Turbofan Engine Testing Oil Collection System Re-Design

Final Report

Price Faculty of Engineering
MECH 4860 - Engineering Design

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Executive Summary

StandardAero, one of the world's largest independent providers of maintenance, repair, and overhaul (MRO) services, has provided service for two configurations of the CF34 engine: the CF34-8C, and CF34-E. The CF34 engine was commercially developed by General Electric. Bombardier and Embraer have used this engine on select models of their regional aircraft.

The goal of this project was to re-design the oil collection system for StandardAero's testing of the CF-34 turbofan engine. The oil collection system connects to the high pressure drain line, where it is intended to collect oil from the engine's bearing sumps while the engine is in operation in the test cell. The amount of oil leakage in volume and rate is required for StandardAero to certify their repaired engines as airworthy. The existing oil collection for this drain line consisted of a drain mast made of stainless steel tubing connecting to a plastic bottle. This plastic bottle was intended to capture all oil as exits the engine. However, since the bottle is subjected to the high pressure air-oil mixture, holes were drilled through the top to relieve pressure build-up. These holes prevent the bottle from becoming dislodged during testing. As a consequence of these holes, the air-oil mixture escapes the bottle, which means that oil leakage volume rate cannot be accurately captured or measured while the engines are undergoing testing.

StandardAero tasked Team 22 with re-designing the oil collection system. Design needs were identified and built upon to develop a list of target specifications for which their importance could be ranked. Where applicable the target specifications were given a quantifiable metric. The list of specifications served as a means to evaluate the final design's ability to meet the clients needs. With consultation of the client and through site visits, Team 22 identified some design constraints and limitations. Given the design needs, constraints, and limitations, the group was able to establish a scope for the design project.

Team 22 completed a concept generation phase of the project in which the oil collection system was broken down into several components. The components were the drain mast, air-oil separation, oil collection, and flow regulation. A weighted decision matrix was applied to each component section to evaluate each concept for that particular component section. The selected novel oil collection system was the combination of the best components determined through the weighted decision matrix. The final conceptual design included a cyclone air-oil separator which separated air from the oil via centripetal motion, forcing the oil to the walls of the device as the air swirls inside.

StandardAero expressed interest in sourcing and adapting existing products that could be incorporated into the current system. For ease of use and quick design implementation, the client also expressed interest in retaining as much of the current system as possible. The Mishimoto Carbon Fiber Baffled Oil Catch Can was determined to be the best commercially available air-oil separator. Team 22 designed the necessary modifications and sourced parts required to mate the catch can to teh current drain mast system.

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1 Introduction

The client, StandardAero, is an independent maintenance, repair, and overhaul (MRO) service provider of aircraft gas turbine engines. Plant 6 in Winnipeg, Manitoba provide MRO services for CF34-8C and CF34-8E turbofan engine configurations. After MRO services, the CF34-8C and CF34-8E engine configurations are tested in StandardAero's test cells to measure engine performance. One critical metric measured during engine testing is the oil leakage volume and rate from the bearing sumps, which is used to determine adherence to the airworthiness and aircraft operational requirements of the engine. Currently, the oil collection system used by StandardAero is unable to effectively collect oil leaking from bearing sumps. Team 22 has been tasked with re-design of the oil collection system to collect leaking oil from the bearing sumps during engine testing from idle to high throttle settings.

The team has developed a final design for the new oil collection system following concept selection that will effectively collect the leaking oil from the bearing sumps. This report presents the operating principle and detailed analyses of the new oil collection system design. Additionally, changes in the scope of the project, the cost of the final design, and standard operating procedure for the new oil collection system design are also addressed in this report.

1.1 Project Definition Overview

The project initiated through developing an understanding of the project background, from which the problem statement was developed. The needs and target specifications, and the constraints and limitations of the design were then determined through meetings with the client.

1.1.1 Background Information

Gas turbine engines require plenty of rotating components, and lubricating oil is used to reduce the friction between the static and rotating parts. Due to the nature of the design of the CF34-8C and CF34-8E engines, oil leakage from the bearing sumps is to be expected. The leakage is acceptable within limits set by airworthiness requirements, airline operational requirements, and original equipment manufacturer (OEM) specifications. The serviced engines are tested to determine the oil leakage volume and rate. These measurements are then compared to the specifications to determine adherence to the specifications.

Oil collection during testing is performed through the use of plastic bottles connected to drain masts. The drain masts are connected to a singular mast plate which is then connected to different regions of the engine. Shown in Figure 1 is an approximation of the oil collection system used by StandardAero in the test cell, and Figure 2 illustrates the approximate location of the oil collection system attached to the engines during testing. Due to proprietary reasons, images of the actual oil collection system and interface with the engines were not provided.

Figure 1: Approximation of the Current Oil Collection System

[redacted]

Figure 2: Mounting Location for the Oil Collection System [1]

The problem with the current oil collection system is only related to the highlighted bottle in Figure 1 and therefore it is the only bottle and drain mast system that requires a redesign. The other bottles collect oil with negligible oil losses while the highlighted bottle connected to the bearing sump experiences significant oil losses due to modifications to the bottle. Holes were drilled through the top of the bottle to relieve pressure during testing as this particular bottle is connected to a high pressure region of the engine. Without the holes, the pressure build up can dislodge the bottle during testing. The other bottles do not require pressure relief holes as these bottles do not experience high pressures at any stage of the testing.

The engine is tested through a range of throttle settings. At idle, the engine is operating at low pressures, allowing the oil to slowly drip into the bottles. As the throttle is increased, both the pressure and temperature and the incoming oil and air increases for the high pressure line. The high pressure air-oil mixture flows through the bottle at a high flow rate and is released through the holes at the top of the bottle. The oil is unable to separate from the high flow rate mixture to be collected. Therefore, the actual oil leakage volume and rate is unknown when the engines are returned to operation.

If excessive oil leakage is observed during operation, the passengers on the aircraft may feel unsafe and complain to the airlines. Additionally, excessive oil leakage may collect within the engine chamber that delivers air into the aircraft cabin. If the oil begins to burn due to high engine operating temperature, the smoke is carried into the aircraft cabin as well. While oil leaks on the tarmac do not present any safety risks to passengers, cabin smoke due to oil leakage could result in minor health concerns among passengers, like shortness of breath, and may result in an emergency landing. These issues may also impair the airlines' trustworthiness and consequently StandardAero's credibility of MRO services.

1.1.2 Problem Statement and Project Objectives

The oil collection system currently used by StandardAero during testing of the CF34-8C and CF34-8E engine configurations does not allow the leaking oil to be collected and measured from the bearing sump location. The purpose of this project is to re-design the oil collection system that serves to collect leaking oil from the bearing sumps of the CF34-8C and CF34-8E engine configurations during testing after MRO services. The following deliverables are expected upon completion of the project:

1. CAD models of the oil collection system for both the CF34-8C and CF34-8E engine configurations.
2. CFD analysis to provide proof of concept for the minimization of oil loss.
3. Bill of Materials which consists of a comprehensive inventory of parts and assemblies as well as the quantities needed to manufacture the product.
4. Engineering drawings of the oil collection system.
5. A set of instructions for the assembly and disassembly of the oil collection system for the operators and technicians.

The client emphasized the importance of the assembly and disassembly instructions. All test cell operators and technicians will be responsible for knowing how to assemble and disassemble the oil collection system. Therefore, a clear set of instructions outlining the assembly and disassembly procedure is necessary to ensure the oil collection system is installed and operated appropriately.

1.1.3 Needs and Target Specifications

The identified needs of the oil collection system re-design mainly fall into one or more of the following overarching categories emphasized by the client:

1. Safety
2. Functionality
3. Ease of Use

TABLE I contains the primary 'parent' design needs identified during the meeting with the client. Secondary 'child' needs were then derived from the primary needs to further breakdown the design needs into manageable needs.

TABLE I: OIL COLLECTION SYSTEM DESIGN NEEDS

Need Number	Parent Need	Child Need	Importance
1	System Collects Leaking Oil During Engine Testing	-	5
2	System Functions when Exposed to High Pressure	Oil Remains within the System	5
		System Remains Attached to Engine	5
3	Capable of Withstanding Stresses Induced During Testing	Withstands Engine Vibrations Produced during Full Throttle Testing	5
		Capable of Withstanding Forces from Airflow	5
		Able to Support its Own Weight	5
4	Safe for Technicians to Handle/Assemble/Disassemble	-	5
5	Easy to Assemble/Disassemble	Design can be Manually Installed	4
		Accessible When Cowling is Closed	4
		The System Can be Installed Quickly	4
6	Design is Convenient to Handle	Design is a Manageable Size for the Technicians	4
		Portable	4
		Lightweight	4
		Easily Stored	4
		Can be Roughly Handled by Technicians without Risk of Failure	4
7	Design is Reusable	-	4
8	System Compatible with CF34-8C and CF34-8E Engines	-	4
9	System Can Attach to Engine Match Plate in All Servicing Environments	-	4
10	Volume of Oil Collected can be Determined from Testing Control Room	-	4
11	System can Operate in Ambient Temperature Conditions	-	4
12	System can Operate in Test Temperature Conditions	-	4
13	Design is Affordable	-	3
14	The System is Chemically Inert	-	3
15	System can be Easily Maintained	Oil can be Easily Removed from the System	2
		System can be Cleaned Efficiently	2

Having identified the design needs, a list of target specifications was created as a means to evaluate the final design's ability to meet the established needs. Each target specification is composed of an engineering metric with marginal and ideal values the design team will be striving to achieve, all of which have been tabulated in TABLE II. Recent meetings with the client has provided the team with additional information to further define the target specifications. This included the maximum gauge pressure and temperature output of the engine which was determined to be 25 psi and 250 $^{\circ}F$ respectively. Additionally, the vertical distance between the mast plate and the shop floor where the engine undergo preparation for testing was found to be 12 in.

TABLE II: TARGET SPECIFICATIONS

Metric Number	Need Number	Metric	Importance	Units	Marginal Value	Ideal Value
1	1,3,6	Collection System Volume	5	Litre	0.2	0.25
2	2,4	Minimum Internal Pressure Rating Requirement	5	psi	40	80
3	9,15	Total Vertical Distance from Mast Plate	5	m	0.3	0.25
4	3,4,5,6,13	Total Mass	5	kg	<2.2	<0.5
5	2,3,7	Minimum Yield Strength Factor of Safety	5	N/m^2	2	4
6	4	Potential to Injure	5	Subjective	-	-
7	2	Permissible Collection System Oil Loss%	4	Percentage	1%	1%
8	5	Time to Assemble/Disassemble	4	min	2	1
9	8	System Configuration	4	List	CF34-8C or -8E	CF34-8C and -8E
10	10	Oil Level is Observable During Testing	4	Binary	True	True
11	11,12	Operational Temperature	4	Degree Fahrenheit	-30 to 250	-40 to 300
12	13	Manufacturing Cost	3	CAD	<25000	<20000
13	14	Chemically Inert	3	Binary	True	True
14	5,15	Time to Clean Between Tests	2	min	2	1

1.1.4 Constraints

A list of constraints for the project was established during meetings with the client. The project constraints are listed as follows:

1. The oil collection apparatus must be able to be installed by one to two technicians.
2. The size of the oil collection design is constrained vertically. There is a maximum height available for the design apparatus when the engine is mounted in the shop. The shop is the location where the oil collection system is installed prior to moving the engine into the test cell. This vertical dimension is approximately 1 foot.
3. The oil collection device is also constrained by the engine cowling; there is a channel that the oil collection system must fit through to mate with the match plate.
4. When disassembled, the oil collection design must fit onto a StandardAero cart with the volume constrained to 3 feet long, 2 feet wide, and 1 foot tall.
5. The oil collection device must not damage or significantly deform any engine components.
6. The oil collection system is required to mate to the current match plate with OEM specified connections.
7. The budget for the design project is $25,000.00 CAD.
8. The team is constrained by the course schedule to complete the project by December 7, 2022.
9. The team is constrained to four members working on the project.

1.1.5 Limitations

The limitations of the project were initially defined following the first site visit with StandardAero. The project limitations are as follows:

1. Limited access to proprietary information such as engineering drawings and documentation of the CF34-8 engines.
2. Limited access to the CF34-8 engines in the test cell due to StandardAero's busy on-going engine testing schedule.

1.2 Concept Generation and Selection Summary

Following project definition phase, concept generation and selection was conducted to develop conceptual design alternatives based on the client's needs and target specifications. The team used the following five-step concept generation methodology to develop conceptual designs:

1. Clarify the problem
2. External search
3. Internal search
4. Systematic exploration
5. Reflect on process

The problem identified is to re-design the oil collection system for use by StandardAero in the test cells during testing of the CF34-8C and CF34-8E engine configurations to collect leaking oil from the engine. The system was then decomposed into four components: the drain mast, air-oil separation, oil collection, and flow regulation devices. Several concepts were generated for each component through external search and internal idea generation. The concepts were evaluated through the use of weighted decision matrix.

The engineering selection criteria used to generate the weighted decision matrix were based on the client's needs and target specifications which are listed as follows:

Safety: Safety is essential in all engineering design and must be taken into consideration during the concept selection process. Not only does the oil collection system need to be safe for the technicians handling the device, but it also must be safe for the engine during testing.

Functionality: The designs ability to serve its intended purpose. Each concepts ability to satisfy needs such as collecting oil, engine configuration compatibility, attaching to the engine match plate, and operational functionality in the testing environment will be taken into consideration.

Ease of Use: Due to the constant engine testing being performed at StandardAero, it is important that the design be easy to use, handle, service and assemble/disassemble to minimize setup and take down time.

Cost: Due to the project budget constraint, it is necessary to consider the cost of the concept prior to selection. Manufacturing costs, Maintenance costs, and replacement cost will all be taken into account. However, since the design team was granted a fixed budget, concepts will only be given a lower rating if they are estimated to cost more than the budget.

Durability: Ideally the final design will be able to be used indefinitely and therefore each concepts ability to withstand the high pressure and temperature air entering the system and the stresses induced by external forces will be taken into consideration during selection.

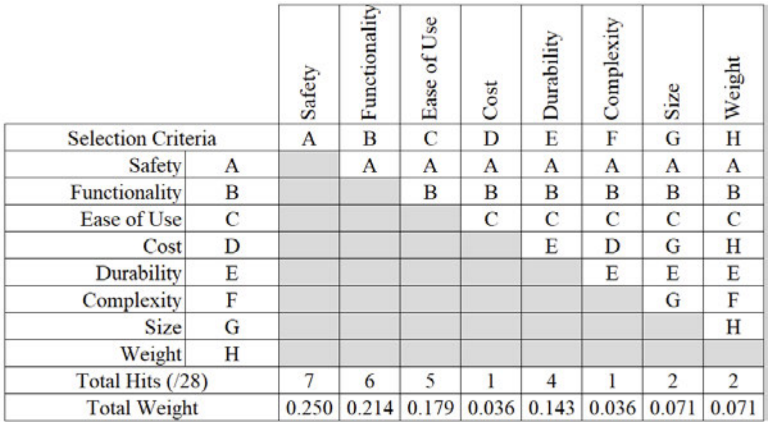
Complexity: Complexity will be used as a selection criteria due to inherent complications that arise due to increased complexity. As a design becomes more complex, it often becomes more expensive, harder to use/handle, and less durable. While these factors are already being used as selection criteria, evaluating complexity is important in itself especially when designing what should be a simple collection device of low risk to user or product. Simpler designs are preferable.

Size: The collection system is constrained to a specific design space, therefore it is important to consider the size of the concept and its potential to fit within the space. Additionally, smaller designs will be easier for the technicians to handle.

Weight: Weight needs to be considered for two main reasons, the safety of both the technicians and the engine itself. By choosing concepts that are lightweight, technicians will not injure themselves handling the device and the device will not damage the engine.

Each selection criteria was compared against all other selection criteria to establish the relative importance and weighting for use in the weighted decision matrix. The result of comparing selection criteria is summarized in TABLEIII.

TABLE III: WEIGHTED SELECTION CRITERIA



		Safety	Functionality	Ease of Use	Cost	Durability	Complexity	Size	Weight
Selection Criteria		A	B	C	D	E	F	G	H
Safety	A		A	A	A	A	A	A	A
Functionality	B			B	B	B	B	B	B
Ease of Use	C				C	C	C	C	C
Cost	D					E	D	G	H
Durability	E						E	E	E
Complexity	F							G	F
Size	G								H
Weight	H								
Total Hits (/28)		7	6	5	1	4	1	2	2
Total Weight		0.250	0.214	0.179	0.036	0.143	0.036	0.071	0.071

The weighted decision matrix was applied to select the optimal concept from each component, which were combined together to develop the optimal overall oil collection system. The concept generation and selection process can be found in Appendix A. The final conceptual design is illustrated in Figures 3 and 4.

Figure 3: CAD model of final conceptual design

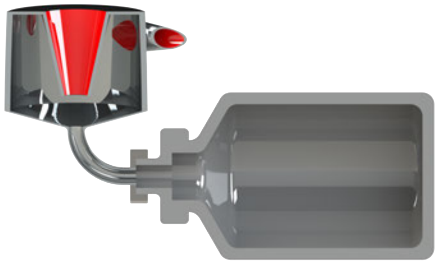


Figure 4: Section view of final conceptual design

The final conceptual design selected consists of a cyclone separator, where the entrance and exit are highlighted in red in Figure 4. The air-oil mixture enters and flows tangentially to the inner wall of the separator. The higher density oil will then be forced by momentum towards the outer edge of the flow to be captured, and the air free of oil is released from the center of the flow.

The final concept was presented to the client and was approved to move forward into detailed design. The client also expressed interest in procuring and adapting commercially available products into the new oil collection system design, as well as retaining as much of the current design as possible. To comply StandardAero's preferences, the team sourced and integrated existing products into the current oil collection system. Detailed analyses was then conducted to ensure the final design met the client's needs and target specifications.

2 Detailed Design

The redesigned oil collection system is presented in Figure 5 with the various components labelled. The new system uses the Mishimoto Carbon Fiber Baffled Oil Catch Can to separate and collect the oil from the air-oil mixture. The final design also recycled the exiting drain mast by modifying the drain mast to accommodate the catch can. The same connecting hardware from the previous oil collection system are used to fasten the drain mast to the engine mast plate .

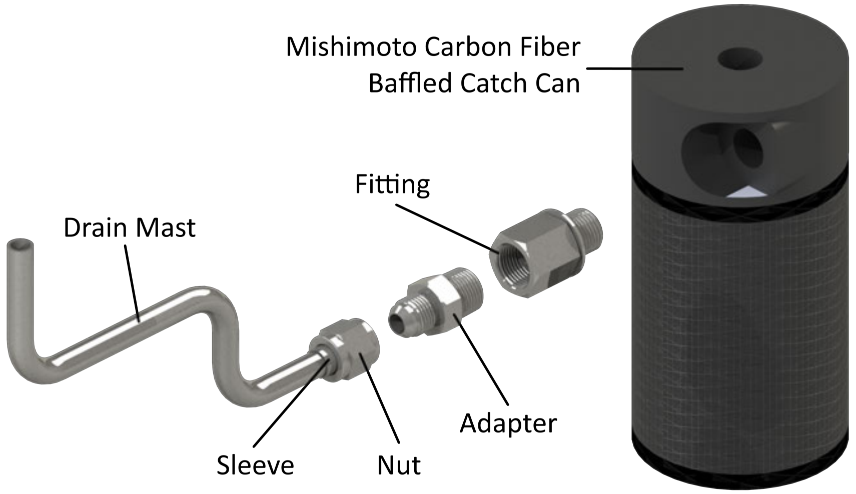


Figure 5: The final oil collection system design consisting of the original drain mast that connects to the Mishimoto Carbon Fiber Baffled Catch Can. CAD models of the nut, sleeve, tubing fitting, and adapter were sourced from [redacted] with component drawings provided in Appendix C [2] [3] [4] [5].

The details and analysis for each component of the oil collection system are presented in the following section.

2.1 Mishimoto Carbon Fiber Baffled Catch Can

The Mishimoto Carbon Fiber Baffled Catch Can (Model Number MMBCC-CF [6]), hereafter referred to as the catch can, is a commercially available air-oil separation device designed for automotive applications. The intended design function is to separate oil and other contaminants from air entering the intake of a vehicle combustion engine to reduce engine performance losses overtime [7]. For this project, the catch can has been repurposed to separate and collect oil from airflow exiting a turbofan engine.

The operating principle behind the catch can is a cyclone separator utilizing the principle of inertia to separate heavier, more dense particulates from airflow [8]. The catch can lid contains a spiral inlet as illustrated in Figure 6 to produce a cyclic flow pattern within the catch can. The heavier, higher density particulates within the airflow are then forced towards the outer perimeter of the cyclic flow, while the air free of the particulates exit through the center of the cylinder. The heavy particulates are then collected within the catch can.

Figure 6: Spiral inlet of the catch can lid [9]

The catch can also includes a quick release feature that allows the lid and the catch can to be separated through a quarter turn of the catch can relative to the lid [10]. This allows the collecting and measuring of the oil leakage volume and rate between engine tests to be conducted quickly. Additional product specifications of the catch can provided by the manufacturer are listed as follows:

- Operating pressure of 40 *psi* for over 100 000 cycles [10]
- Burst pressure of 100 *psi*
- Chemically resistant
- 7.4 fluid ounce capacity [6]
- MRSP of $471.35 USD

Based on the information provided, the catch can satisfies the minimum internal pressure rating of 40 psi, the requirement for non-reactivity, the minimum volume capacity of 0.2 litres, and the maximum cost of \$25000 CAD established by the client. The design team reached out to Mishimoto in an attempt to acquire a full specification breakdown of the catch can. However, Mishimoto would not provide any information that was not already available on their website. Therefore, specifications such as dimensions, materials, and weight cannot be accurately provided. As a result, physical testing of the catch can operating in StandardAero engine test conditions will be required to confirm application suitability.

2.1.1 Computational Fluid Dynamics

A computational fluid dynamics (CFD) simulation was conducted using SolidWorks to visualize the air-oil mixture fluid flow within the catch can as requested by the client. The objective of the study was to determine whether the catch can would be able to retain 99% of the oil passing through the system as specified by the client. Since the team could not obtain access to dimensions or CAD models of the catch can, the geometry and dimensions were approximated based on the available imagery. A cross section of the simulation domain is shown in Figure 7.

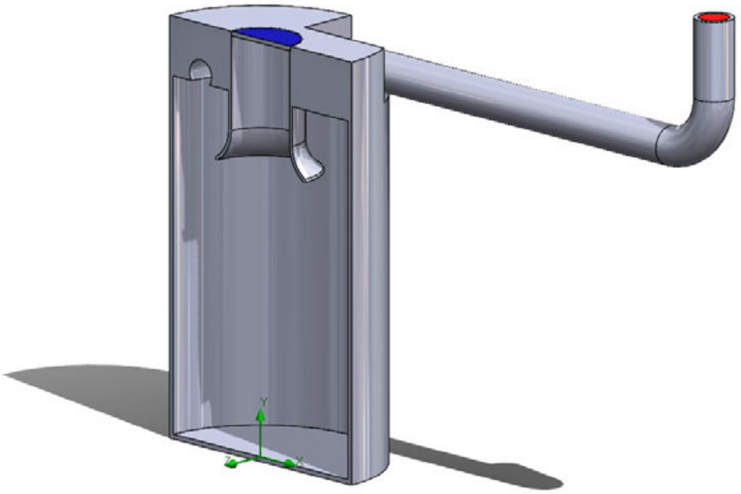


Figure 7: Cross section view of the catch can for CFD analysis. The inlet highlighted in red and outlet highlighted in blue

The simulation assumed worse case scenario of 40 *psi* static pressure and 250 $^{\circ}F$ temperature at the inlet of the domain. These inlet parameters were specified by the client as maximum pressure and temperature of the bearing sump during engine testing. The simulation outlet parameters were set to 14.7 *psi* and 68.1 $^{\circ}F$ to simulate the ambient atmospheric conditions of the engine during engine testing. The outlet conditions are standard room conditions established in SolidWorks [11]. Engine testing at StandardAero occurs throughout all Winnipeg climates, and air pressure variation with climate is minimal. Hence the outlet pressure was set to standard room pressure to approximate the average ambient pressure during engine testing. Ambient temperature does vary greatly with climate. However, heat transfer and effects of temperature are not the focus of this project. Therefore, the standard room temperature was used as a blanket condition for all engine testing conditions. A convergence study was conducted for the CFD simulation with the results presented in Figure 8.

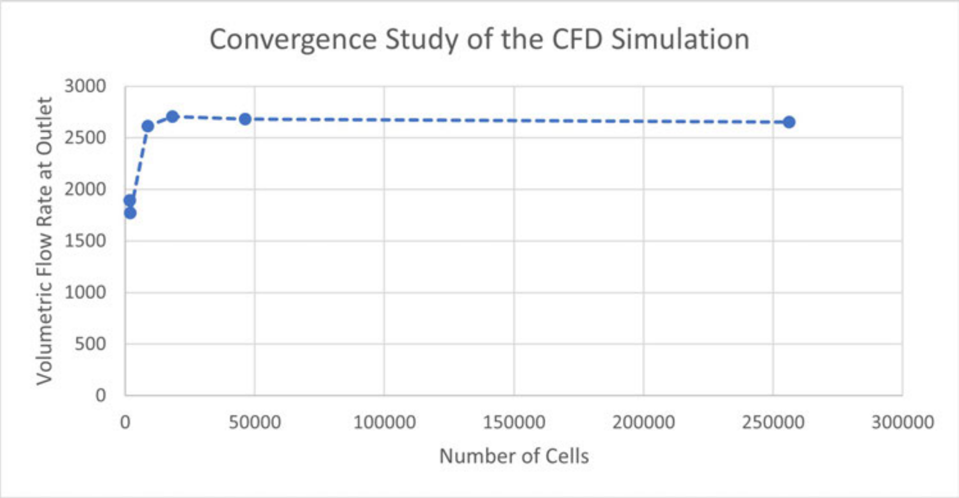


Figure 8: Simulation convergence study indicating that the results have converged with 46000 cells

As shown by Figure 8, the volumetric flow rate of the air flow exiting the catch can began to plateau with 18129 cells in the simulation. The corresponding relative error is 3.4% and reduces to 1% with increasing number of cells. This means that the volume flow rate across the catch can exit does not vary significantly with changes in the number of cells used in the simulation. This is an indication that the simulation results are independent of the number of cells used.

The client also raised a concern that the catch can could introduce back pressure into the engine from pressure losses. This was a concern as back pressure could affect the measurement of engine performance metrics during testing of the engine. Flow trajectory of the CFD simulation show that the air is able to exit the catch can through the designated outlet, as seen in Figure 9. This indicates that there is no flow reversal, which implies that there is no back pressure produced through the use of the catch can.

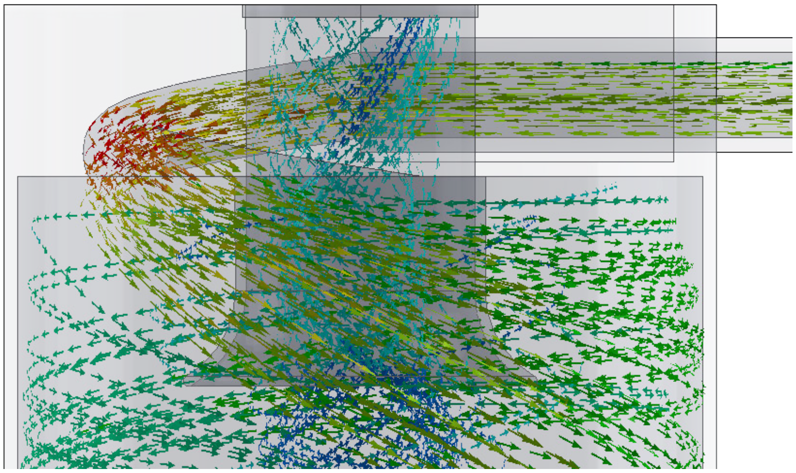


Figure 9: Catch can outlet air flow results that show a close up view of the air flowing toward the designated outlet of the catch can

A particle study was subsequently conducted using the results of the CFD simulation to track oil droplets introduced into the airflow. The oil used in the CF34 engines is Mobil Jet Oil II which has density of 1.0035 kg/l and kinematic viscosity of 5.1 mm^2/s [12]. Oil droplet diameter was varied between 0.5 to 100 micron to determine the smallest diameter that can be captured. The result of particle study show that all oil droplets of 10 micron diameter or larger should be captured by the oil catch can. The results of the particle study are visualized in Figure 10. Since the team was not able to conduct CFD analysis using accurate models of the catch can, the simulation results are indefinite and only serve as reference to the actual system. Further prototyping that would involve procuring the catch can and testing on an engine is necessary to validate the functionality of the new oil collection system.

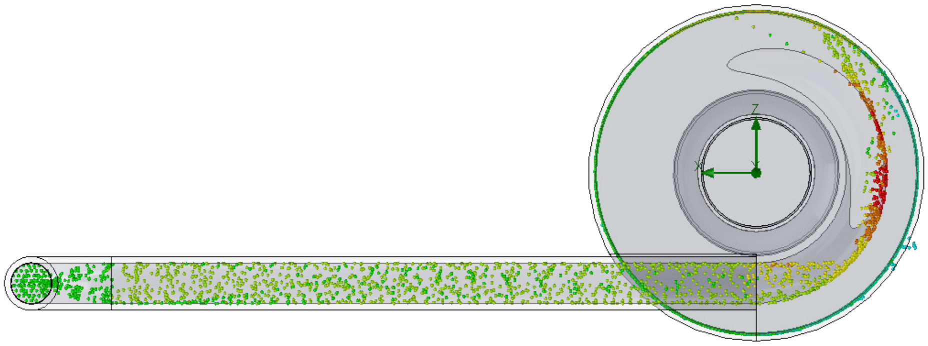


Figure 10: Top view of particle study results. Notice that there are no oil particles in the center of the flow

2.2 Drain Mast

The client expressed interest in retaining as much of the previous system as possible, so the drain mast from the previous system was modified for the oil collection system re-design. The drain mast is a hollow tube that connects the engine and direct the airflow to the catch can. The drain mast also serves as a cantilever beam that must support the mass of the catch can and all oil collected during testing. The client have also specified the drain mast to be made of 304 grade stainless steel with inner diameter of 0.277 *in* and outer diameter of 0.375 *in*.

In the current design, the drain mast contains two bends with end connecting to the plastic bottle pointing towards the ground. For the new oil collection system, the drain mast must have an additional bend to allow the catch can to be positioned upright. A comparison of the original and modified drain mast in presented in Figure 11.

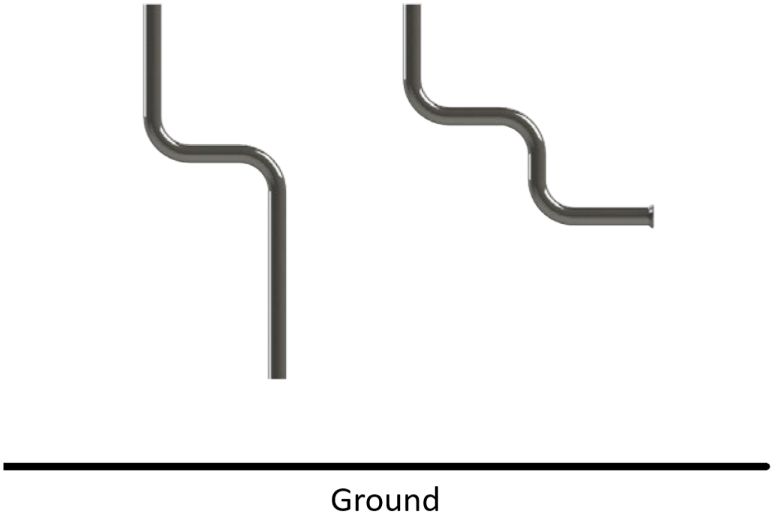


Figure 11: Original drain mast on the left and the modified drain mast on the right

A drawing of the modified drain mast to accommodate the catch can is presented in Appendix C.

2.2.1 Stress and Deflection

Since the catch can mass is only supported by the drain mast, stress analysis was conducted to determine areas of concern for inspection after repeated engine tests. The drain mast was approximated as a bent cantilever beam supporting a concentrated mass that represents the catch can. Since Mishimoto did not provide mass of the catch can, the team approximated the mass of the catch can by comparing to similar products offered by Mishimoto. A larger Mishimoto catch can with a 9 fluid ounce capacity made of aluminum has a mass of 1.6 *lb* [13]. Since the carbon fiber catch can has a smaller capacity and constructed from a lighter material, the team estimated a mass of 1 *lb* for the carbon fiber catch can. The oil mass under worst case scenario is when the catch can is full. The maximum oil mass was determined to be 0.25 kg based on the catch can capacity and the oil density. The concentrated mass was then determined to be 0.70 *kg*. Under static loading, the forces exerted on the system would be the gravitational force acting on the full catch can. A schematic of the system is shown in Figure 12. Locations B and C as noted in Figure 12 were areas of concern for stress analysis as these locations would experience the highest stresses due to bending.

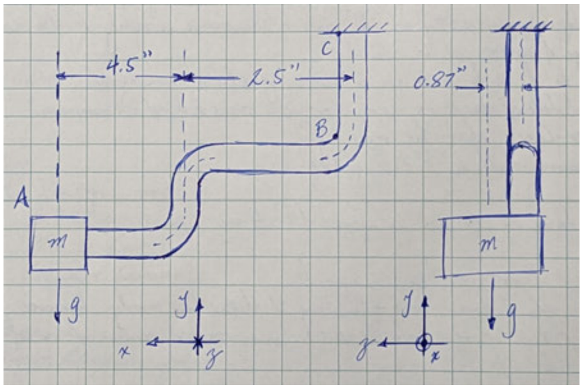


Figure 12: Schematic of the catch can used for stress analysis (not to scale)

Stress analysis was conducted through analytical calculations and finite element analysis (FEA) using SolidWorks. The highest stress was found at location B. The results of the study are tabulated in TABLE IV, with the hand calculation procedure presented in Appendix B.

TABLE IV: STRESS ANALYSIS RESULTS FOR DRAIN MAST AT LOCATION B

	Maximum Stress (MPa)	Maximum Deflection (mm)
Analytical Calculation	24.38	0.47
FEA	23.94	0.44

The stress distribution of the drain mast from the FEA is presented in Figure 13.

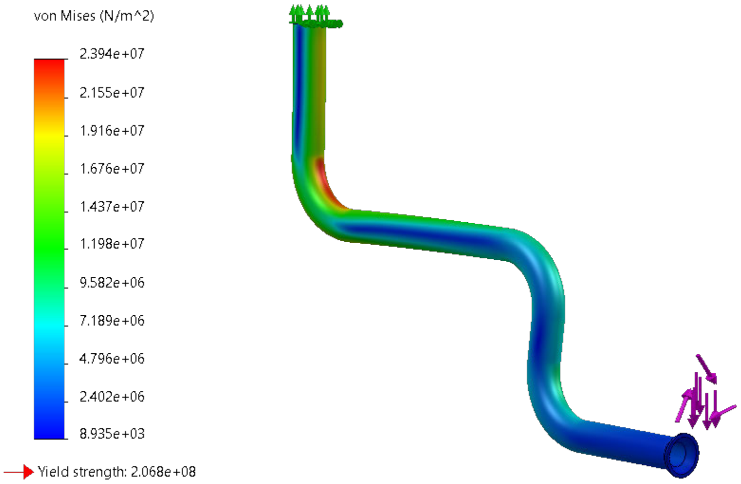


Figure 13: Stress distribution of the drain mast, with maximum von Mises stress at location B of 23.98 MPa

The displacement of the drain mast is presented in Figure 14.

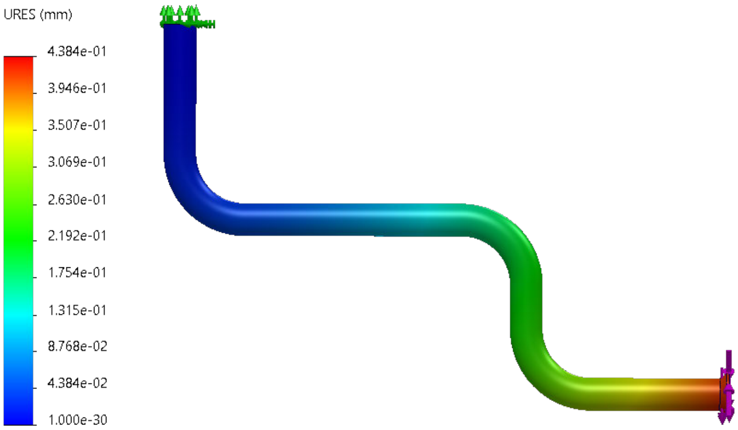


Figure 14: Deflection of the drain mast, with maximum displacement at the catch can of 0.44 mm

Comparing the results of FEA to analytical calculations, the results are reasonably similar to each other where the margin of difference between the stress and displacement are 0.44 MPa and 0.03 mm respectively. The percent difference relative to the FEA results is 1.6% for stress, and 6.8% for displacement. This indicates that the results are sufficiently close to verify the stress analysis of the system. For 304 stainless steel with yield strength of 205 MPa [14], the factor of safety under static loading is 8.4. Therefore, the drain mast will not fail under static loading. However, this also indicates that location B should be regularly inspected for fatigue due to the having the highest stress. Additionally, the small deflection of the drain mast is also an indication that the new oil collection system would not significantly deflect engine components during engine testing at worst case scenario.

2.2.2 Connection to Catch Can

To connect the catch can to the drain mast, the client has specified that the catch can must mate to a 9/16" – 18 internal thread profile, or a male 3/8 NPT Pipe Size, 18 Threads Per Inch profile [2] [4]. The catch can inlet has a female M16x1.5x1/2" thread profile [6]. An adapter was sourced from [redacted] which contains the female 3/8 NPT Pipe Size, 18 Threads Per Inch and the male M16x1.5x1/2" thread profiles as illustrated in Figure 15 [5]. This adapter allows the catch can to mate to the existing drain mast hardware.

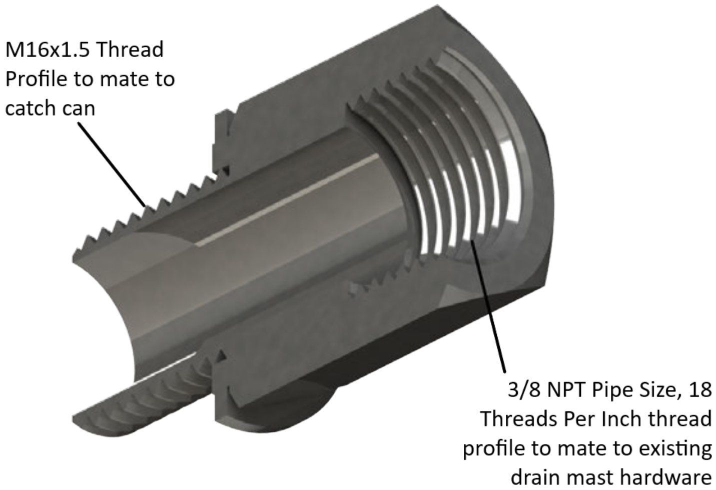


Figure 15: Cross section view of the adapter [5]

2.3 Cost

This section details the cost of the oil collection system. The scope of the cost includes component procurement. The scope of the cost does not include engineering overhead cost to install and train employees on the implementation of the oil collection system or initial testing cost to verify suitability.

2.3.1 Bill of Materials

The bill of materials, see TABLE V, includes the required components and cost for the oil collection system.

TABLE V: BILL OF MATERIALS

Item	**Part**	**Description**	**Unit**	**Quantity**	**Cost (USD)**
1	Carbon Fiber Baffled Catch Can	7.4oz Carbon Fiber Baffled Catch Can	1	1	471.35
2	304 Stainless Steel Flared Tubing	3/8” tube OD Precision AN 37 Degree Flared Tubing	1	1	-
3	304 Stainless Steel Sleeve	For 3/8” tube OD Precision AN 37 Degree Flared Fitting (5482K83)	1	1	2.40
4	304 Stainless Steel Nut	For 3/8” tube OD Precision AN37 Degree Flared Fitting (5482K76)	1	1	4.90
5	304 Stainless Steel Adapter	For 3/8” tube OD x 3/8 ANPT Male Precision AN37 Degree Flared Fitting (5482K15)	1	1	15.40
6	316 Stainless Steel Threaded Pipe Fitting	Adapter, 3/8 NPT Female M16 x 1.50 mm Thread Male (4822T395)	1	1	58.13
			Total Cost		552.18

The bill of material details the components required to assemble the oil collection system. The drain mast assembly, including the 304 stainless steel flared tubing, sleeve, and nut are components that StandardAero use for the current oil collection system. The 304 stainless steel adapter and the 316 stainless steel threaded pipe fitting are intended to be purchased from [redacted]. The Carbon Fiber Baffled Catch Can is intended to be purchased from Mishimoto Automotive. The estimated total cost for all materials of the re-design oil collection system is approximately $552.18.

3 Assembly Instructions

This section aims to assist the client to create an official standard operating procedure (SOP) for the assembly and use of the oil collection system for CF34-8C/-8E engine testing. Following the assembly instructions are important to ensure the safety of the operators and the functionality of the oil collection system. A detachable copy of the assembly instructions for the new oil collection system is presented in Appendix D.

3.1 Front Matter

This section contains the general procedures for assembling the bearing sump oil collection system for the test engine. This set of instruction describes procedures that result in suitable preparation of the oil collection system for testing purposes. The steps can be performed out of order, provided the outcome is equivalent to that described in this document. These instructions are applicable within the test cell only.

1. Examine all test equipment for damage prior to installation of the oil collection system to the engine.
2. All general-purpose protective caps, plugs, or other protective coverings that are not serviceable parts must be removed before test or otherwise prevented from coming loose, becoming damaged, or from damaging engine parts. No such items are allowed inside the cowls.
3. All test cell supplied parts and hardware used directly on the engine must be given a general visual inspection for mechanical integrity by the technician installing the item.
4. Prior to assembly, clean Mishimoto catch can of all contaminates. Confirm all parts of the assembly are accessible and disassembled.

3.2 Oil Collection System

The assembly instruction for the oil collection system are presented as follows:

1. Secure the Mishimoto collection container to the Mishimoto catch can lid using the quarter-turn locking mechanism.
2. Securely fasten 316 stainless steel threaded pipe fitting to the catch can inlet located on the side of the catch can lid.

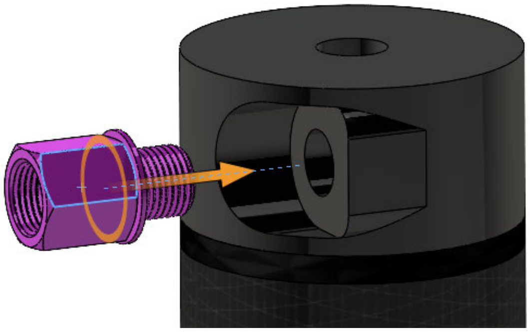


Figure 16: 316 stainless steel threaded pip fitting assembly

3. Securely fasten the 304 stainless steel adapter to the 316 stainless steel threaded pipe fitting.

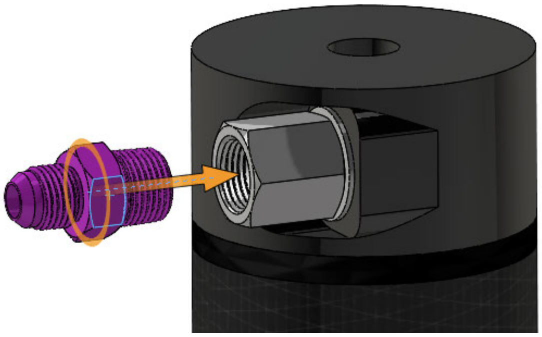


Figure 17: 304 stainless steel adapter assembly

4. Attach the high pressure drain mast line, 304 stainless steel flared tubing, to the mast plate.
5. Place the 304 stainless steel sleeve and nut at the base of the high pressure drain mast line.
6. Securely fasten 304 stainless steel nut located at the base of high pressure the drain mast line to the catch can assembly.

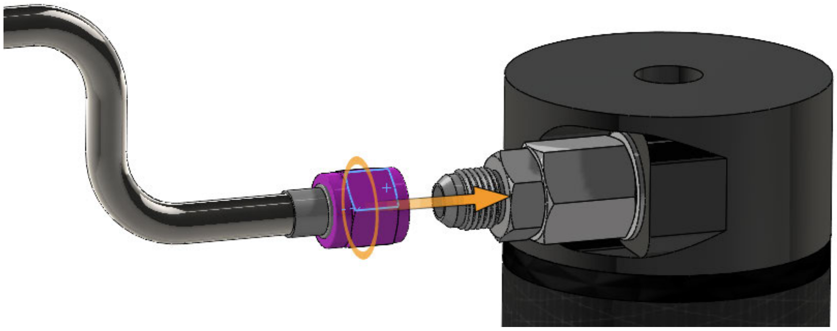


Figure 18: Drain mast to catch can assembly

Note: the catch can must be properly aligned vertically with the airflow outlet facing up for optimal performance.

Final assembly of the oil collection system is shown in Figure 19. No modifications were made to the connection between the drain mast and the mast plate. The drain mast to mast plate connection will use the same connecting hardware from the current oil collection system.

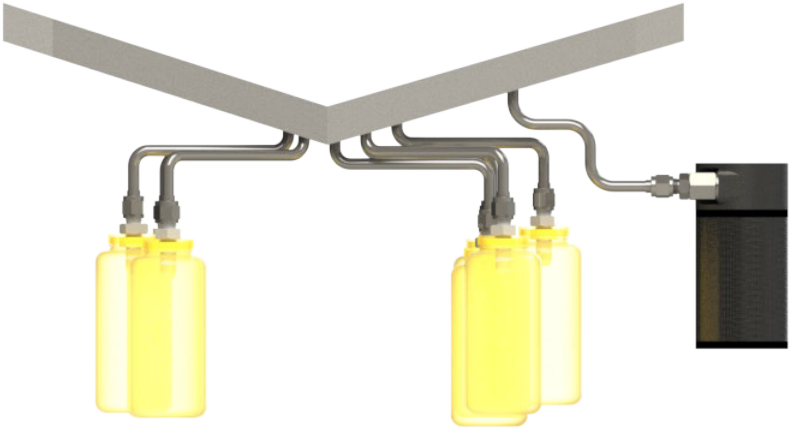


Figure 19: Fully assembled mast plate system including low pressure oil collection bottles. CAD model of fittings connecting to the bottles were sourced from [redacted] [15].

The above assembly instructions were created prior to prototyping and physical testing of the final design concept. As a result, the instructions detailed in this report are meant to provide a general understanding of how to assemble the initial design and will be subject to change moving forward. Additionally, the design team does not have access to StandardAero's internal documentation and therefore cannot include any StandardAero assembly procedure standards such as acceptable torque ranges for fittings.

4 Conclusion

The final design of the oil collection system is shown in Figure 20. A Mishimoto Carbon Fiber Baffled Catch Can is used to separate and collect the leaking oil from the CF34 engines during testing. CFD simulations were performed using SolidWorks and the results indicate that more than 99% of the oil of 10 micron or larger passing through this design will be collected. However, since the team was unable to obtain dimensions or CAD model of the catch can, the CFD results are approximate and only serves as a reference to the performance of the actual design.

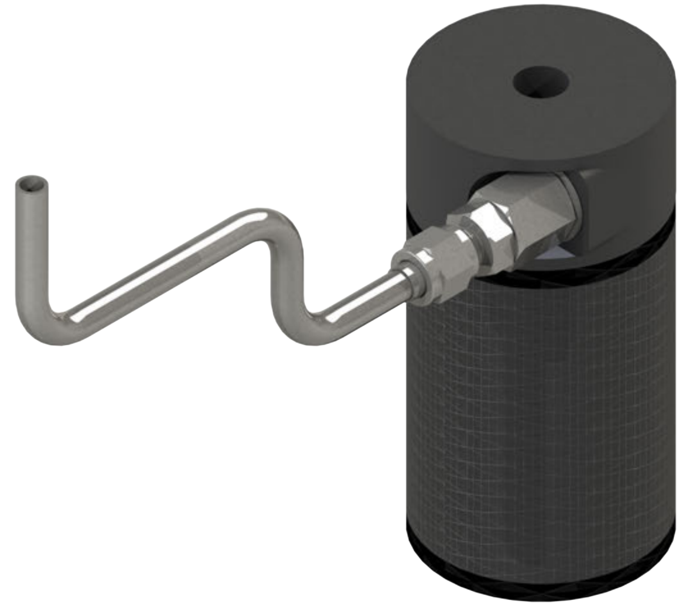
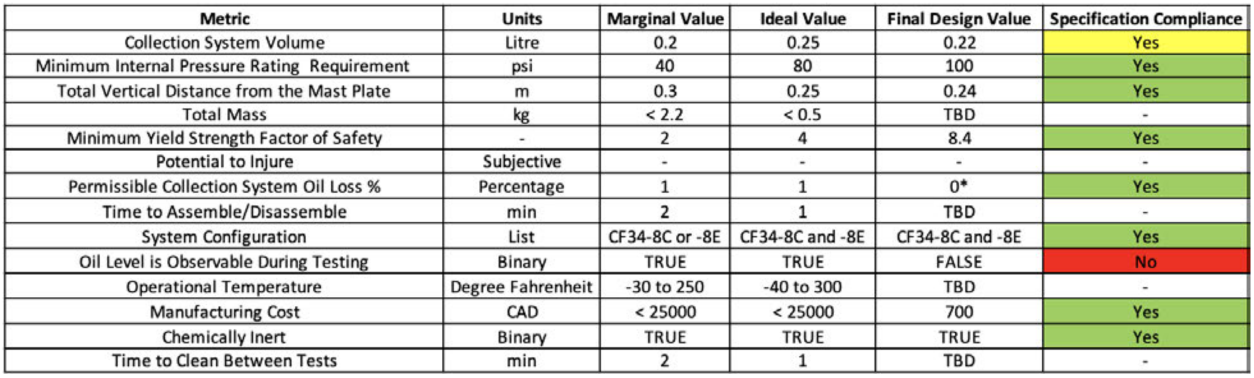


Figure 20: Render of the assembled final oil collection system design. CAD models of the nut, sleeve, tubing fitting, and adapter were sourced from [redacted] [2] [3] [4] [5].

A summary of the new oil collection system specifications compared to the project target specifications is tabulated in TABLE VI.

TABLE VI: FINAL DESIGN SPECIFICATIONS COMPARED TO THE TARGET SPECIFICATIONS



Metric	Units	Marginal Value	Ideal Value	Final Design Value	Specification Compliance
Collection System Volume	Litre	0.2	0.25	0.22	Yes
Minimum Internal Pressure Rating Requirement	psi	40	80	100	Yes
Total Vertical Distance from the Mast Plate	m	0.3	0.25	0.24	Yes
Total Mass	kg	< 2.2	< 0.5	TBD	-
Minimum Yield Strength Factor of Safety	-	2	4	8.4	Yes
Potential to Injure	Subjective	-	-	-	-
Permissible Collection System Oil Loss %	Percentage	1	1	0*	Yes
Time to Assemble/Disassemble	min	2	1	TBD	-
System Configuration	List	CF34-8C or -8E	CF34-8C and -8E	CF34-8C and -8E	Yes
Oil Level is Observable During Testing	Binary	TRUE	TRUE	FALSE	No
Operational Temperature	Degree Fahrenheit	-30 to 250	-40 to 300	TBD	-
Manufacturing Cost	CAD	< 25000	< 25000	700	Yes
Chemically Inert	Binary	TRUE	TRUE	TRUE	Yes
Time to Clean Between Tests	min	2	1	TBD	-

*Assuming an oil droplet diameter of 10 microns or larger

As shown by TABLE VI, the newly design oil collection system is within marginal value and ideal values of certain metrics. Mishimoto did not provide the team with information regarding the catch can mass, material strength, and operational temperature. Therefore, these metrics remain unknown until the construction and testing of a prototype. With regards to the metric of potential to injure, the Mishimoto Carbon Fibre catch can has been burst tested to pressures of 100 *psi* during product design and development. The operating pressure of the engine sump area is 40 *psi* maximum. Therefore, the catch can is unlikely to burst and injure any technician during testing. The time to assemble and time to clean remains unknown, as this requires procuring and performing a test to determine the duration of these activities. However, the assembly procedure of the new oil collection system is similar to the current system. Therefore, the assembly duration of the new system should remain similar to the assembly duration of the current system, and the same applies for cleaning.

The new system was not able to meet the target specification of oil level being observable during the engine testing as there were no commercially available catch cans that are transparent or translucent. This was addressed in a meeting with the client where ease of use and the ability to collect the leaking was the utmost importance of the new oil collection system. The client indicated the opaque catch can is acceptable despite being a non-ideal solution. This leaves room for improvement for future work to develop an improved system with a clear catch can for observation of the oil levels during engine testing.

4.1 Future Work

While the new oil collection system is an improvement over the current system, additional work can be made to further improve the new oil collection system design. As mentioned previously, the team was unable to obtain dimensions nor CAD models of the catch can used in the final design.

Therefore, the results of the CFD simulations are approximated and only serve as reference to the functionality of the actual system. Future work to address this problem would be procuring the catch can to develop a prototype of the new oil collection system. Testing of the prototype would be able to indicate the validity of the oil collecting capabilities of the catch can. Construction and testing of a prototype design would also verify and validate whether the oil collection system can satisfy the following target specifications:

- Total Mass
- Potential to Injure
- Time to Assemble/Disassemble
- Operational Temperature
- Time to Clean Between Tests

Future work can also be targeted towards developing a design that feature a transparent or translucent catch can. This would satisfy the client's target specification of being able to observe the oil level during engine testing.

Additional analysis can be conducted to determine the effects of vibration and fatigue of the oil collection system. Vibration of the engine would induce fatigue on the drain mast as it supports the weight of the catch can and any oil collected during testing. The team was unable to obtain engine vibration data from testing, and no fatigue analysis was conducted. Future work to determine the fatigue performance of the drain mast could further change the design to extend the service life of the drain mast.

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A Conceptual Design Phase Supplementary Information

The following sections present the initial concepts that were generated and the concept selection process.

A.1 Initial Concept Generation

This section presents all concepts that were generated during the conceptual design phase of the project.

A.1.1 Drain Mast

Beginning with drain masts, the following concepts were developed to assist in oil collection primarily through the method of reducing flow pressure and velocity to allow the oil to separate and be collected.

Helical Coil: A helical drain mast as shown by Figure 1 extends the distance that the flow will take before reaching the collection section of the system. The helical path extends the travel distance for the air and the added surface area serves to reduce the pressure and speed of the flow. Reducing the speed would facilitate oil separation and reduces oil loss from oil being blown out of containing vessel. However, a disadvantage of the helical coil is that the reduced velocity and pressure may result in pressure buildup upstream of the drain mast which could result in engine component damage. Additionally, the added length would increase the weight and cost of the system which are undesirable.

Figure A - 1: Helical coil drain mast

90 Degree Bend: Current design has two 90° bends in the drain mast. Additional bends in the drain mast as shown by Figure 2 would further reduce the pressure and speed of the airflow through the drain mast. The reduced speed would facilitate the oil separating from the air mixture and reduce the oil loss from the oil containing vessel. Similar to the helical coil, while the reduced flow speed and pressure would help with oil staying in the system and mitigate over pressurization of the collection device, pressure may increase upstream with potential for back flow and may damage the engine during testing.

Figure A - 2: Drain mast with multiple 90° bends

Expansion Tube: The cross section area of the drain mast expands as illustrated in Figure 3. Through conservation of mass, the speed of the airflow reduces as the area expands. The reduced flow speed helps to reduce the oil loss from being blown out of the bottle by high speed airflow entering the bottle. A disadvantage of this drain mast is the size. Due to how the engine cowling closes and latches, there is no room for drain mast expansion near the mast plate. Therefore, the drain mast will require extra length to facilitate the expansion required to reduce airflow velocity and may result in the system extending outside of the design space.

Figure A - 3: Expansion tube where the cross section area of flow expands

Multiple Drain Masts: The drain mast splits into multiple lines and connects to two or more bottles as shown in Figure 4. The airflow is divided across these drain masts, reducing the speed entering each bottle and prevents the oil from being blown out of the bottle. The advantage of this setup is that it allows for an increase in the volume available to collect oil, ensuring that even in the worst oil leakage scenario the bottles will never overflow. However, due to the turbulent flow of the air-oil mixture, it may not be possible to divide the airflow equally amongst the various drain masts resulting in one collection container being subjected to a majority of the flow.

Figure A - 4: Drain mast splitting into multiple lines

U-Bend Split Drain Mast: The drain mast has a U bend as shown by Figure 5 that splits away that allows air to exit. The higher density oil will continue to flow straight into the bottle through the momentum imparted by the airflow. The U-bend allows excess air to bypass to relieve pressure build up in the oil collection system. The advantage of the U-Bend drain mast is that it is very compact and requires very little modification of the existing drain mast. However, similar to the multiple drain mast concept, the turbulent nature of the flow may result in a majority of the air-oil mixture entering the U-Bend. Additionally only a small amount of oil enters the air-flow at a given time so the oil droplets in the mixed into the air may not be weigh enough to resist the air current exiting through the U-Bend.

Figure A - 5: Drain mast with U bend

Vented Drain Mast: Similar to the U bend, the vented drain mast contains "backward facing" vents as shown in Figure 6 that allows air to pass through in an effort to reduce pressure in the oil collection system. The higher density oil droplets would continue to flow into the bottle from the kinetic energy imparted by the airflow. An advantage of the vented drain mast is that it can be easily implemented into the existing drain mast, removing the need for the fabrication of a new part. However, since the venting only reduces pressure by having the high pressure air in the drain mast flow to the surrounding low pressure zone through the air vents, small particulates of oil may become trapped in the air flow and may also exit the vents.

Figure A - 6: Vented drain mast

A.1.2 Air-Oil Separation

The following concepts generated are means of separating the oil from the airflow mixture through exploiting physical properties of oil, or through some physical barrier that separate the oil from the air mixture.

Cyclone Separator: Operating principle consists in using a centrifugal force to separate fractions of the introduced mixture. The air mixture enters a cylindrical containing vessel tangentially as illustrated in Figure 7. The mixture is forced to flow around the cylindrical device and the high density oil is forced toward the inner wall surface. An opening in the middle of the cylindrical container allows the air to escape, while the higher density oil remains in the device. The advantage of this device is that it can be relatively compact and does not require any reduction in airflow pressure or velocity to operate. For these reasons the cyclone separator can be fitted to the existing oil collection system with little change to the drain mast and bottle. The disadvantage of this system is that it will require regular inspection to ensure there is no contaminant buildup in the separator which may impact airflow and produce harmful back flow to the engine.

Figure A - 7: Air-Oil Cyclone Separator [1]

Continuous Flow Centrifuge: The continuous flow centrifuge, Figure 8, acts on a similar principal to the cyclone separator. As the mixed flow enters the device, it generates rotational energy which drives the stacked impellers. These impellers force heavier oil particles outward by centripetal motion and allow the air to exit the device. The oil can then be collected through another collection device. A continuous flow centrifuge is an effective method for separating air from oil. However, the complexity and size of the device may not be feasible for this project.

Figure A - 8: Continuous flow centrifuge cross section [2]

Fine Mesh Filter: The fine mesh filter depicted in Figure 9 operates by allowing air to pass through the mesh, while filtering out any contaminants trapped in the airflow. The separated contaminants, in this case oil, is then collected in a container. A disadvantage of a filtration system is that oil may become stuck in the filter and the leakage rate and volume may not be measurable by the technicians.

Figure A - 9: Air-Oil Fine Mesh Filter Separation System [3]

Perforated Exhaust Pipe: A stainless steel perforated cylinder as shown in Figure 10 is attached to the drain line and inserted into the collection bottle. This perforated cylinder acts a filter for the oil, and a diffuser for the air. The fast moving air would be slowed, as it is expelled through the perforations. The cylinder would also disrupt the air so it is not allowed to recirculate as easily through the collection bottle. The oil would then be allowed to slowly drip from the cylinder and into the collection bottle. The benefit of this device is that it can be added to the existing system without increasing the size of the system and does not change the the assembly instructions, making the implementation of the device seamless for the technicians. However, the repeated use of the device will eventually build up residue that will block airflow, therefore the pipe will require consistent cleaning which will increase assembly/disassembly time.

[redacted]

Figure A - 10: Perforated exhaust tube [4]

A.1.3 Oil Collection

The following concepts were developed for the oil collecting vessel. The overall system is constrained by the design volume available. There is a height restriction of 12 *inches* for the system between the bottom of the engine where the system is installed and the shop floor. The client emphasized that there should be clearance between the floor and the system once installed. Additionally, the system is to be stored on the shop carts with dimensions of $3ft$ by $2ft$ by $1ft$.

Variable Volume Container: The variable volume of air-oil containment system stems from the working principle of the relationship between pressure and volume. The container would be designed to have a variable size mechanism to provide pressure relief to the oil collection system during engine testing. A drawback for the implementation of a variable volume collection system would be that the upper limit volume may exceed the design space limits for it to be effective.

[redacted]

Figure A - 11: Pressure Volume Diagram to Illustrate Variable Volume [5].

Plastic Bottle: The current oil collection system at StandardAero utilizes translucent plastic bottles to collect the oil. The maximum temperature of air entering the bottles was determined to be 250 $^\circ F$, which is below the melting point of most plastics. Therefore the existing bottles shown in Figure 12 (the render is made solid for visual clarity) is an acceptable container option for oil collection. Using the existing bottle would be beneficial to the project because the technicians are already familiar with the assembly/disassembly of the container and the bottle will reduce costs since StandardAero already has the bottles in stock. However, since the bottles do not provide a solution to the oil loss problem, another solution will have to be implemented in addition to the bottles which will make the system more complex.

Figure A - 12: Approximate bottles currently used at StandardAero.

Collapsible Bottle: Like a corrugated pipe, the bottle can be expanded to allow for a larger volume container that results in reduced pressure within the oil collection system. Additionally, the bottle can be collapsed during installation on the shop floor to fit within the available space. Once the engine is mounted in the test cell, the bottle can be expanded to the larger volume for oil collection. However, due to the required flexibility of the bottle, the bottle will not be as durable as some of the other options and may need to be replaced more frequently. The expanded and collapsed configurations are represented by Figure 13.

[redacted]

Figure A - 13: Collapsible bottle [6]

Secondary Catchment System: The oil collection system will be composed of two stages. Air and oil will enter a container similar to the current collection system of a bottle with holes in the top to vent the air flow. This primary stage will capture a majority of the oil, however, some oil will be carried out of the vents in the air flow. Therefore, the second stage of the design will be an additional container surrounding first container to capture the oil loss of the first container. The second container as shown by Figure 14 will also contain vents to allow the air flow to escape but they will be positioned in such a way that the oil will be trapped in the second container. This design provides a sense of security during engine testing as it is essentially a contingency feature that ensures no oil will be lost if the primary solution is not 100% successful. However, given that the device is composed of two containers, the size of the system will be much larger than any of the other proposed concepts and may not fit within the design space.

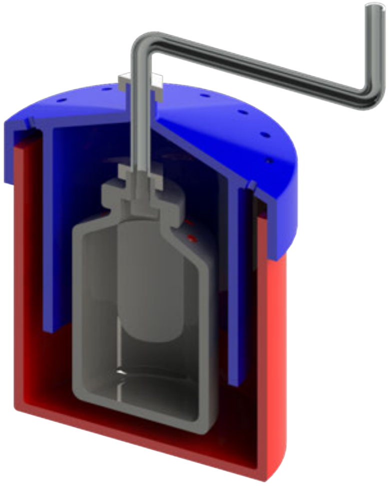


Figure A - 14: Two stage oil collection system

Oil Absorption: The issue at the moment with the current oil collection system is that oil and air is entering the system increases the internal pressure and requires venting so the bottle does not become a projectile, but these vents contribute to oil loss and result in inaccurate oil leakage data. This concept provides a solution in the form of a material capable of absorbing the oil in the system, see Figure 15. The material can then be weighed before and after testing to determine the amount of oil leaking from the engine. The advantage of this solution is that it does not require any adjustment to the existing system apart from adding the material into the bottle. However, there are a few concerns with this concept. Having to replace the material for every test will be a recurring cost, the oil flow rate will be difficult to determine if necessary as the absorption material will conceal the oil in the container, and if the need arises that the oil quality needs to be tested, the absorbed oil will have been contaminated and unusable.

Figure A - 15: Fluid absorption plug [7]

A.1.4 Flow Regulating Devices

Flow regulating devices are being considered for the design as they are capable of decreasing the downstream pressure of the flow. The benefit of these devices is that the reduction in pressure of the air-oil mixture entering the collection system will mitigate or even eliminate the possibility that a closed container will explode due to over pressurization. However, the design team acknowledges that many flow regulating devices increase pressure upstream, which may result in damage to the engines, and has taken this fact into account during concept selection.

Tesla Valve: The Tesla valve can increase or reduce fluid flow speed when fluid flows in the blue or red path indicated in Figure 16 respectively [8]. For the purposes of this project to collect oil, the air mixture would flow in the direction indicated by the black and red path which reduces the airflow speed. The reduced speed would allow the oil to settle and be collected. A drawback of the Tesla valve is that oil could be trapped within the channels and requires full disassembly to collect all oil. The reduces the ease of use of the design.

Figure A - 16: Tesla Valve [9]

Suppressor: Suppressors function to suppress the expanding gases in a gun chamber by reducing the pressure and speed [10]. For the application of oil collection, the suppressor as shown in Figure 17 would suppress the air mixture coming from the engine by reducing the pressure and speed. The reduced speed then allows the oil to settle and be collected. Like the Tesla valve, the baffles within the device could trap air and require full disassembly to fully collect oil. Again reducing the ease of use.

Figure A - 17: Suppressor attached to oil collection bottle

Electric field Separation: The Oil would act as a charged particle passing through an electric field as illustrated by Figure 18. Based on the strength of the field and it's orientation, the oil droplet would follow a parabolic arc. This field would force the particles to pass down one of the walls and out into a separate collection area; the air would flow freely. This design requires the oil to be atomized to function as intended, which is a setback on the design. Additionally, the design requires an electric field to be established which may require additional equipment in the test cell, increasing the difficulty and complexity.

[redacted]

Figure A - 18: Charged particle suspended in electric field [11]

Over pressure Relief Valve: An over pressure relief valve shown in Figure 19 integrated into the design as a safety measure. The valve allows for the system to off gas when the upper pressure limit is reached. Valve selection considerations can be made to insure minimal oil loss. The advantage of installing an over pressure relief valve is that the valve will safeguard the systems components from over pressurization.

[redacted]

Figure A - 19: Over pressure relief valve [12]

Oil Deflector: Oil deflectors, shown by Figure 20, serve to obstruct fluid flow, this is done by diverting, and restricting the oil once it is in the bottle. Concentric rings are used with gaps between them which trap the oil. In turn this can slow down the oil, and prevent from swirling and recirculating within the collection device. This design component would then allow for the oil to later drip into another collection device or to be collected without being blasted back out the pressure release holes.

[redacted]

Figure A - 20: Oil deflector [13]

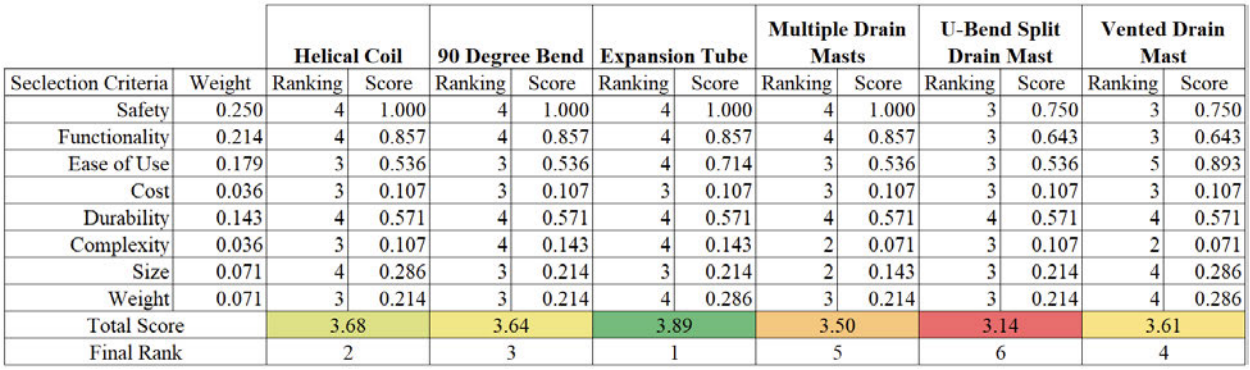
A.2 Initial Concept Selection

This section presents the methodology used for concept selection during the conceptual design phase. A weighted decision matrix was applied to each component to evaluate the concepts generated for that component. The results are presented as follows.

A.2.1 Drain Mast

Shown in Table I is the weighted decision matrix applied to evaluate the different concepts developed by the team.

TABLE A - I: DRAIN MAST WEIGHTED DECISION MATRIX



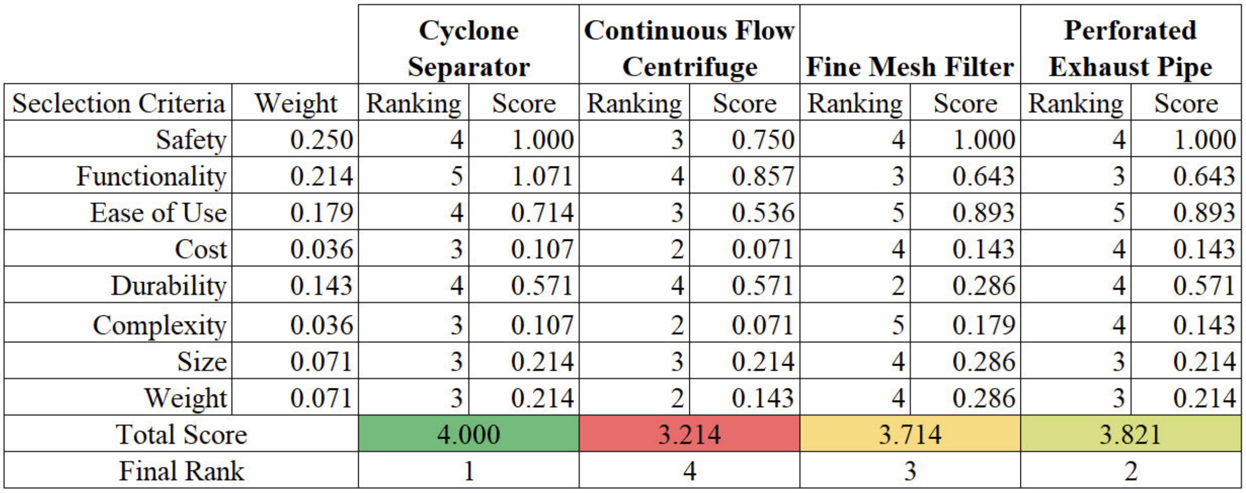
		Helical Coil		**90 Degree Bend**		**Expansion Tube**		**Multiple Drain Masts**		**U-Bend Split Drain Mast**		**Vented Drain Mast**	
Seclection Criteria	Weight	Ranking	Score	Ranking	Score	Ranking	Score	Ranking	Score	Ranking	Score	Ranking	Score
Safety	0.250	4	1.000	4	1.000	4	1.000	4	1.000	3	0.750	3	0.750
Functionality	0.214	4	0.857	4	0.857	4	0.857	4	0.857	3	0.643	3	0.643
Ease of Use	0.179	3	0.536	3	0.536	4	0.714	3	0.536	3	0.536	5	0.893
Cost	0.036	3	0.107	3	0.107	3	0.107	3	0.107	3	0.107	3	0.107
Durability	0.143	4	0.571	4	0.571	4	0.571	4	0.571	4	0.571	4	0.571
Complexity	0.036	3	0.107	4	0.143	4	0.143	2	0.071	3	0.107	2	0.071
Size	0.071	4	0.286	3	0.214	3	0.214	2	0.143	3	0.214	4	0.286
Weight	0.071	3	0.214	3	0.214	4	0.286	3	0.214	3	0.214	4	0.286
Total Score		3.68		3.64		3.89		3.50		3.14		3.61	
Final Rank		2		3		1		5		6		4	

As shown through the weighted decision matrix, the expansion tube was determined to be the best option for drain mast design. The expansion tube scored consistently high across all selection criteria. The expansion tube attained the second highest score for ease of use on the basis that the design could be simply installed and remain attached without requiring any additional adjustments. Since ease of use is a higher weighted selected criteria, this allowed the expansion tube to achieve the highest total score and as the best option for drain mast design.

A.2.2 Air-Oil Separation

Shown in Table II is the WDM used in evaluating the air-oil separation methods generated.

TABLE A - II: AIR-OIL SEPARATION WEIGHTED DECISION MATRIX



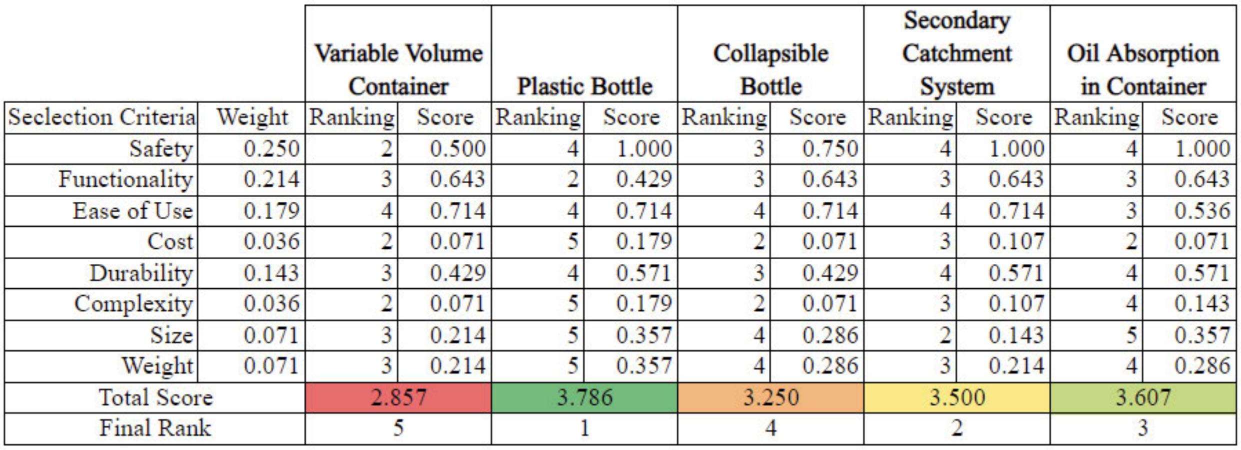
		Cyclone Separator		**Continuous Flow Centrifuge**		**Fine Mesh Filter**		**Perforated Exhaust Pipe**	
Seclection Criteria	Weight	Ranking	Score	Ranking	Score	Ranking	Score	Ranking	Score
Safety	0.250	4	1.000	3	0.750	4	1.000	4	1.000
Functionality	0.214	5	1.071	4	0.857	3	0.643	3	0.643
Ease of Use	0.179	4	0.714	3	0.536	5	0.893	5	0.893
Cost	0.036	3	0.107	2	0.071	4	0.143	4	0.143
Durability	0.143	4	0.571	4	0.571	2	0.286	4	0.571
Complexity	0.036	3	0.107	2	0.071	5	0.179	4	0.143
Size	0.071	3	0.214	3	0.214	4	0.286	3	0.214
Weight	0.071	3	0.214	2	0.143	4	0.286	3	0.214
Total Score		4.000		3.214		3.714		3.821	
Final Rank		1		4		3		2	

The cyclone separator was determined to be the best option for separating oil from the air flow mixture. The functionality of the cyclone separator was given a score of 5 since external search revealed many existing designs that uses the principle of cyclic airflow to separate air. Since functionality is a high weight selection criteria, the cyclone separator was the selected concept for air-oil separation devices.

A.2.3 Oil Collection

Table III is the weighted decision matrix results following the evaluation of different oil collection components.

TABLE A - III: OIL COLLECTION WEIGHTED DECISION MATRIX



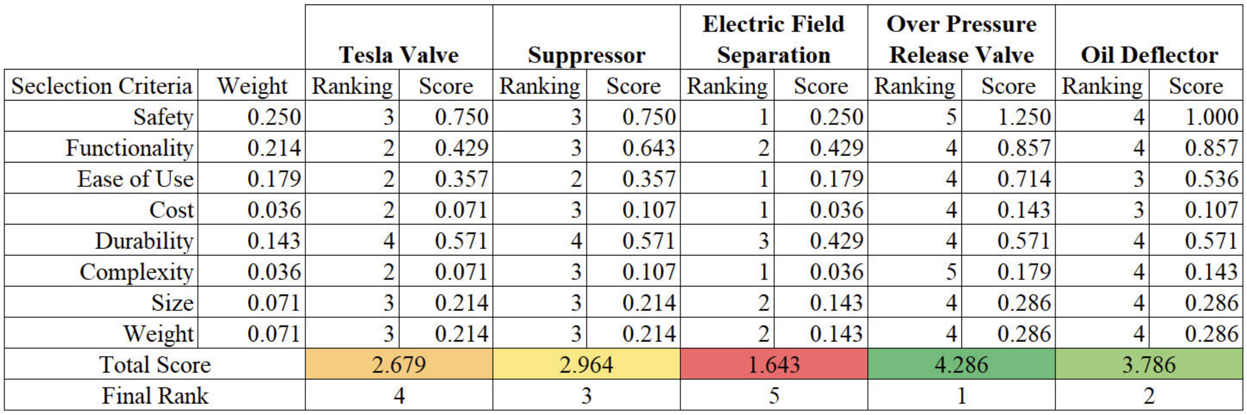
		Variable Volume Container		**Plastic Bottle**		**Collapsible Bottle**		**Secondary Catchment System**		**Oil Absorption in Container**	
Seclection Criteria	Weight	Ranking	Score	Ranking	Score	Ranking	Score	Ranking	Score	Ranking	Score
Safety	0.250	2	0.500	4	1.000	3	0.750	4	1.000	4	1.000
Functionality	0.214	3	0.643	2	0.429	3	0.643	3	0.643	3	0.643
Ease of Use	0.179	4	0.714	4	0.714	4	0.714	4	0.714	3	0.536
Cost	0.036	2	0.071	5	0.179	2	0.071	3	0.107	2	0.071
Durability	0.143	3	0.429	4	0.571	3	0.429	4	0.571	4	0.571
Complexity	0.036	2	0.071	5	0.179	2	0.071	3	0.107	4	0.143
Size	0.071	3	0.214	5	0.357	4	0.286	2	0.143	5	0.357
Weight	0.071	3	0.214	5	0.357	4	0.286	3	0.214	4	0.286
Total Score		2.857		3.786		3.250		3.500		3.607	
Final Rank		5		1		4		2		3	

The current plastic bottle was determined to be the best option for oil collection. Despite the bottle currently having a low functionality, by introducing system improvements to the drain mast and air-oil separation device we believe that this will increase the functionality of the plastic bottle. The plastic bottles ability to adequately collect oil will be verified during the detailed design phase.

A.2.4 Flow Regulating Devices

The weighted decision matrix was also applied to various flow regulating devices to facilitate in the oil collection. The results are shown in Table IV.

TABLE A - IV: FLOW REGULATING DEVICES WEIGHTED DECISION MATRIX



		Tesla Valve		**Suppressor**		**Electric Field Separation**		**Over Pressure Release Valve**		**Oil Deflector**	
Seclection Criteria	Weight	Ranking	Score	Ranking	Score	Ranking	Score	Ranking	Score	Ranking	Score
Safety	0.250	3	0.750	3	0.750	1	0.250	5	1.250	4	1.000
Functionality	0.214	2	0.429	3	0.643	2	0.429	4	0.857	4	0.857
Ease of Use	0.179	2	0.357	2	0.357	1	0.179	4	0.714	3	0.536
Cost	0.036	2	0.071	3	0.107	1	0.036	4	0.143	3	0.107
Durability	0.143	4	0.571	4	0.571	3	0.429	4	0.571	4	0.571
Complexity	0.036	2	0.071	3	0.107	1	0.036	5	0.179	4	0.143
Size	0.071	3	0.214	3	0.214	2	0.143	4	0.286	4	0.286
Weight	0.071	3	0.214	3	0.214	2	0.143	4	0.286	4	0.286
Total Score		2.679		2.964		1.643		4.286		3.786	
Final Rank		4		3		5		1		2	

The over pressure release valve was determined to be the best option for flow regulating devices. This was because the pressure release valve is a small attachment that would seal the device and prevent the airflow from escaping until a certain pressure was reached. This would restrict the airflow to allow for the oil to separate and be collected.

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B Analytical Calculation for Stress Analysis of Drain Mast

This following section presents the analytical calculations for stress analysis of the drain mast.

The bending moment at location B and C due to gravity was determined through:

$$\begin{aligned} M &= mgd \\ &= (0.7)(9.81)(0.18) \\ &= 1.23 N \cdot m \end{aligned} \tag{1}$$

The normal stress due to bending moment at location B was determined using Equation 2, where the variables are listed as follows, and Figure 1 illustrates the relation of the variables to the cross-section [1]:

- σ_θ = normal stress
- M = bending moment
- y = distance from neutral axis to location of interest
- A = cross-section area
- e = distance between neutral axis and centroidal axis
- r = radius from center of curvature to position of interest on the cross section

[redacted]

Figure B - 1: Variables of cross section [1]

$$\sigma_\theta = \frac{My}{Aer} \tag{2}$$

Distance between the neutral axis and centroidal axis was determined through Equation 3, where r_o and r_i are the outer and inner radius of the tubing respectively. The dimensions used in the calculations are based on the drawings in Appendix C.

$$\begin{aligned}
e &= \frac{r_o}{2}\left(\frac{2R}{r_o} - \sqrt{\left(\frac{R}{r_o}\right)^2 - 1} - \sqrt{\left(\frac{R}{r_o}\right)^2 - \left(\frac{r_i}{r_o}\right)^2}\right) \\
&= \frac{0.00476}{2}\left(\frac{2(0.019)}{0.00476} - \sqrt{\left(\frac{0.019}{0.00476}\right)^2 - 1} - \sqrt{\left(\frac{0.019}{0.00476}\right)^2 - \left(\frac{0.00375}{0.00476}\right)^2}\right) \\
&= 0.000469m
\end{aligned} \tag{3}$$

The cross-section area of the circle was determined through Equation 4

$$\begin{aligned}
A &= \pi(r_o^2 - r_i^2) \\
&= \pi(0.00476^2 - 0.00352^2) \\
&= 0.0000323m^2
\end{aligned} \tag{4}$$

The distance y was determined through geometric relations as:

$$\begin{aligned}
y &= r_o - e \\
&= 0.00476 - 0.000469 \\
&= 0.004291m
\end{aligned} \tag{5}$$

The distance r was determined through geometric relations as:

$$\begin{aligned}
r &= R - r_o \\
&= 0.019 - 0.00476 \\
&= 0.01424m
\end{aligned} \tag{6}$$

Substituting the variables into Equation 2, the stress was determined to be:

$$\begin{aligned}\sigma_\theta &= \frac{My}{Aer} \\ &= \frac{(1.23)(0.004291}{(0.0000323)(0.000469)(0.01424)} \\ &= 24.27MPa\end{aligned}$$

There also exists a torque B due to the offset center of mass of the catch can. The torque was determined through

$$\begin{aligned}T &= mgl \\ &= (0.7)(9.81)(0.0221) \\ &= 0.15N \cdot m\end{aligned} \tag{7}$$

The shear stress due to the torque at location B was calculated through Equation 8:

$$\tau = \frac{Tr_o}{J} \tag{8}$$

The polar moment of inertia for the cross-section was calculated as

$$\begin{aligned}J &= \frac{\pi}{32}((2r_o)^4 - (2r_i)^4) \\ &= \frac{\pi}{32}((2 \cdot 0.00476)^4 - (2 \cdot 0.00352)^4) \\ &= 5.65e^{-10}m^4\end{aligned} \tag{9}$$

The shear stress at location B due to the torque was determined as follows:

$$\begin{aligned}\tau &= \frac{Tr_o}{J} \\ &= \frac{(0.15)(0.00476)}{5.65e^{-10}} \\ &= 1.26MPa\end{aligned}$$

For a stress element at location B illustrated in Figure 2, the stresses in Figure 2 correspond to the calculated stresses as follows:

- $\sigma_x = \sigma_\theta = 24.27MPa$
- $\tau_{xz} = \tau_T = 1.26MPa$

Figure B - 2: Stresses of a stress element at location B [2]

with all other stresses equal to 0. This characterized the state of stress for a stress element at location B. The principle stresses at location B were calculated through finding the roots of Equation 10 [3].

$$\begin{aligned}\sigma^3 - (\sigma_x + \sigma_y + \sigma_z)\sigma^2 + (\sigma_x\sigma_y + \sigma_x\sigma_z + \sigma_y\sigma_z - \tau_{xy}^2 - \tau_{yz}^2 - \tau_{zx}^2)\sigma \\ - (\sigma_x\sigma_y\sigma_z + 2\tau_{xy}\tau_{yz}\tau_{zx} - \sigma_x\tau_{yz}^2 - \sigma_y\tau_{zx}^2 - \sigma_z\tau_{xy}^2) = 0 \quad (10)\end{aligned}$$

Since most of the variables in Equation 10 are 0, the equation simply reduces to a quadratic equation in Equation 11.

$$\sigma^2 - \sigma_x\sigma - \tau_{xz}^2 = 0 \quad (11)$$

Solving the quadratic equation for principle stresses:

$$\begin{aligned}\sigma &= \frac{\sigma_x \pm \sqrt{\sigma_x^2 + 4\tau_{xz}^2}}{2}\\ &= \frac{24.27 \pm \sqrt{24.27^2 + 4(1.26}^2}{2}\\ &= 12.137 \pm 12.2\end{aligned}\tag{12}$$

The three principle stresses were determined to be 24.34 MPa, -0.063 MPa, and 0 MPa. The effective stress for location B was determined through Equation 13.

$$\begin{aligned}\sigma_{eff} &= \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}\\ &= \sqrt{\frac{(24.34 - (-0.063))^2 + (-0.063)^2 + (-24.34)^2}{2}}\\ &= 24.37MPa\end{aligned}\tag{13}$$

For location C, the stress due to bending was calculated through Equation 14.

$$\sigma = \frac{Mr_o}{I}\tag{14}$$

The second moment of inertia of the cross-section, I, was determine as follows:

$$\begin{aligned}I &= \frac{\pi}{64}((2r_o)^4 - (2r_i)^4)\\ &= \frac{\pi}{32}((2 \cdot 0.00476)^4 - (2 \cdot 0.00352)^4)\\ &= 2.83e^{-10}m^4\end{aligned}\tag{15}$$

The moment at location C is equal to the moment at B since the distance perpendicular to the direction of gravity between the center of mass of the catch can to positions B and C is the same. The bending stress at C was determined to be

$$\begin{aligned}\sigma &= \frac{1.23(0.00476}{2.83e - 10}\\ &= 20.69MPa\end{aligned}\tag{16}$$

The are no other forces that can contribute to the stress at C. Therefore, 20.69 MPa is the maximum effective stress at C. The lowest factor of safety, FoS, for the drain mast was calculated using Equation 17.

$$FoS = \frac{\sigma_{yield}}{\sigma_{eff}} \tag{17}$$

For annealed 304 stainless steel, the yield stress, σ_{yield}, is 205 MPa [4]. The minimum factor of safety under static loading was determined to be

$$\begin{aligned} FoS &= \frac{205}{24.37} \\ &= 8.4 \end{aligned}$$

The deflection of the catch can was calculated through Castigliano's Theorem in Equation 18 [5]. The modulus of elasticity for 304 stainless steel was found to be 193 GPa [4].

$$\delta = \frac{M}{EI}\int_0^L \frac{\partial M}{\partial F}\,dx \tag{18}$$

The deflection at the catch can was calculated as:

$$\begin{aligned} \delta_A &= \frac{M}{EI}\int_0^L \frac{\partial M}{\partial F}\,dx \\ &= \frac{mg}{EI}\int_0^{0.18} -x^2\,dx \\ &= \frac{(1.23)(9.81)}{(193e9)(2.83e-18)}\frac{0.18^3}{3} \\ &= 0.24mm \end{aligned}$$

The angular deflection at position B due to the bending moment was also determined through Castigliano's Theorem in Equation

$$\theta_B = \frac{9.81mLd}{EI} = \frac{9.81(0.7)(0.18)(0.057)}{(193e9)(2.83e-10)} = 0.0013rads \tag{19}$$

The total deflection was using geometric relations through Equation 20. The total deflection was calculated as:

$$\begin{aligned}\delta_T otal &= L\sin(\theta_B) + \delta_A\cos(\theta_B) \\ &= 0.18\sin(0.0013) + 0.00024\cos(0.0013) \\ &= 0.47mm\end{aligned} \tag{20}$$

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C Engineering Drawings

The following section presents the available engineering drawings for the various components used in the re-designed oil collection system. The team was unable to acquire drawings for the Mishimoto Carbon Fiber Baffled Catch Can. Therefore, drawings of the catch can are not provided.

C.1 304 Stainless Steel Sleeve

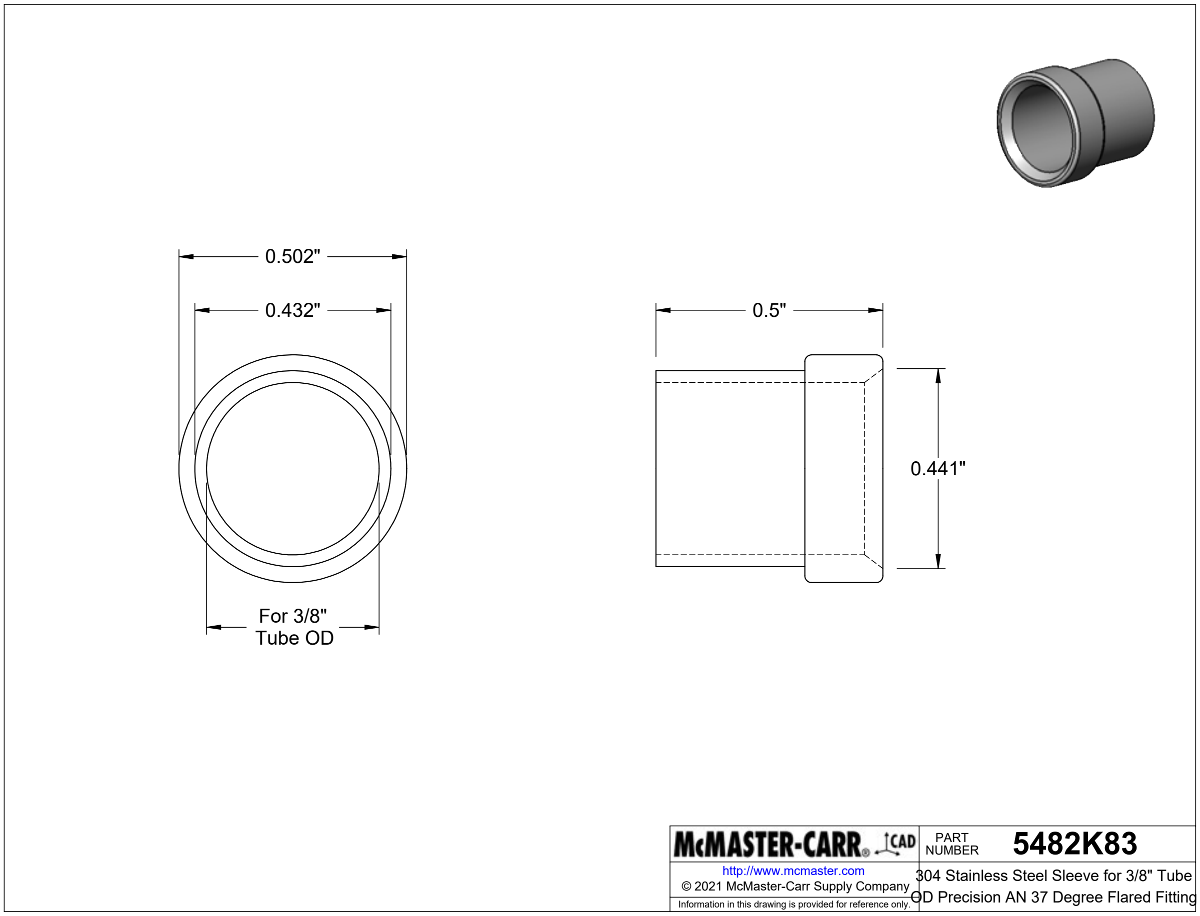


Figure C - 1: 304 Stainless Steel Sleeve for 3/8” Tube OD Precision AN 37 Degree Flared Fitting, 5482K83 [1]

C.2 304 Stainless Steel Nut

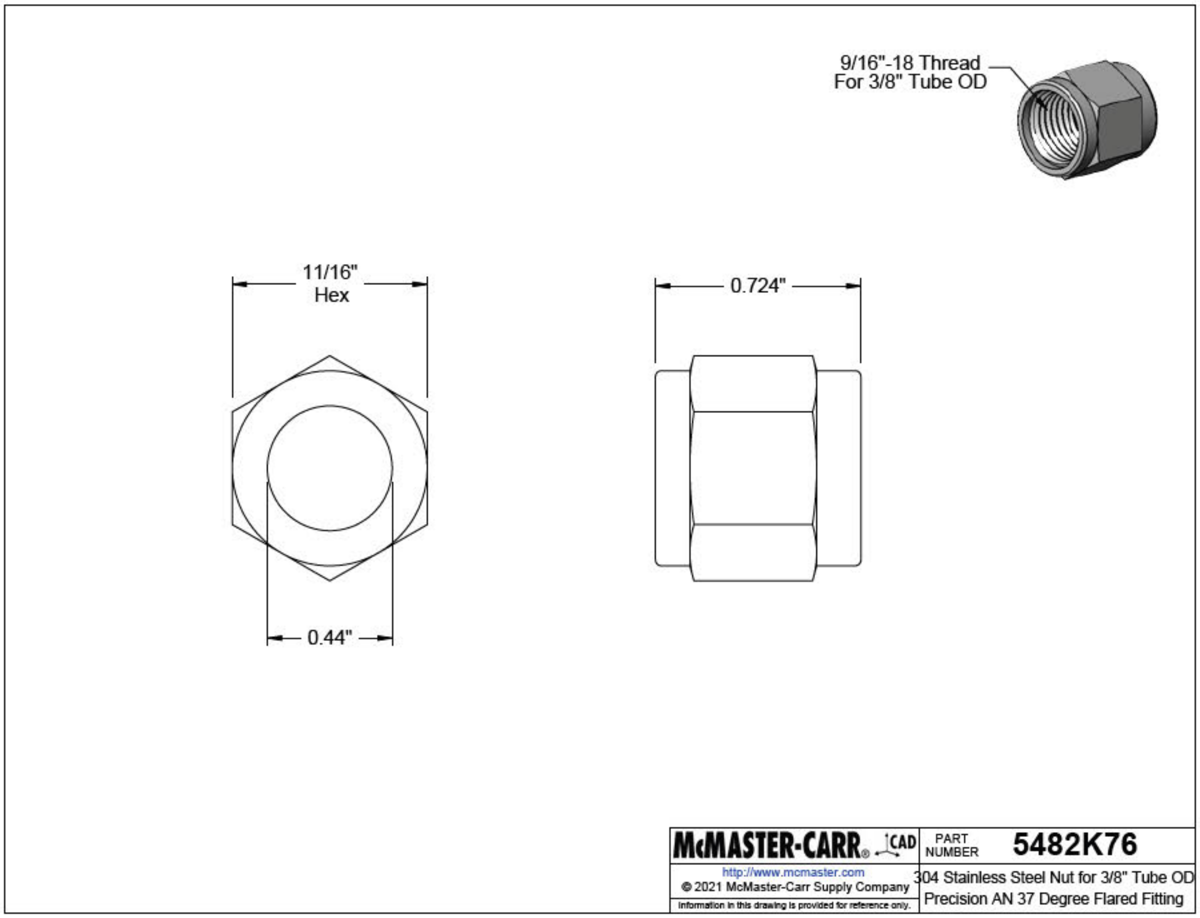


Figure C - 2: 304 Stainless Steel Nut for 3/8” Tube OD Precision AN 37 Degree Flared Fitting, 5482K76 [2]

C.3 Precision AN 37 Degree Flared Fitting

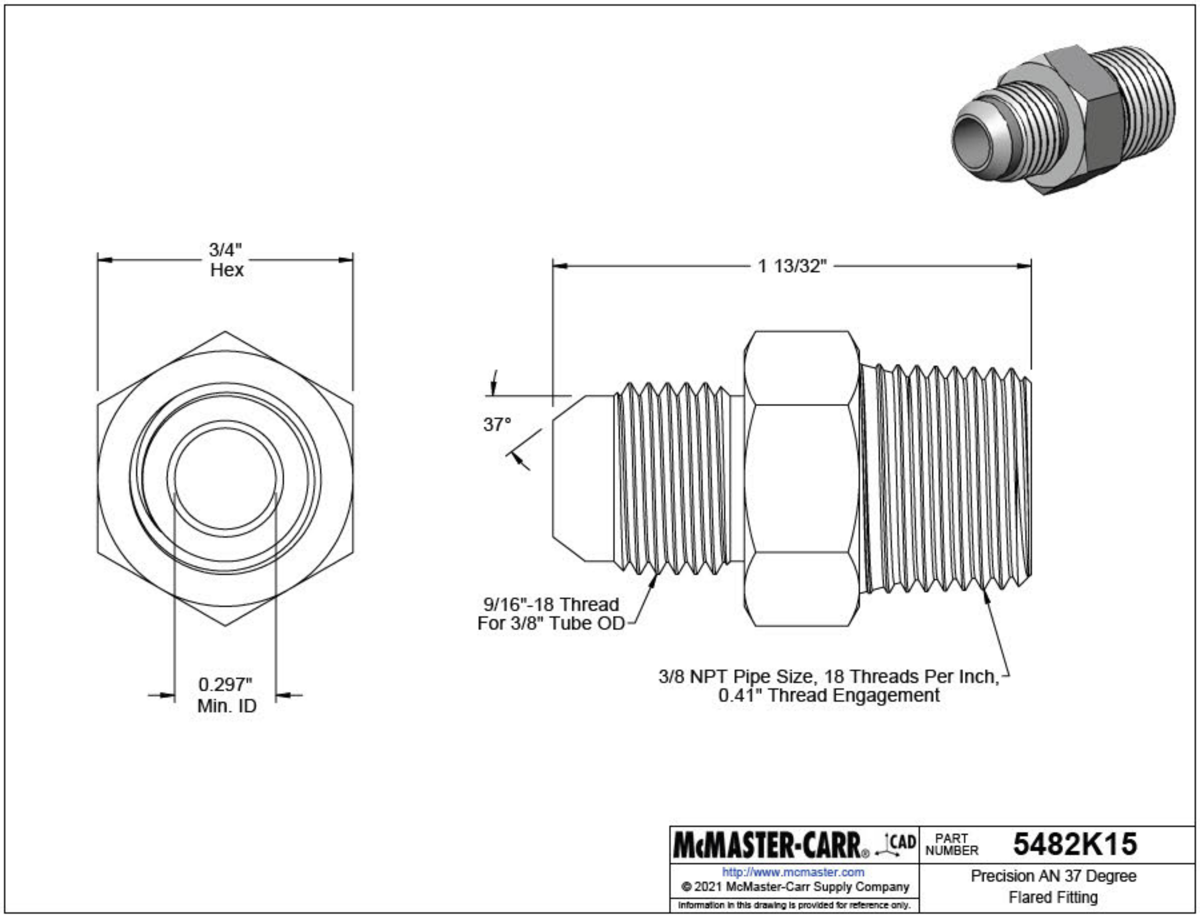


Figure C - 3: Precision AN 37 Degree Flared Fitting, 5482K15 [3]

C.4 316 Stainless Steel Threaded Pipe Fitting

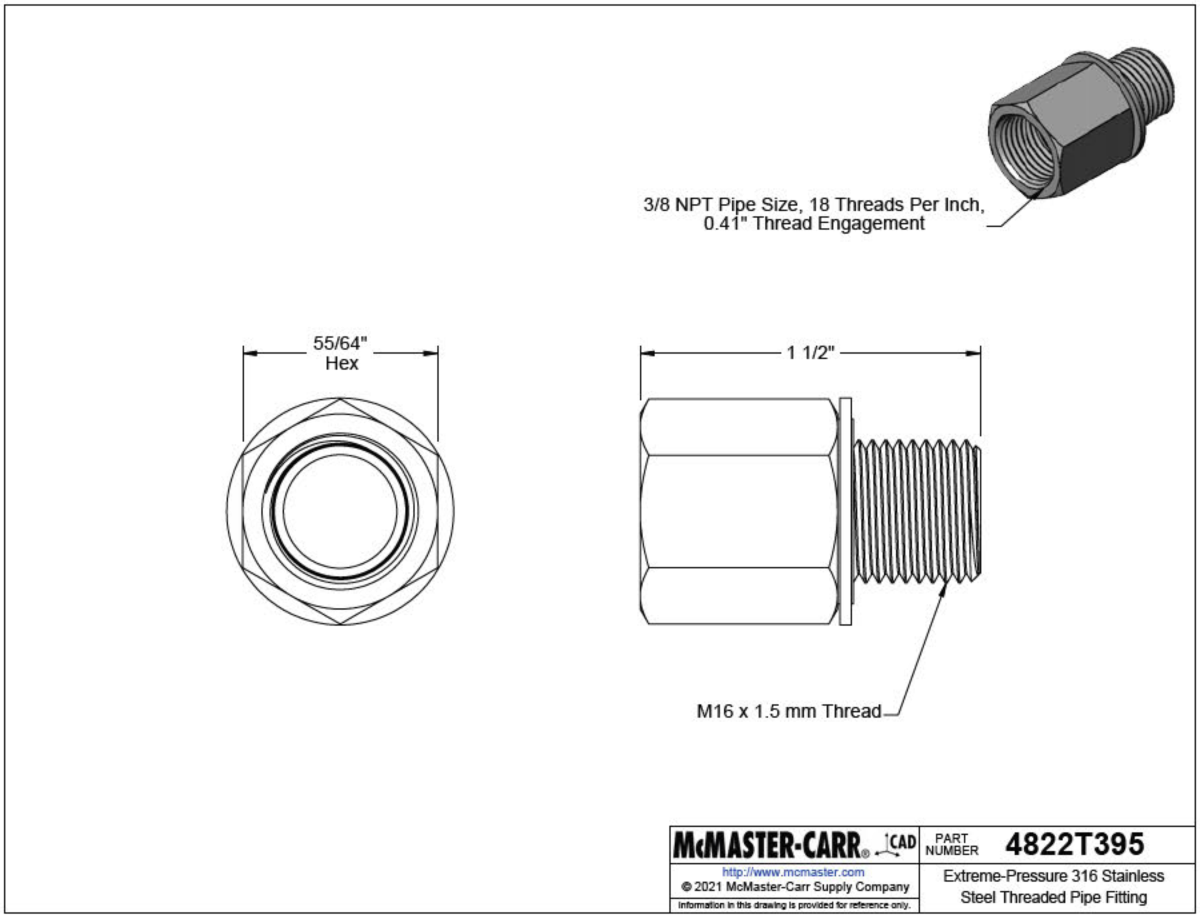
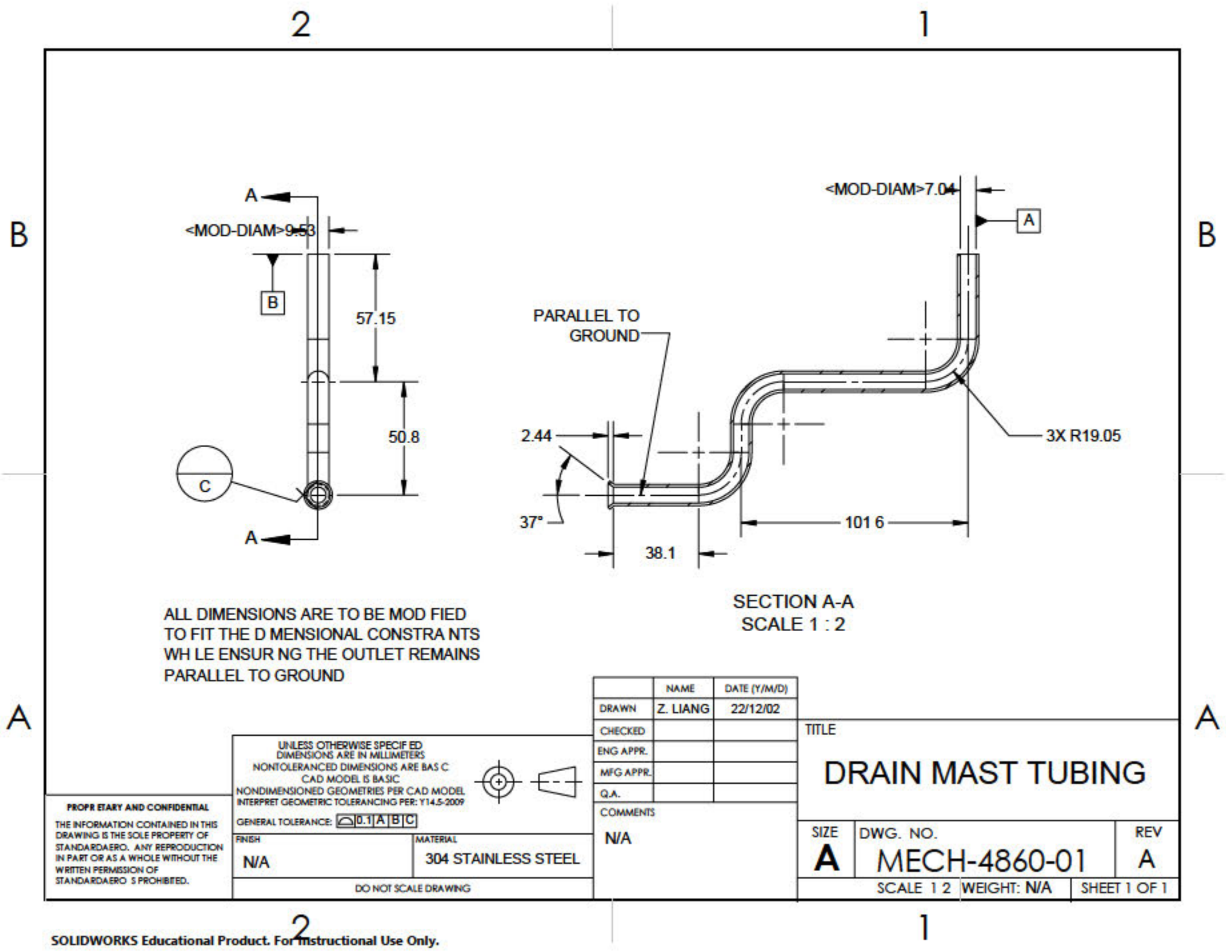


Figure C - 4: Extreme-Pressure 316 Stainless Steel Threaded Pipe Fitting, 4822T395 [4]

C.5 Drain Mast Tubing



ALL DIMENSIONS ARE TO BE MODIFIED TO FIT THE DIMENSIONAL CONSTRAINTS WHILE ENSURING THE OUTLET REMAINS PARALLEL TO GROUND

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL
INTERPRET GEOMETRIC TOLERANCING PER: Y14.5-2009

PROPRIETARY AND CONFIDENTIAL

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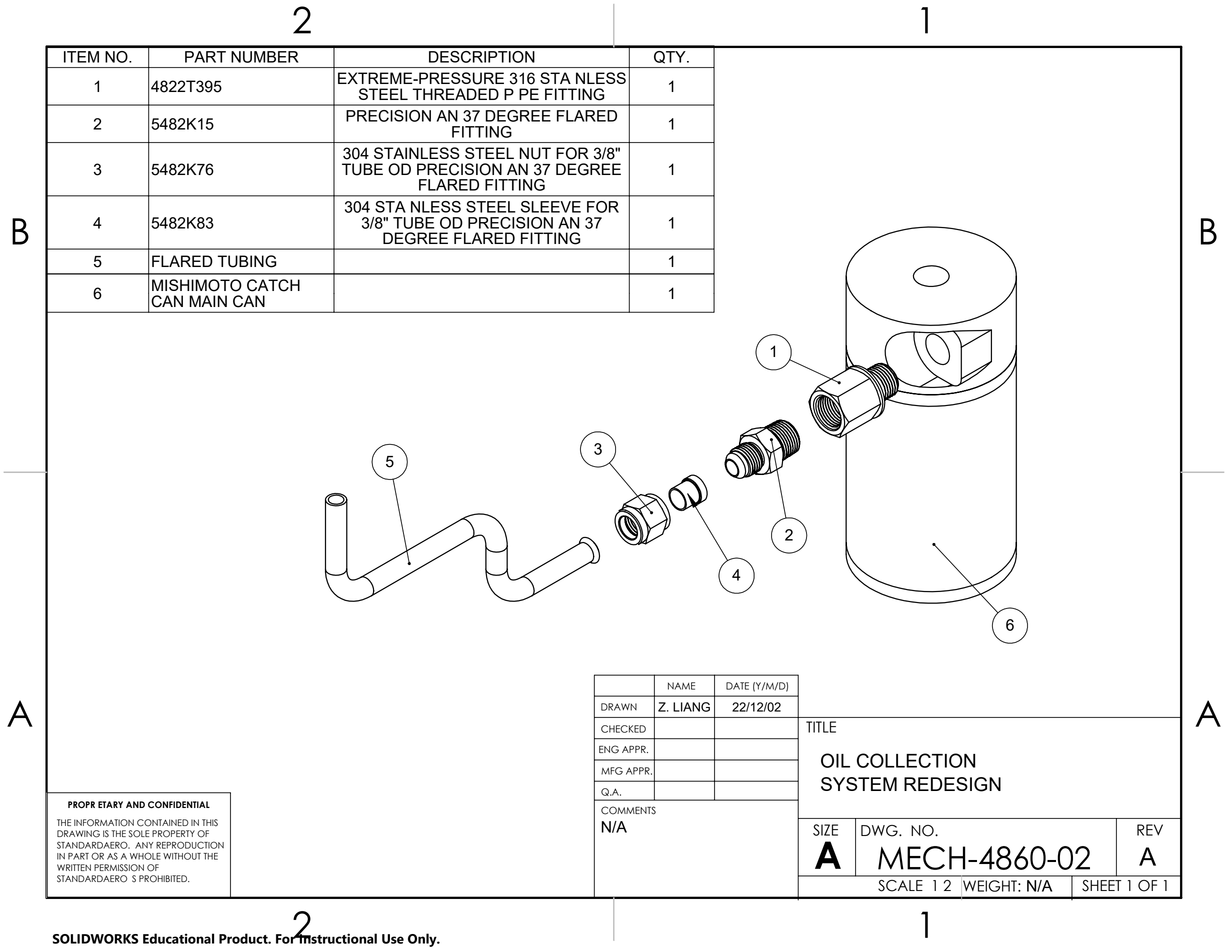
Figure C - 5: Drain Mast Tubing

C.6 Oil Collection System Assembly



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	4822T395	EXTREME-PRESSURE 316 STAINLESS STEEL THREADED PIPE FITTING	1
2	5482K15	PRECISION AN 37 DEGREE FLARED FITTING	1
3	5482K76	304 STAINLESS STEEL NUT FOR 3/8" TUBE OD PRECISION AN 37 DEGREE FLARED FITTING	1
4	5482K83	304 STAINLESS STEEL SLEEVE FOR 3/8" TUBE OD PRECISION AN 37 DEGREE FLARED FITTING	1
5	FLARED TUBING		1
6	MISHIMOTO CATCH CAN MAIN CAN		1

	NAME	DATE (Y/M/D)
DRAWN	Z. LIANG	22/12/02
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS
N/A

TITLE
OIL COLLECTION
SYSTEM REDESIGN

SIZE A
DWG. NO. MECH-4860-02
REV A
SCALE 1:2
WEIGHT: N/A
SHEET 1 OF 1

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Figure C - 6: Final Oil Collection System Assemby and Bill of Material.[1] [2] [3] [4]

References

[1] McMaster-Carr. “304 stainless steel sleeve for 3/8” tube od precision an 37 degree flared fitting.” (), [Online]. Available: `https://www.mcmaster.com/5482K83/` (visited on 12/01/2022).

[2] McMaster-Carr. “304 stainless steel nut for 3/8” tube od precision an 37 degree flared fitting.” (), [Online]. Available: `https://www.mcmaster.com/5482K76/` (visited on 12/01/2022).

[3] McMaster-Carr. “Precision an 37 degree flared fitting.” (), [Online]. Available: `https://www.mcmaster.com/5482K15/` (visited on 12/01/2022).

[4] McMaster-Carr. “Extreme-pressure 316 stainless steel threaded pipe fitting.” (), [Online]. Available: `https://www.mcmaster.com/4822T395/` (visited on 12/01/2022).

Appendix D

Contents

D Standard Operating Procedure **D2**

D Standard Operating Procedure

This following section presents a draft of the standard operating procedure (SOP) requested by the client regarding the assembling and disassembling instructions of the re-designed oil collection system. The SOP is subject to change pending on the progression of the prototyping phase of the project where procedures may be modified for faster assembly and disassembly times.

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StandardAero

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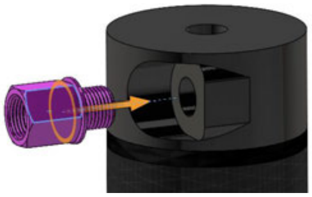

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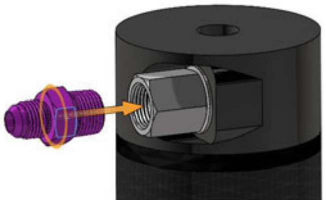

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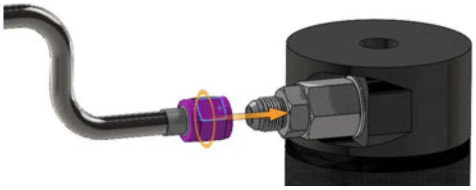

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