiments conducted cannot be determined from the abstract. Has been cited 8 times

Harmel, R.D., King, K.W. & Slade, R.M. 2003, "Automated stormwater sampling on small watersheds", *Applied Engineering in Agriculture,* vol. 19, no. 6, pp. 667-674, viewed 16-9-14, <http://cclynch.com/resources/Harmel_Automated%20Storm%20Water%20Sampling.pdf>

This paper explores automated water sampling strategies on small watersheds and provides guidelines on developing project specific sample strategies.

The paper describes stormwater sampling strategies in which disposable stormwater sampling devices could be included. The paper appears to be a practical guide rather than purely academic. The paper has be cited 29 times for a wide variety of purposes, it appears to be popular.

Standards Australia, Standards New Zealand 1998, *Water Quality – Sampling Part 1: Guidance on the design of sampling programs, sampling techniques and the preservation and handling of samples*, AS/NZS 5667.1:1998, Standards Australia, Standards New Zealand, Australia, New Zealand, viewed 16-9-14, <http://www.saiglobal.com.ezproxy.usq.edu.au/online/autologin.asp>

This is the first part for the AS/NZ water quality sampling standard it includes guidelines for safety, reliability, quality and equipment.

Being the standard officially recognized in Australia the standard can be considered reliable and trust worthy. Information contained in this standard that is of particular value includes recommendations on the selection of containers to be used for water sampling with details on materials, shape and cleaning procedures. There is also information regarding how poor material choice can compromise the sample.

Harmel, R.D., King, K.W., Wolfe, J.E. & Torbert, H.A. 2002, "Minimum flow considerations for automated storm sampling on small watersheds", *Texas Journal of Science,* vol. 54, no. 2, pp. 177-188, viewed 15-9-2014, Scopus

Paper discusses the parameters that effect the determination of minimum qualifying flow that will trigger a water sampling device. The paper provides relevant context for the applications and consideration for automatic water sampling devices.

Graczyk, D.J, Robertson, D.M, Rose, W.J, Steuer, J.J 2000, *Comparison of Water-Quality Samples Collected by Siphon Samplers and Automatic Samplers in Wisconsin*, U.S. Geological Survey USA, USGS Fact Sheet FS-067-00, viewed 16-9-14, < http://wi.water.usgs.gov/pubs/FS-067-00/FS-067-00.pdf>

Fact sheet produced by the USGS details the construction of a common siphon samplers and compare the results obtained from field tested siphon samplers to automatic samplers.

Useful resource clearly shows how to construct and use a siphon sampler. The siphon sampler operation provides a way of setting the minimum and maximum water levels at which sampling will occur. The principle may be transferable to the design of a disposable water sampling device. This is not a peer reviewed journal article but it does come from a reputable source. The document also compares the concentrations of pollutants found in water samples collected by siphon samplers and automatic samplers with minimal differences detected.

Mackay, A.K. & Taylor, M.P. 2012, "Event-Based Water Quality Sampling Method For Application In Remote Rivers", *River Research and Applications,* vol. 28, no. 8, pp. 1105-1112, viewed 15-9-2014, Scopus

An Australian paper on the design and operation of a siphon sampler for use in high intensity flow situation encounter in Australia’s dry land rivers.

This paper provides another example of siphon sampler design and application, this time with a focus on use in fast flowing water. The paper discuses design features including materials selection and geometry. Provides a valuable example of application of sampling devices in Australia.

Harmel, R.D., King, K.W., Haggard, B.E., Wren, D.G. & Sheridan, J.M. 2006, "Practical guidance for discharge and water quality data collection on small watersheds", *American Society of Agricultural and Biological Engineers,* vol. 49, no. 4, pp. 937-948, viewed 15-9-2014, < http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs143_013391.pdf>

Paper describes the practical considerations when collecting samples from small watersheds.

Paper presents some important practical considerations for water sampling. There are details regarding procedures and recommendation for deploying automatic sampling equipment that will be transferable to the deployment of disposable sampling devices. Limitations and difficulties associated with sampling procedures are also presented which can hopefully be reduced by the use of disposable sampling devices. There is mention of mechanical flow-proportion samplers that require no power source to operate. The authors Harmel and King appear to have several published papers relevant to my project.

Brodie, I, Porter, M 2004, Use of Passive Stormwater Samplers in Water Sensitive Urban Design, PHD project, University of Southern Queensland, viewed 17-9-14, <https://eprints.usq.edu.au/3579/1/Brodie_Porter.pdf>

A paper from USQ, Investigates several conventional passive stormwater sampling devices.

This paper contains previous work conducted within USQ. Addresses a variety of passive stormwater sampling devices and explains the water sampler parameters that were considered significant in assessing the designs.

Roseen, R.M., Ballestero, T.P., Fowler, G.D., Guo, Q. & Houle, J. 2011, "Sediment monitoring bias by automatic sampler in comparison with large volume sampling for parking lot runoff", *Journal of Irrigation and Drainage Engineering,* vol. 137, no. 4, pp. 251-257, viewed 15-9-2014, Scopus

Paper detailing a field study testing the ability of auto samplers to catch representative TSS samples.

Provides an insight into the performance of auto samplers along with details on the methodology used for assessing TSS capture performance

Bach, P.M., McCarthy, D.T. & Deletic, A. 2010, "The development of a novel approach for assessment of the first flush in urban stormwater discharges", *Water Science and Technology,* vol. 61, no. 10, pp. 2681-2688, viewed 15-9-2014, Scopus

Discusses the validity of first flush discrete stormwater sampling methods and compares them to true flow weighted methods. Applies to urban environments in Australia.

Dowling, S & Mar, B. 1996, 'Culvert Composite Sampler: A Cost-Effective Storm-Water Monitoring Device.' *Journal of water Resource Planning and Management*, vol. 122. pp 280–286, viewed 28-10-2014, American Society of Civil Engineers, ASCE Library.

Paper describing one team's effort to design, build, test a device that could catch a flow-weighted stormwater sample from a culvert.

The device was fundamentally flawed so it was never going to work well. There is a good bit of relevant background information that the authors have found from other sources.

DeGroot,G.P, Gulliver, J.S, Mohseni, O 2009, Accurate Sampling of Suspended Solids', World Environmental and Water Resources Congress 2009, pp 807-813, viewed 28-10-2014, American Society of Civil Engineers, ASCE Library.

Proposes ways to improve the ways in which samples for TSS are collected using automatic samplers. The paper attribute the main cause of non-representative TSS to be a result of different TSS concentration in the flow column, a device is proposed to solve this problem by capturing the sample at multiple heights in the flow. The device is not built or tested. Provides useful information regarding the significance of TSS particle sizes.

Bent, G.C, Gray, J.R, Smith, K.P, Glysson, G.D 2001, 'A Synopsis of Technical Issues for Monitoring Sediment in Highway and Urban Runoff'. PDF, U.S. Geological Survey USA, viewed 29/10-2014, <http://pubs.usgs.gov/of/2000/ofr00-497/pdf/ofr00497.pdf>

Quality article. Discusses the importance and difficulty of sampling stormwater for the purpose of quantifying sediment load in runoff water.

Information of most value includes details of passive and automatic sampling devices. Also provides additional information regarding the handing and analysis of sediment samples.

Surface water sampling methods and analysis — technical appendices 2009, PDF, Government of Western Australia Department of Water, viewed 15/11-2014, <http://www.water.wa.gov.au/PublicationStore/first/87152.pdf>

A large collection of WA government approved standard operating procedures for sampling and analysing of surface waters.

Of particular interest provide good instructions for the collection and preservation of TSS samples. References the Australian standards relevant to the testing procedures.

Weiss, P.T, Erickson, A.J, Gulliver, J.S, Hozalski, R.M, Mohseni, O, Herb W.R 2010, *Samples per storm events*, University of Minnesota, St. Anthony Falls Laboratory USA, viewed 29/10-2014, <http://stormwaterbook.safl.umn.edu/content/samples-storm-events>

Extract from the book 'Optimizing stormwater Treatment Practices'

Very valuable resource. Provides good information on flow-weighted, time-weighted and user-defined sampling. Also explains composite and discrete samples. Gives details on the benefits and applications of different methods along with details regarding the analysis of such sampling methods.

Chemical tracers 2013, CSIRO Australia, viewed 15/11-2014, <http://www.csiro.au/Outcomes/Energy/Energy-from-coal/Chemical-tracers.aspx>

Information regarding the CSIRO's range of chemical tracers.

Intended for ground water but of possible use for testing the devices ability to protect samples from dilution. Also provides information on different classes of chemical tracers.

Understanding Tracers & Groundwater modelling n.d, PDF, National centre for groundwater research and Training Australia, viewed 15/11-2014, <http://www.groundwater.com.au/media/W1siZiIsIjIwMTIvMTIvMTkvMTZfNTFfMjlfNjgyX1RyYWNlcnNfRklOQUwucGRmIl1d/Tracers_FINAL.pdf>

Paper describing the different types of water traces both chemical and non-chemical.

Additional information on traces.

Measuring Total Suspended Solids and Turbidity in lakes and streams, n.d, Department of Ecology State of Washington USA, viewed 16/11-2014, <http://www.ecy.wa.gov/programs/wq/plants/management/joysmanual/4tss.html>

Practical guide to TSS measurements.

Good instructions on how to perform a TSS analysis. Indicates that equipment will be cost prohibitive.

Keith, L 1991, *Environmental Sampling and Analysis,* Lewis Publishers, USA

A guide to environmental sampling procedures and analysis. Provides good information regarding the practical considerations of and environmental sampling plan.

APPENDIX C - EXPERIMENTAL DATA

In this appendix raw data from experimentation is presented.

Flow splitting experimental data

Splitter configuration: P=1/30, S=1/5		Theoretical sampling rate: 0.667%	Water Temperature:13°C
	Nominal flow rate: 5.5L/min	Nominal flow rate: 3.5L/min	Nominal flow rate: 1.8L/min
Run 1			
Sample Time	0:18:15	0:08:31	0:16:24
Start crane scale reading (kg)	0	0	0
End crane scale reading (kg)	-101.5	-30.1	-30.0
Sample weight (kg)	0.876	0.206	0.055
Actual sampling rate (%)	0.863%	0.684%	0.183%
Run 2			
Sample Time	0:18:06	0:08:32	0:16:20
Start crane scale reading (kg)	0	0	0
End crane scale reading (kg)	-100.3	-30.1	-30.1
Sample weight (kg)	0.845	0.206	0.069
Actual sampling rate (%)	0.842%	0.684%	0.229%
Run 3			
Sample Time	0:18:09	0:08:33	0:16:15
Start crane scale reading (kg)	0	0	0
End crane scale reading (kg)	-100.8	-30.1	-30.1
Sample weight (kg)	0.836	0.207	0.075
Actual sampling rate (%)	0.829%	0.688%	0.249%

Flow splitting experimental data

Splitter configuration: P=3/30, S=1/5		Theoretical sampling rate: 2%	Water Temperature:13°C
	Nominal flow rate: 5.5L/min	Nominal flow rate: 3.5L/min	Nominal flow rate: 1.8L/min
Run 1			
Sample Time	0:18:21	0:08:25	0:16:25
Start crane scale reading (kg)	0	0	0
End crane scale reading (kg)	-101.1	-30.0	-30.0
Sample weight (kg)	1.931	0.401	0.378
Actual sampling rate (%)	1.910%	1.367%	1.260%
Run 2			
Sample Time	0:17:54	0:08:30	0:16:16
Start crane scale reading (kg)	0	0	0
End crane scale reading (kg)	-100.1	-30.0	-30.1
Sample weight (kg)	1.842	0.404	0.380
Actual sampling rate (%)	1.840%	1.347%	1.262%
Run 3			
Sample Time	0:17:41	0:08:32	0:16:30
Start crane scale reading (kg)	0	0	0
End crane scale reading (kg)	-100.2	-30.2	-30.1
Sample weight (kg)	1.916	0.398	0.385
Actual sampling rate (%)	1.912%	1.318%	1.279%

Flow splitting experimental data

Splitter configuration: P=1/30, S=N/A		Theoretical sampling rate: 3.33%	Water Temperature:13°C
	Nominal flow rate: 5.5L/min	Nominal flow rate: 3.5L/min	Nominal flow rate: 1.8L/min
Run 1			
Sample Time	0:17:04	0:08:35	0:16:25
Start crane scale reading (kg)	0	0	0
End crane scale reading (kg)	-100.0	-30.0	-30.0
Sample weight (kg)	3.35	0.968	1.034
Actual sampling rate (%)	3.350%	3.227%	3.447%
Run 2			
Sample Time	0:17:12	0:08:32	0:16:15
Start crane scale reading (kg)	0	0	0
End crane scale reading (kg)	-100.1	-30.1	-30.0
Sample weight (kg)	3.33	0.998	0.991
Actual sampling rate (%)	3.327%	3.316%	3.303%
Run 3			
Sample Time	0:17:14	0:08:38	0:16:16
Start crane scale reading (kg)	0	0	0
End crane scale reading (kg)	-100.1	-30.2	-30.1
Sample weight (kg)	3.50	1.058	1.052
Actual sampling rate (%)	3.497%	3.503%	3.495%

Flow splitting experimental data

Splitter configuration: P=3/30, S=N/A		Theoretical sampling rate: 10%	Water Temperature:13°C
	Nominal flow rate: 5.5L/min	Nominal flow rate: 3.5L/min	Nominal flow rate: 1.8L/min
Run 1			
Sample Time	0:17:11	0:08:37	0:16:28
Start crane scale reading (kg)	0	0	0
End crane scale reading (kg)	-100.3	-30.0	-30.0
Sample weight (kg)	9.48	2.98	2.85
Actual sampling rate (%)	9.452%	9.867%	9.500%
Run 2			
Sample Time	0:17:08	0:08:29	0:16:43
Start crane scale reading (kg)	0	0	0
End crane scale reading (kg)	-100.4	-30.0	-31.5
Sample weight (kg)	9.48	2.91	3.03
Actual sampling rate (%)	9.442%	9.700%	9.619%
Run 3			
Sample Time	0:17:06	0:08:32	0:16:24
Start crane scale reading (kg)	0	0	0
End crane scale reading (kg)	-100.1	-30.1	-30.1
Sample weight (kg)	9.60	2.95	2.91
Actual sampling rate (%)	9.590%	9.801%	9.668%

Flow duration experimental data

	Flow duration indicator			Water Temperature:14
	Nominal flow rate: 7.0L/min	Nominal flow rate: 4.8L/min	Nominal flow rate: 1.6L/min	Nominal flow rate: 0.6L/min
Run 1				
Sample Time	0:20:15	0:32:19	0:32:45	0:32:10
Start crane scale reading	199.8	204.0	202.5	157.2
End crane scale reading	54.5	50.7	149.8	137.0
Sample weight	0.456	0.720	0.705	0.708
Sampling rate (L/hour)	1.351	1.337	1.292	1.321
Run 2				
Sample Time	0:20:01	0:31:32	0:32:08	0:33:15
Start crane scale reading	203.5	201.9	149.8	137.0
End crane scale reading	60.9	49.9	96.4	117.9
Sample weight	0.449	0.706	0.718	0.716
Sampling rate (L/hour)	1.346	1.343	1.340	1.292

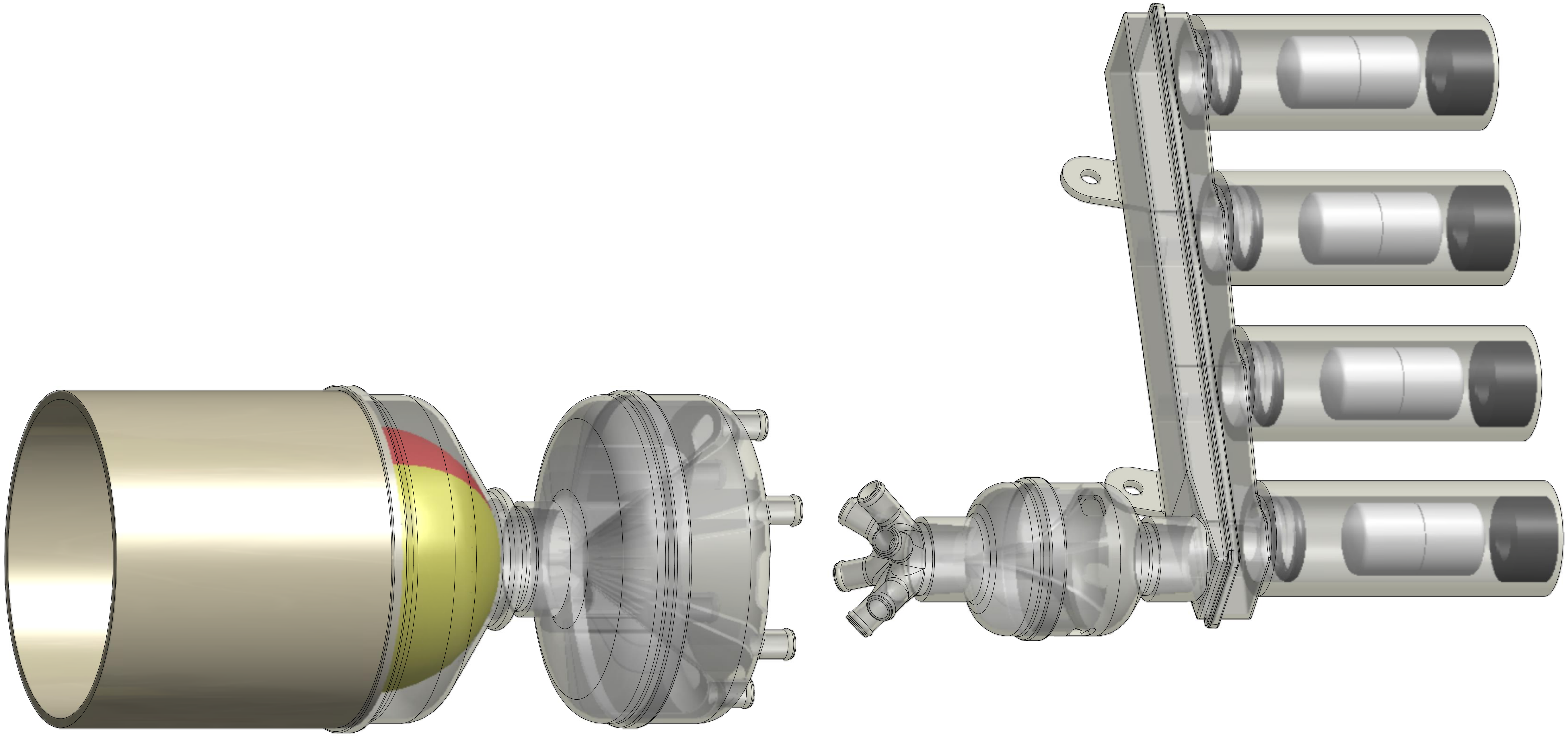
Turbidity testing experimental data sheet

	Run 1	Run 2	Run 3	Run 4
Sample time	0:30:00	0:30:00	0:30:00	0:30:00
Total flow (L)	90	90	180	180
Sample volume (L)	2.82	2.65	5.21	5.84
Sample turbidity (FTU)	150	180	185	230
Flow turbidity (FTU)	155	180	180	225
Turbidity difference	-5	0	5	5

Sample contamination experimental data

	Run 1	Run 2
Test water free copper concentration, simulation start	46mg/L	46mg/L
Test water free copper concentration, simulation end	46mg/L	46mg/L
Flow duration	0:29:17	0:29:44
Start crane scale reading	0	0
End crane scale reading	-150.2	-150.1
Sample bottle 1 free copper concentration	0mg/L	0mg/L
Sample bottle 2 free copper concentration	0mg/L	0mg/L
Sample bottle 3 free copper concentration	0mg/L	0mg/L
Sample bottle 4 free copper concentration	0mg/L	0mg/L

APPENDIX D - STORMWATER SAMPLING DEVICE DETAILS



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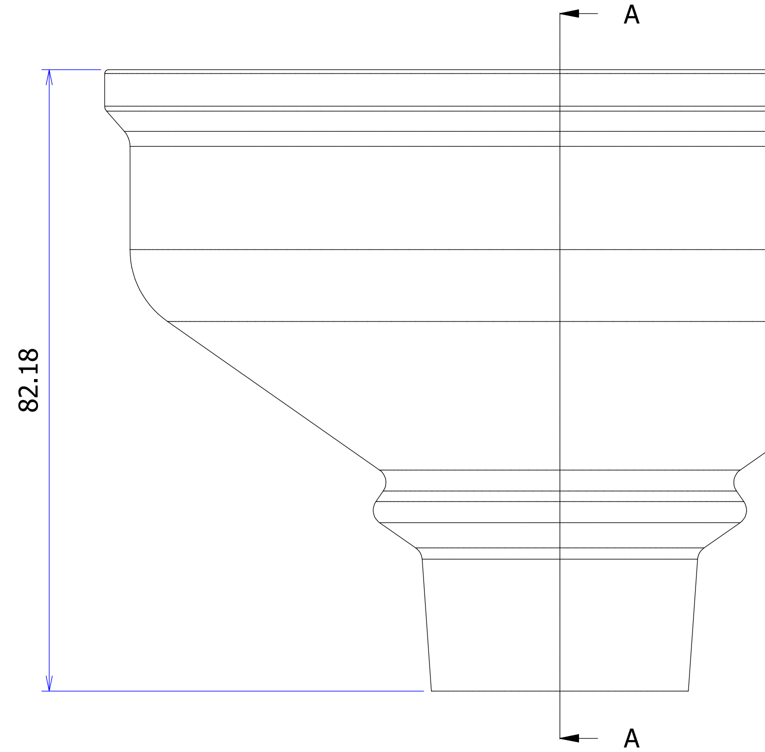
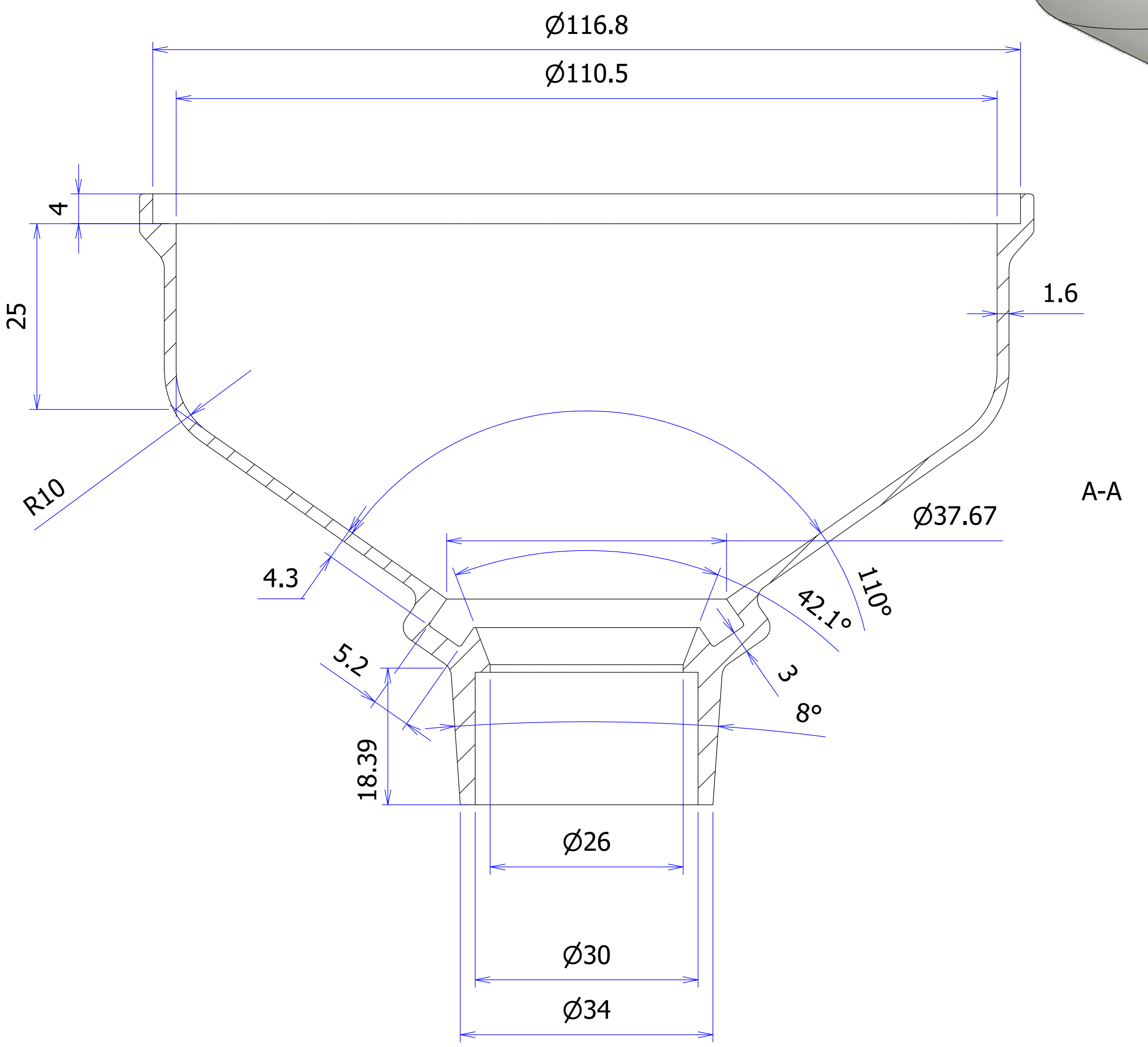
	Overview	Edition	Sheet 1 / 10





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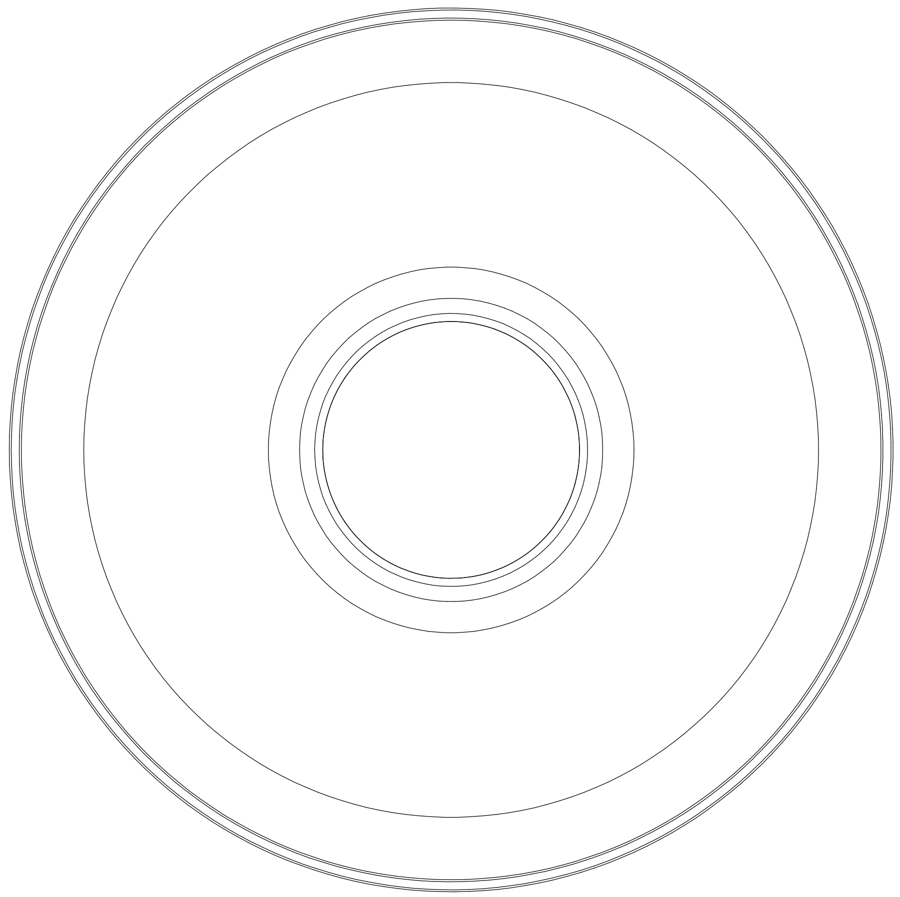

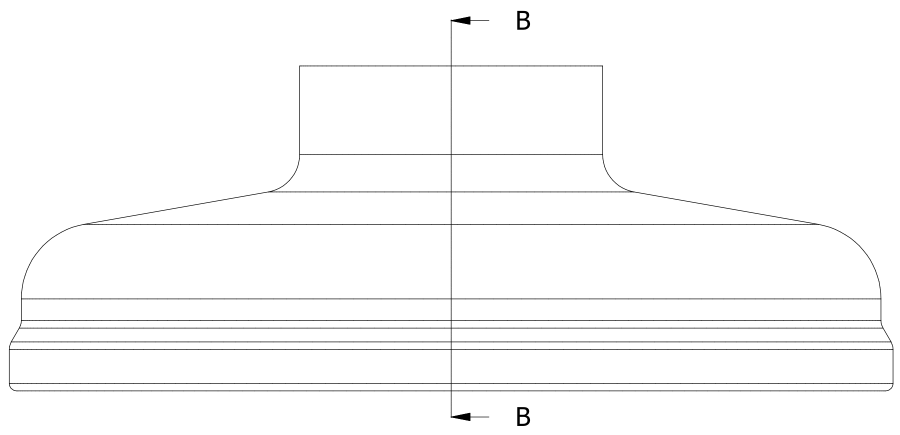

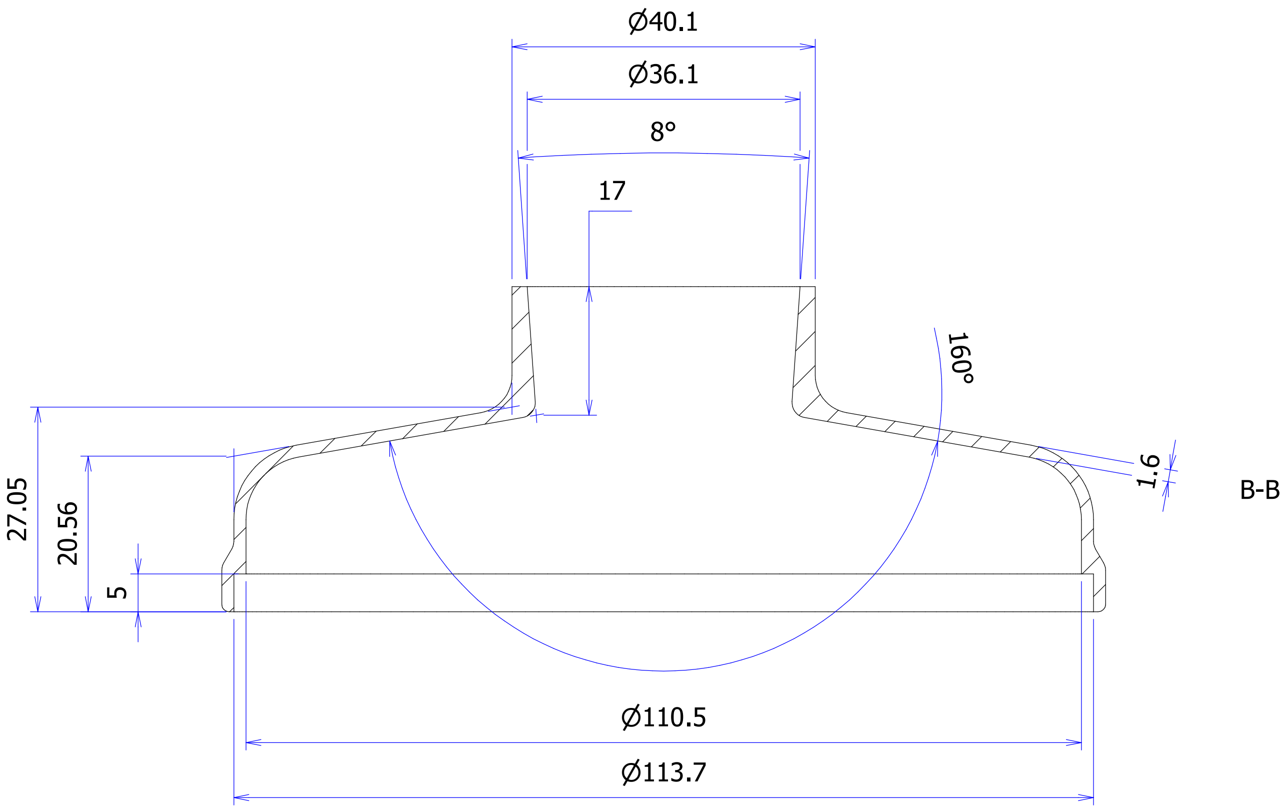

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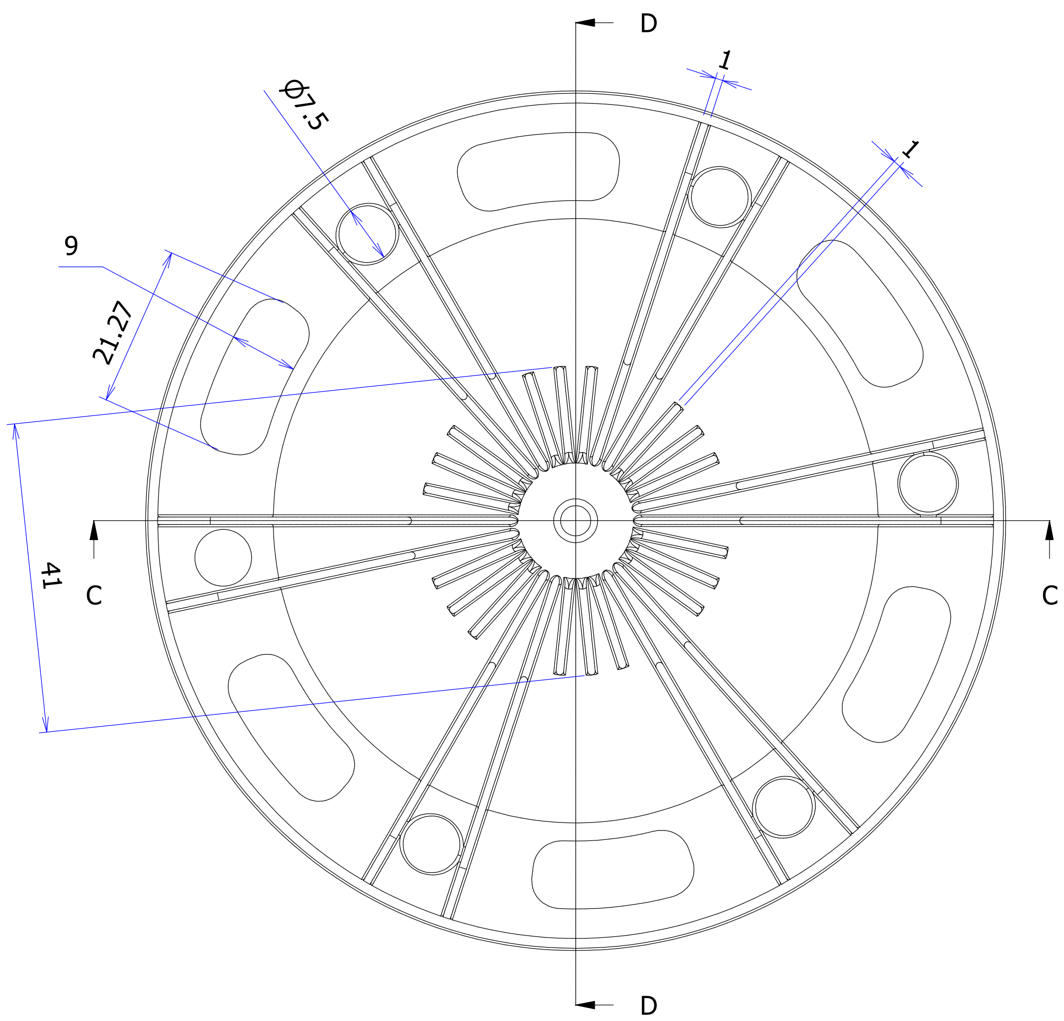
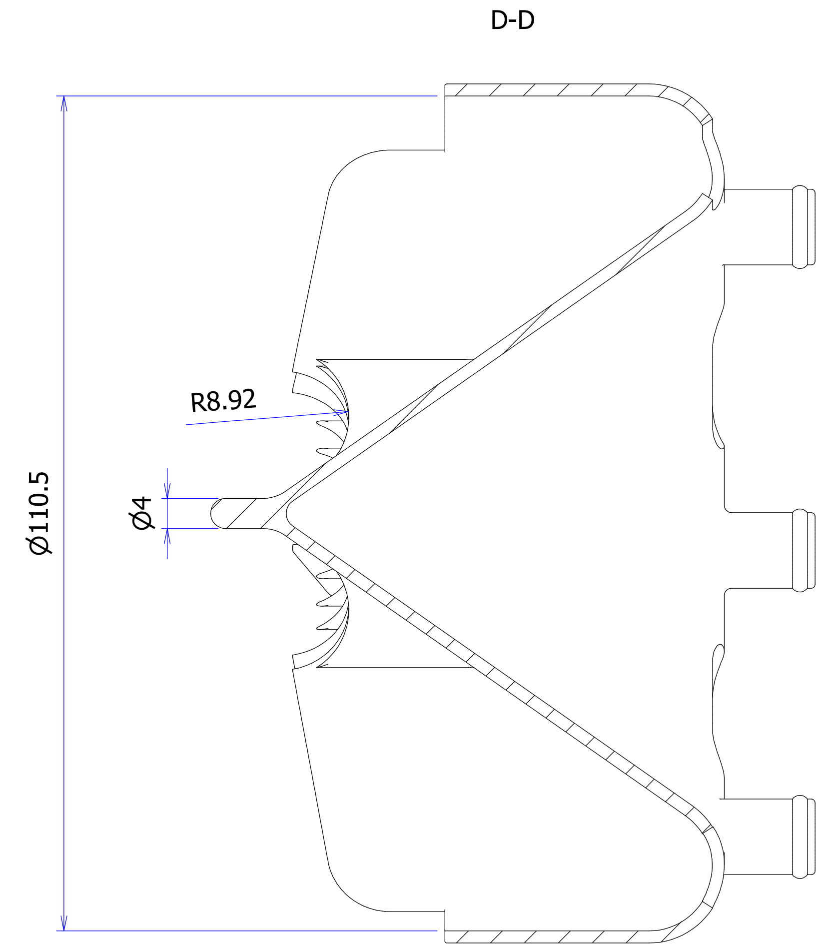
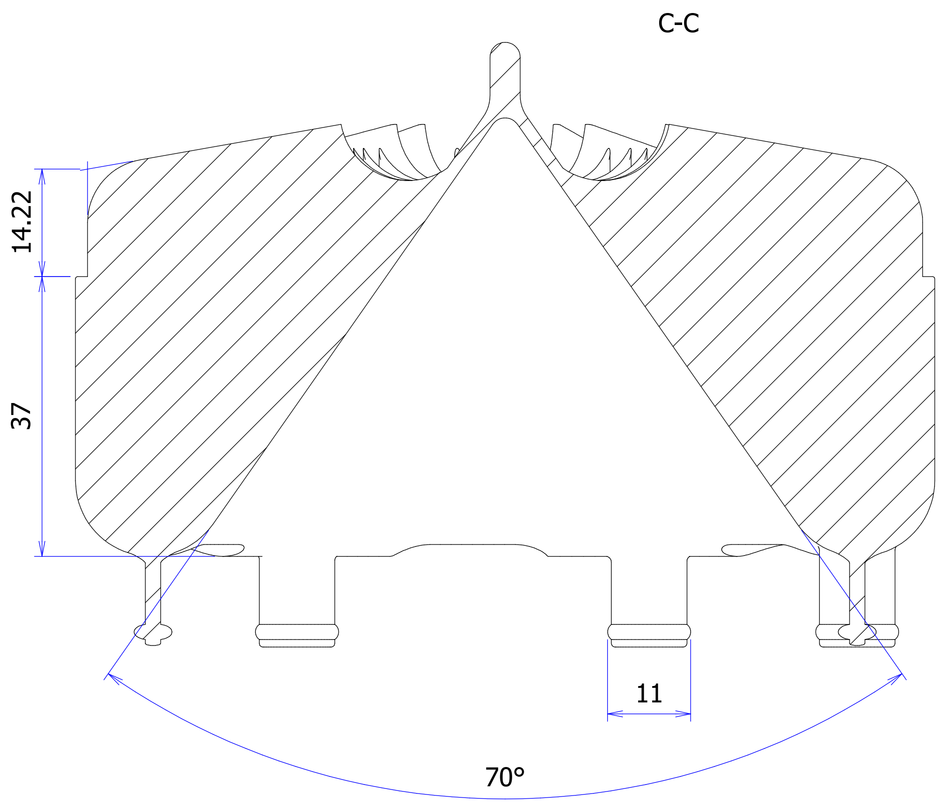
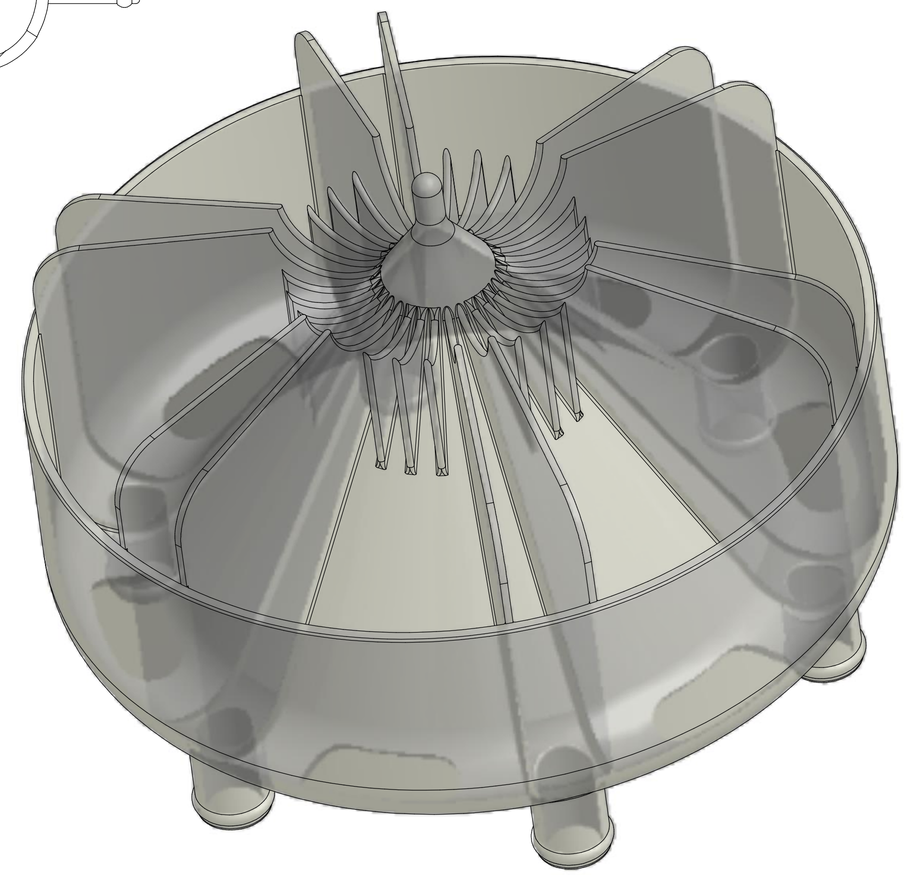
Primary Splitter Cap	Edition	Sheet 3 / 10









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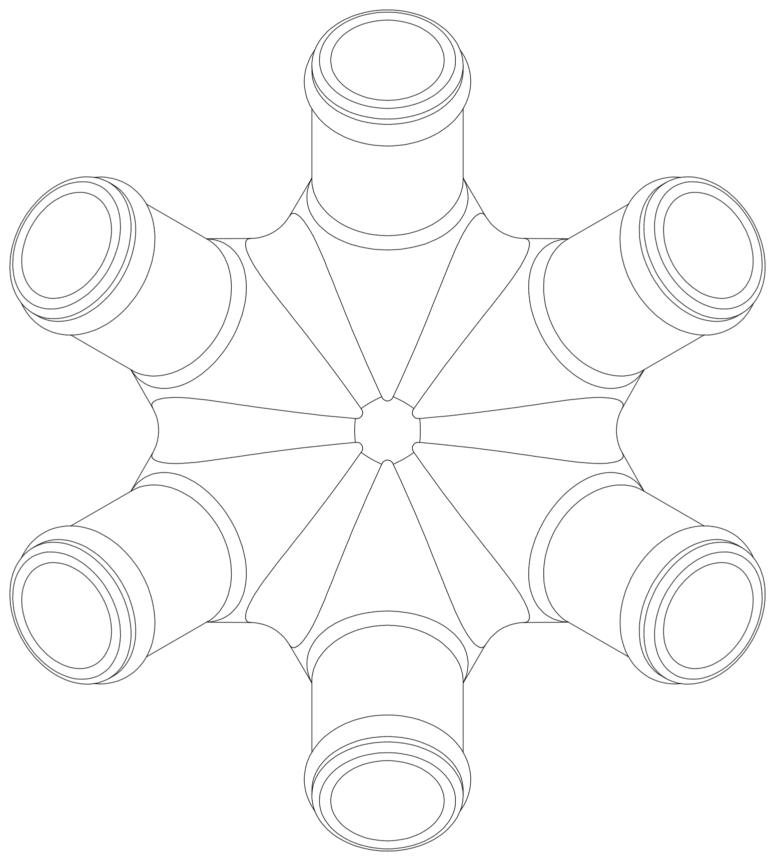

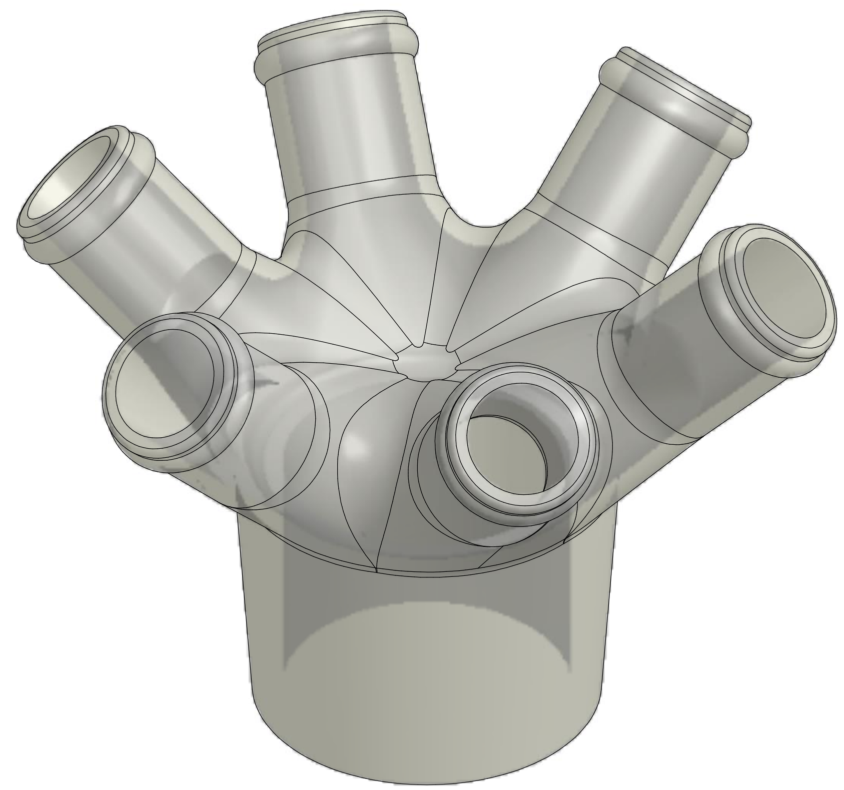

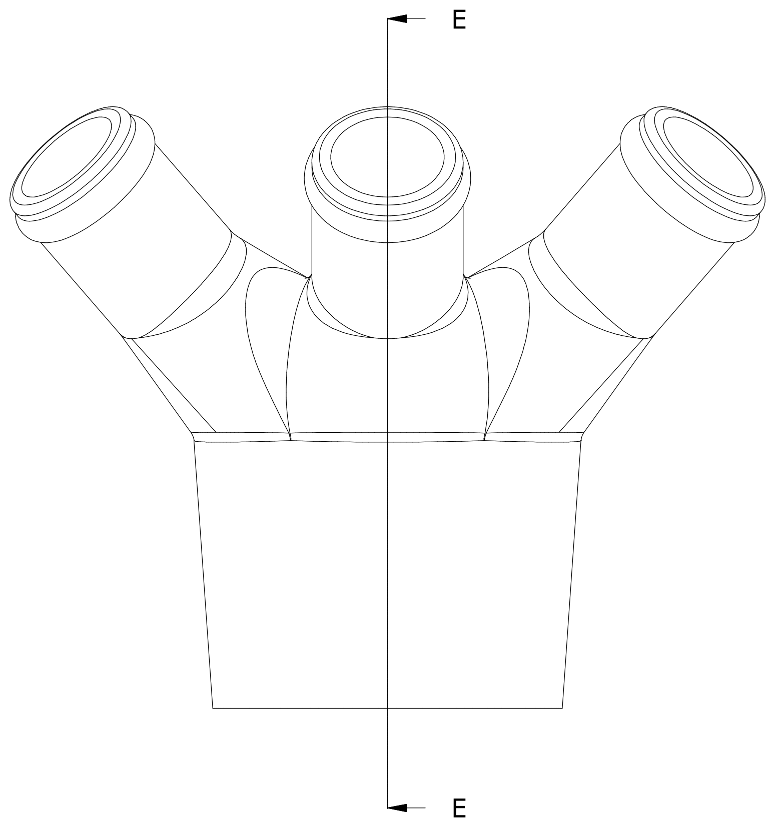

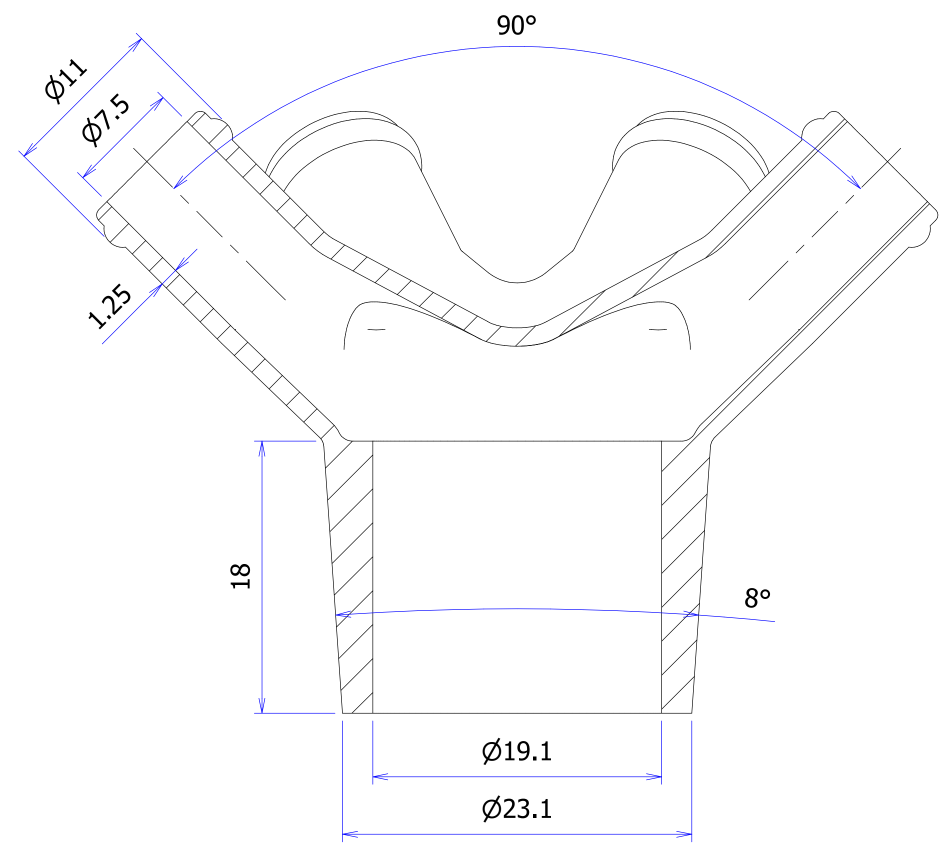

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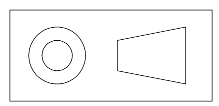

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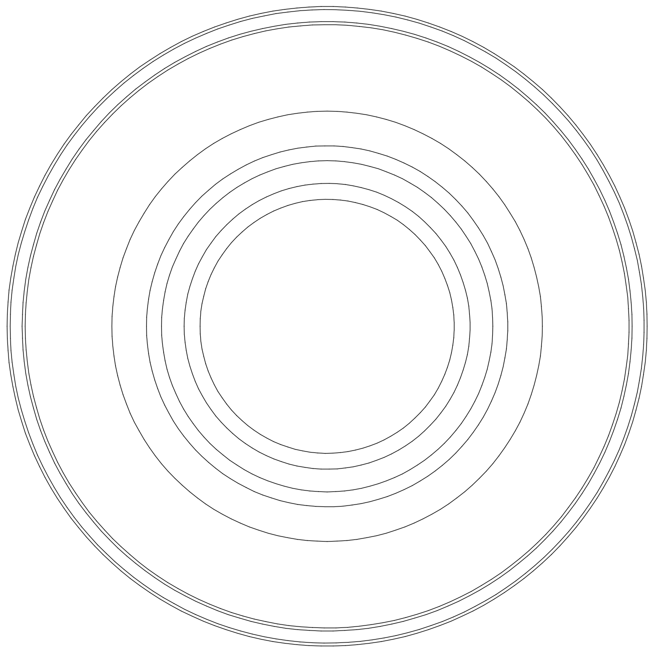

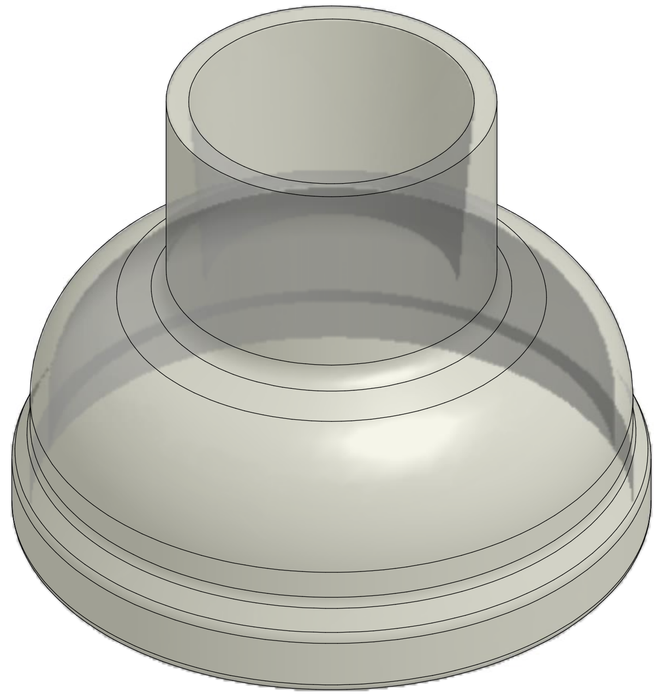

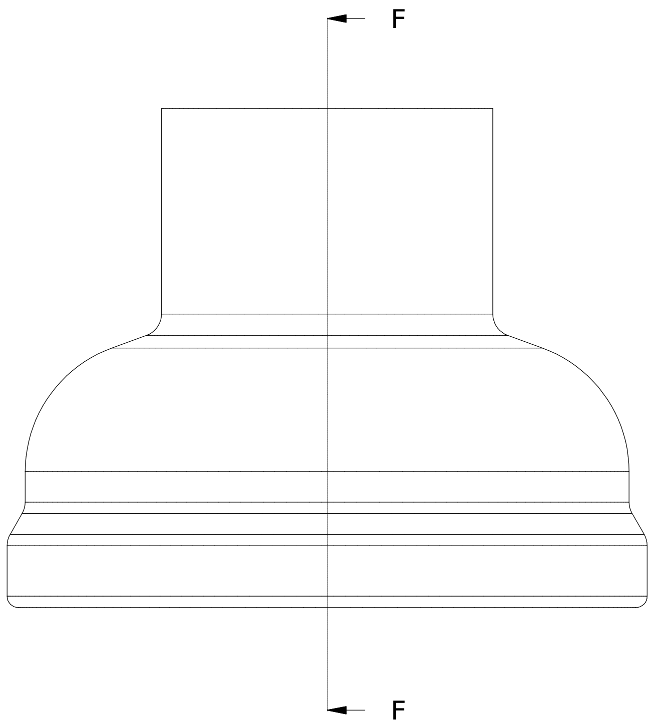

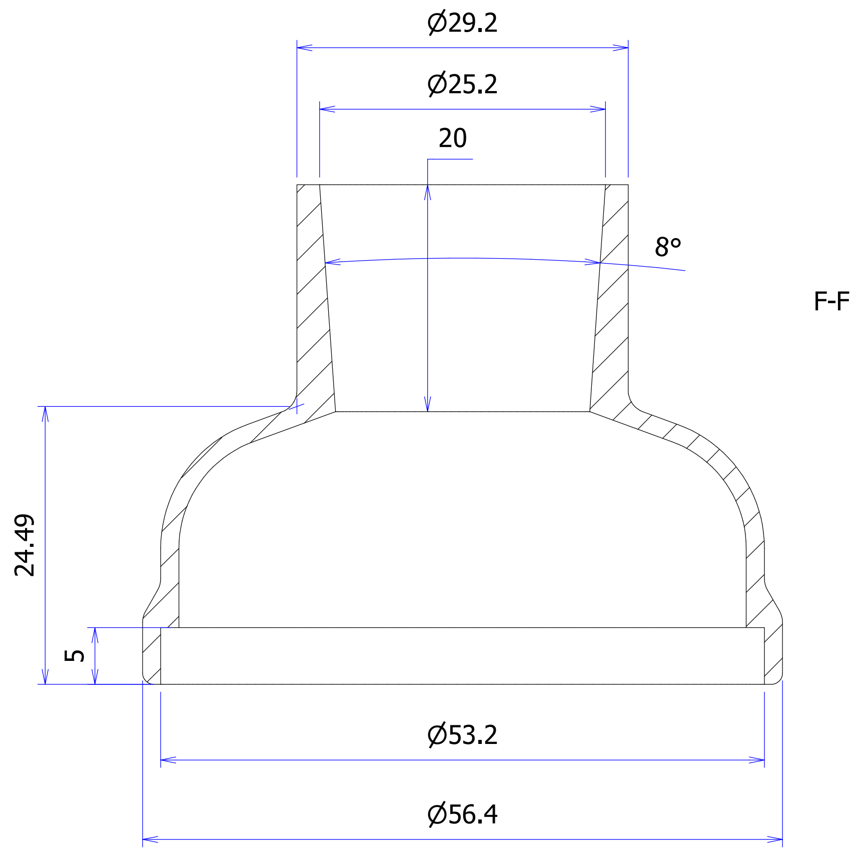

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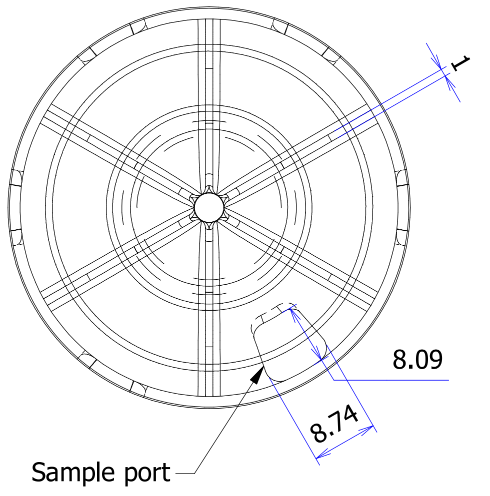

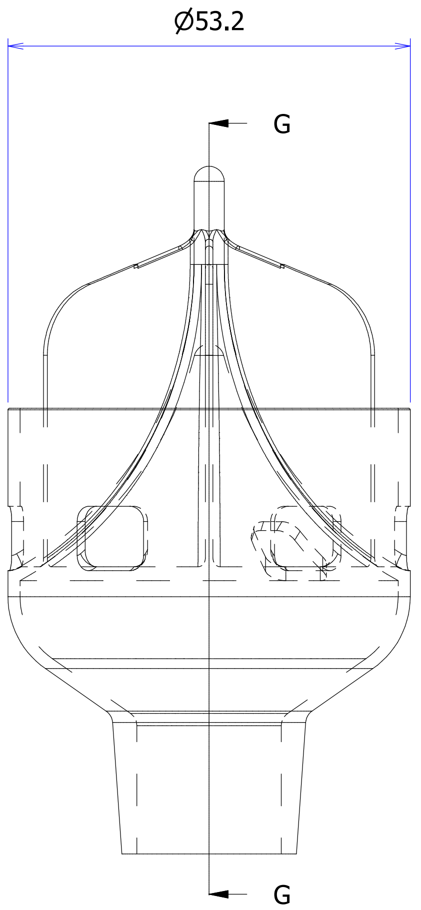

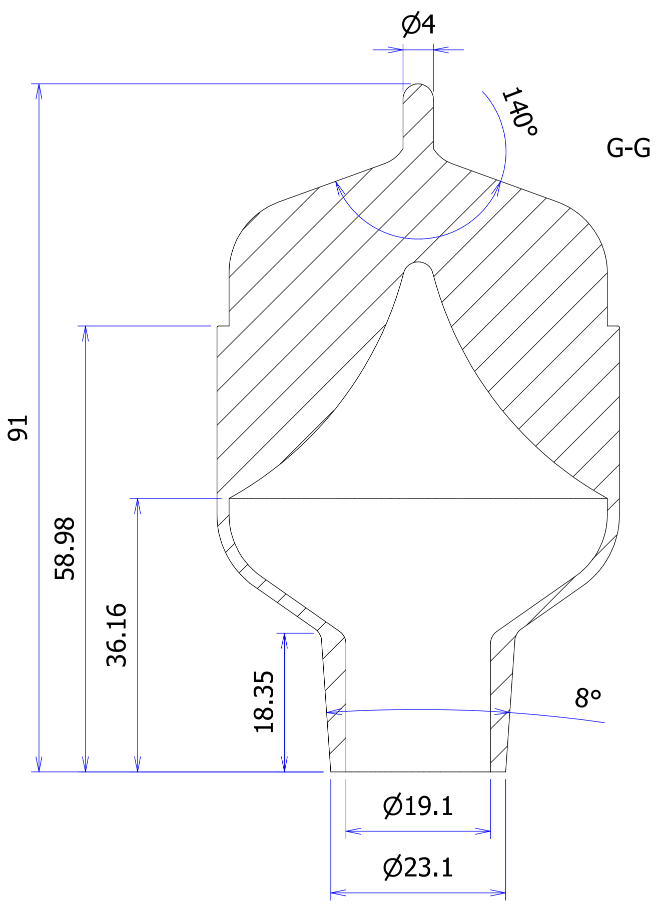

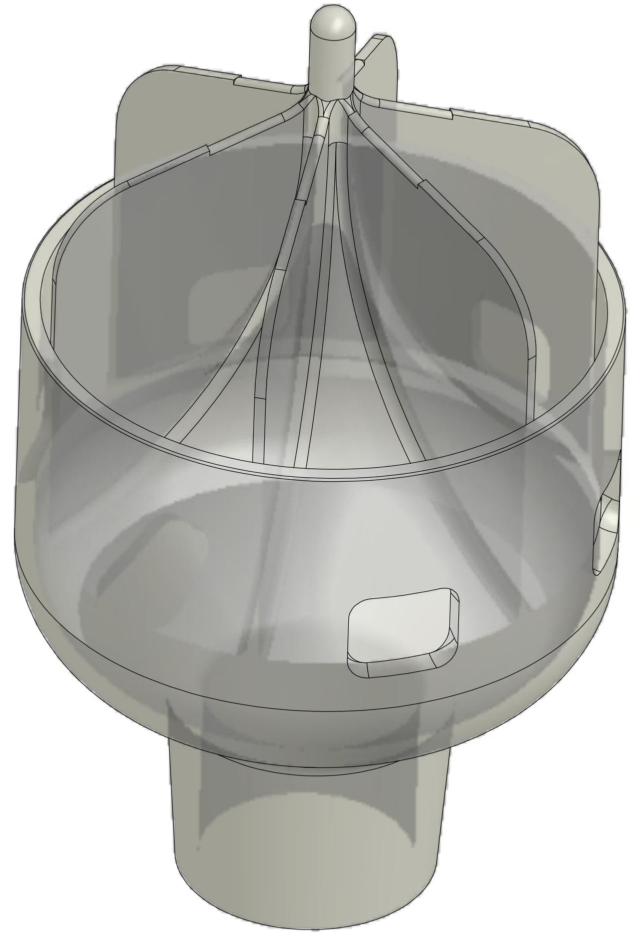

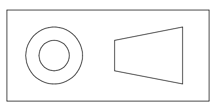

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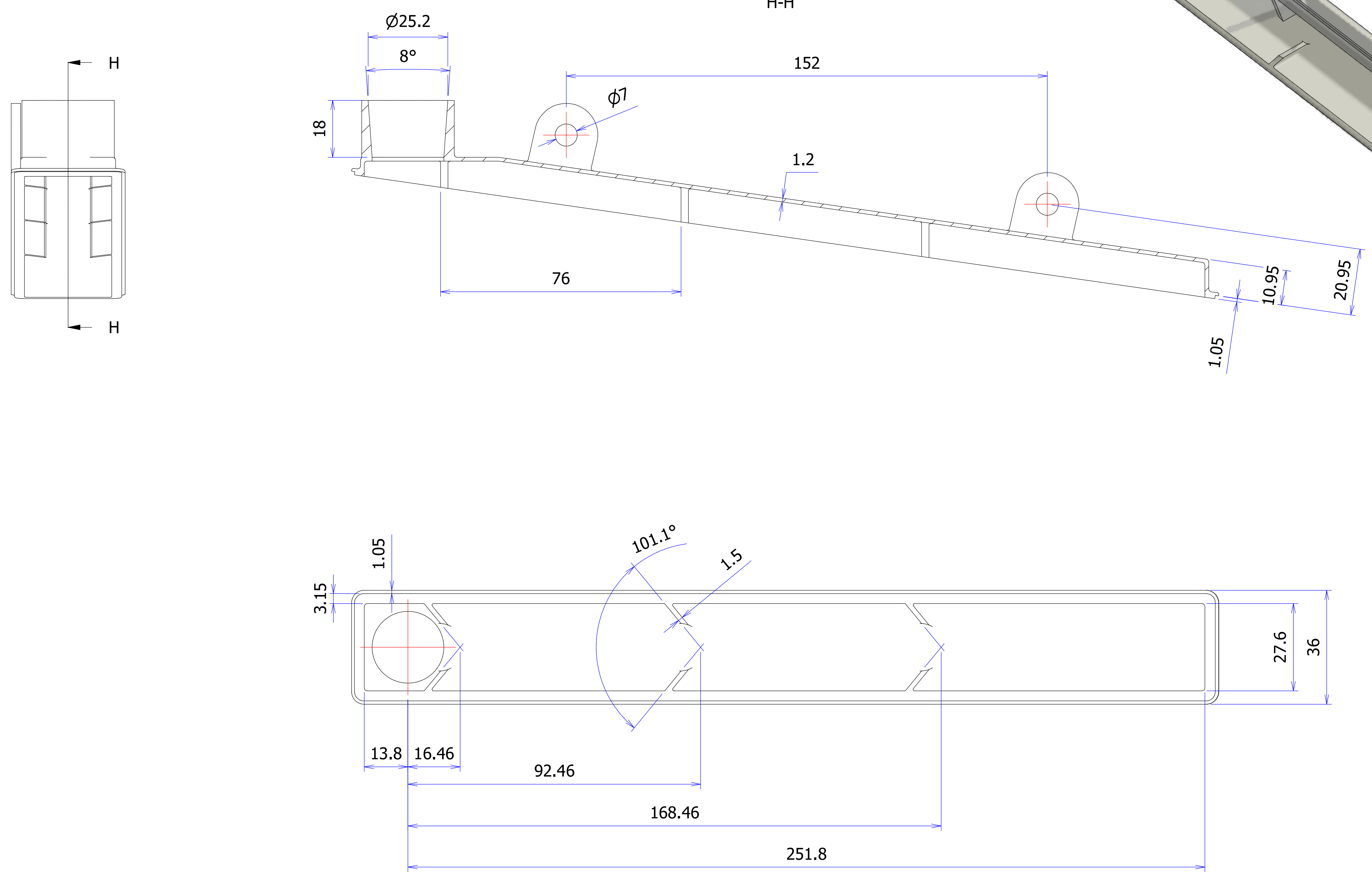

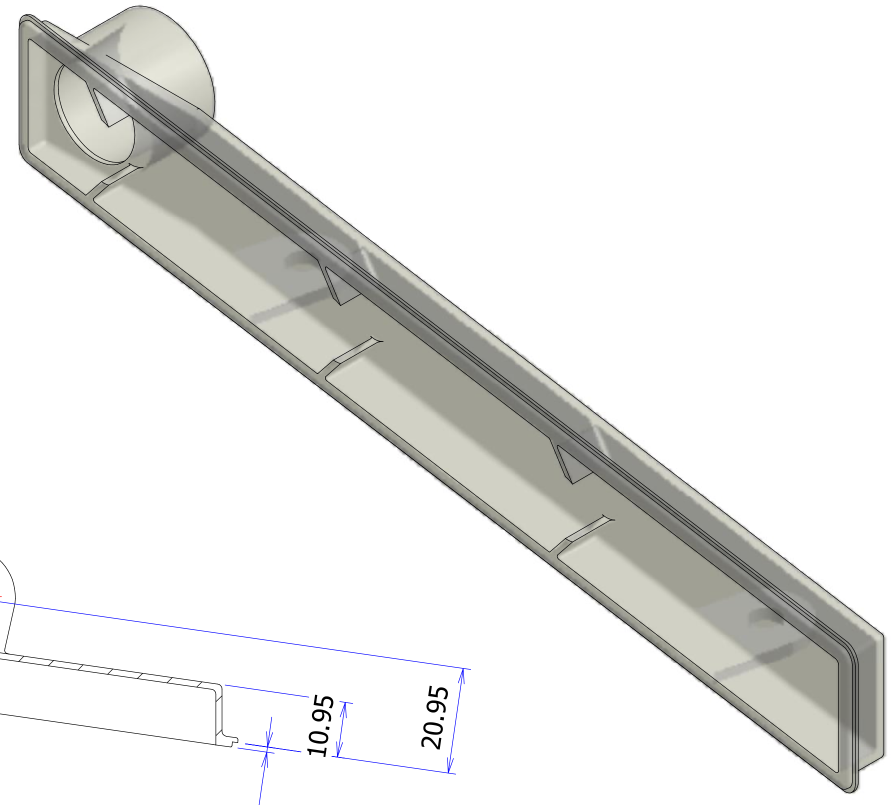

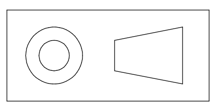

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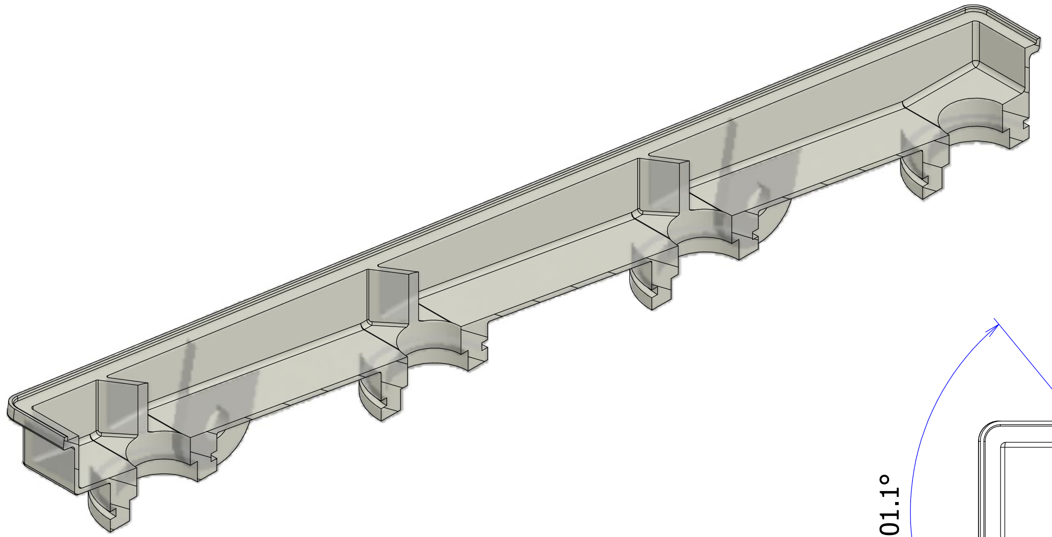
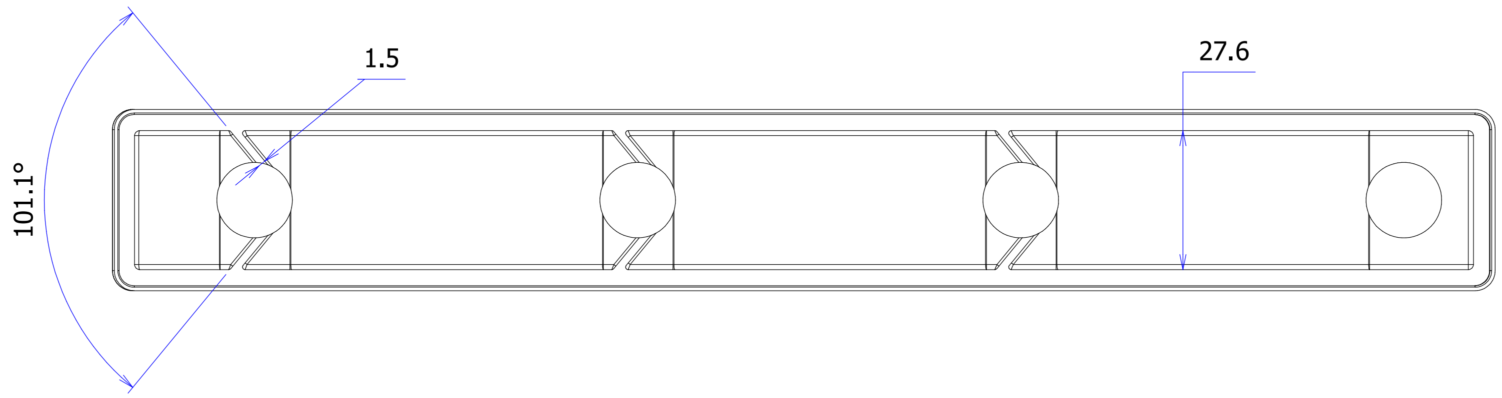
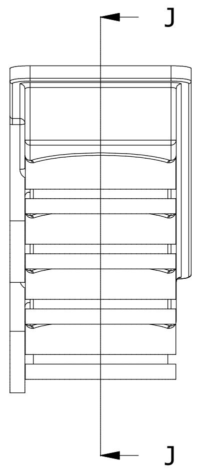
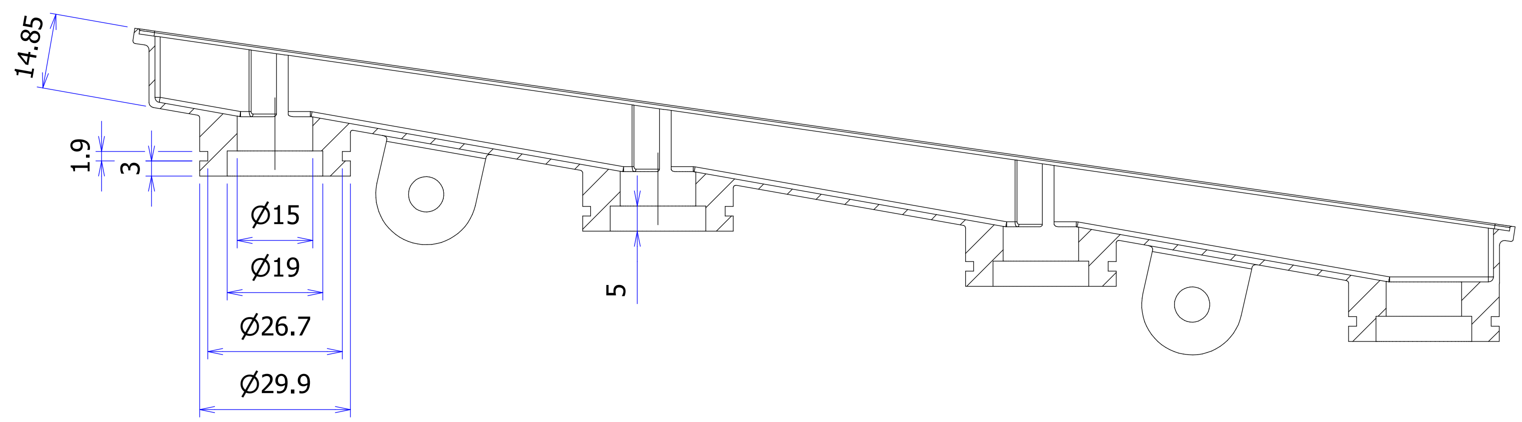
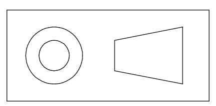






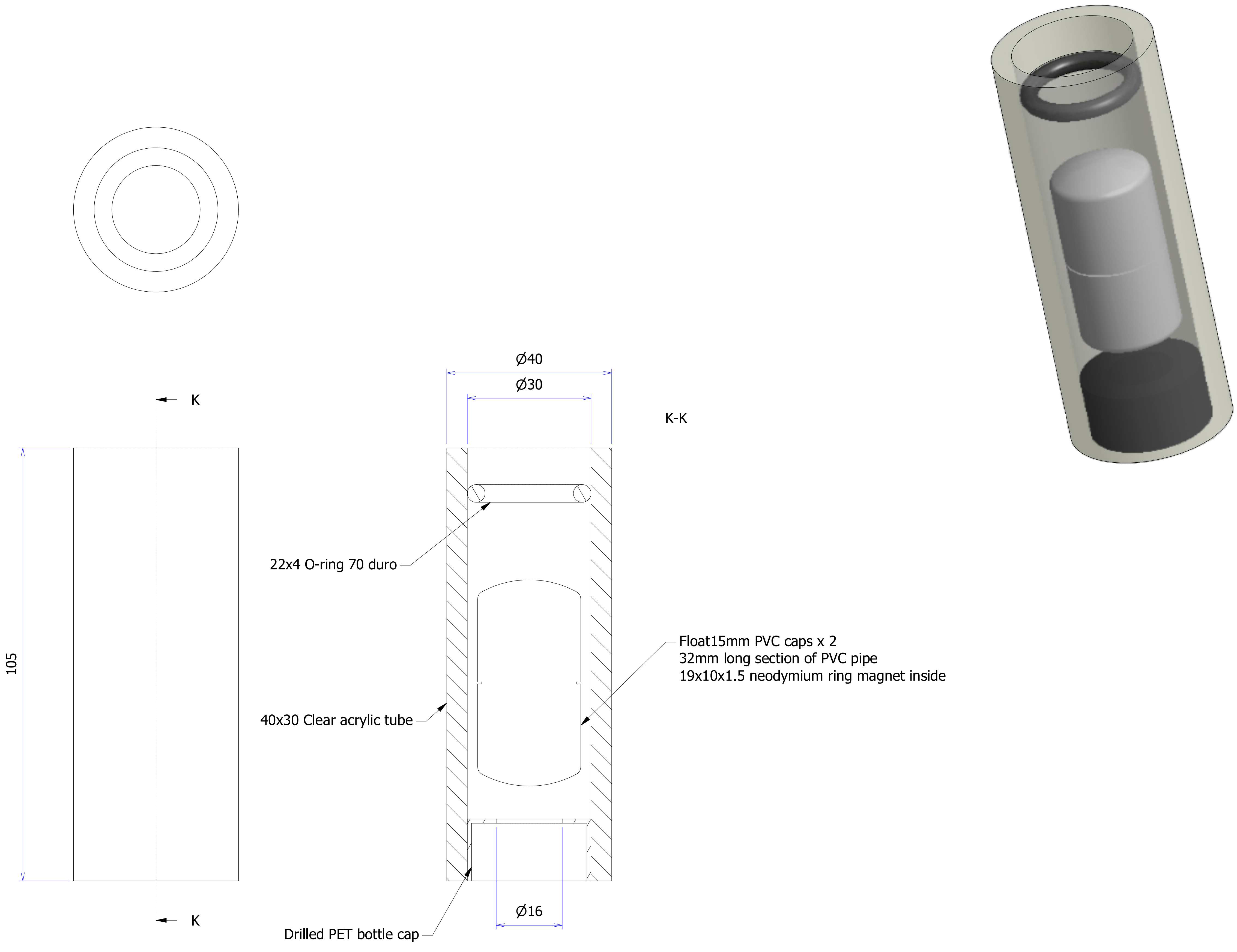


J-J



DO NOT SCALE
ALL DIMENSIONS IN MM

Designed by	Checked by	Material	Date	
Bryan Triaca		VeroClear-RGD810	4/10/2015	
		SWS1		
		Sampling Rail Bottom	Edition	Sheet 9 / 10



DO NOT SCALE
ALL DIMENSIONS IN MM

Designed by	Checked by	Material	Date	
Bryan Triaca			4/10/2015	
		SWS1		
		Sample Sealing Valve	Edition	Sheet 10 / 10