MUFFLER DESIGN AND CAT INTEGRATION
for the University of Idaho
Clean Snowmobile Challenge Team

Presented by Stealth CATs:
Amanda Bolland, Eric Buddrius, Ian Lootens, and Greg Hilbert
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StealthCAT@uidaho.edu
This project focused on solving a couple of the many problems facing modern-day snowmobiles, specifically noise level and emissions. The University of Idaho wishes to better its sled for the SAE Clean Snowmobile Challenge (CSC). We have to reduce the sound level of the sled to below competition requirements. Also Stealth CATs set a goal of achieving National Park Standards (NPS) for emissions. In order to accomplish both of these goals, the team integrated a catalytic converter (CAT) into a new muffler design utilizing Hushpower mufflers.

Using the J-192 sound testing procedure, the team tested several different Hushpower configurations and discovered that two Hushpower in series provided similar sound dampening to the stock system. Stealth CATs built a prototype based on this conclusion and set about testing it. The sound testing results came back showing the prototype was quieter than stock. Upon further examination the team found that the reduction in noise level was caused by the muffler restricting flow out of the engine severely limiting its performance. The team was not willing to give up engine performance for sound reduction and set about finding a solution to this problem.

The team was building a flow bench and looking into flow simulation software. Using both of these tools Stealth CATs discovered that the backpressure of the muffler could be greatly reduced using larger inner diameter Hushpowers. Due to the timing of this discovery, the team decided not to push the completion of the muffler for the 2011 completion. There was too much at stake for the University of Idaho CSC team and this was a complex project that needed to be done correctly.

Stealth CATs worked with Aristo Catalytic Technologies to choose a CAT to meet our specific needs. We provided Aristo with size limits, engine data, past emissions data, and targeted emissions. Even though the new muffler did not make it to the 2011 competition the CAT did. The team saw a reduction as compared to the 2010 results in all but carbon monoxide. We passed the CSC emissions portion of the competition but did not come close to meeting NPS. The University of Idaho team had the second lowest in-service emissions and the fourth lowest laboratory emissions.

The final muffler with larger Hushpowers was manufactured and the testing results came back very positive. The muffler is quieter and does not seem to limit engine performance. Future works includes tuning the engine to run best with the new muffler and measuring sound level and engine performance. This can then be directly compared to the stock specifications and the best system picked for the University of Idaho for the 2012 Clean Snowmobile Challenge Competition.
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1.0 BACKGROUND

Snowmobiles have traditionally been loud, with high levels of exhaust emissions and poor fuel economy. The snowmobile’s negative impact on the environment prompted the snowmobile community to challenge college students to design a cleaner, quieter snowmobile. The Society of Automotive Engineers (SAE) organized the Clean Snowmobile Challenge (CSC) in 1999 [1]. The competition is currently held at the Keweenaw Research Center in Houghton, Michigan. The competition focuses on increasing fuel economy, reducing emissions, and reducing the noise of snowmobiles to make them more environmentally friendly. This project is focusing specifically on the sound and emissions portions of the competition.

Prior to this project the University of Idaho CSC Team has worked on several different projects to decrease the emissions and noise of the sled. The team added a CAT to the snowmobile in 2007, 2008 and 2009. In 2008 and 2009 the team did not complete the emissions part of the competition for various reasons but in 2007 the team passed emissions. The team could have passed without the CAT but it helped to lower emissions further.

To reduce sled noise the team added sound dampening material to the inside of the hood and blocked unnecessary air vents. Sound absorbing material and stiffeners were added to the tunnel to reduce noise from tunnel vibrations and track noise. Experiments were performed to determine which type of bogie wheels, belt drives, and many other components were quieter. These small changes did not lower the overall sled noise significantly but there was a measurable difference. The reason why the change was small is that the main source of noise in a snowmobile is the exhaust. To reduce exhaust noise the team has previously developed and tested a Helmholtz resonator and a laminar flow muffler. Both projects did not dampen exhaust noise as much as the stock muffler and were not used in competition.

For this year’s competition the sled team saw an opportunity to use an available aftermarket technology to design a new muffler for the snowmobile. Hushpower is a branch of Flowmaster out of Coeur D’Alene Idaho. They have been making mufflers for many years and last year they donated a Hushpower muffler to be used by the University of Idaho Formula SAE Hybrid Car. Also Hushpower manufactures a unit for ATV’s to be added after the stock exhaust system. Neither of these applications requires the low sound level the CSC competition does but the sled team hopes to be able to create a muffler that is quiet enough using Hushpower’s design.

In the 2010 competition the snowmobile received a sound score of 85 dBA. In order to pass sound, the snowmobile must pass the standard J-192 test with a sound pressure less than 78 dBA. For 2011 the overall noise of the sled must be reduced for the team. The sled has passed the emissions potion of the competition most years and we hope to continue the trend this
Two-strokes exhaust emissions are typically dirtier than four-strokes and as a result extra measures need to be taken for two-strokes come out cleaner than their competitors.

If the team is able to make a muffler using Hushpower technology that is quieter than the current stock muffler the team will have a high chance of passing sound this year and winning the competition. Also incorporating a CAT will increase the team’s performance in the emissions categories. If the muffler design doesn’t work then at least the team knows that Hushpower technology is not currently the way to go in the snowmobile industry.

### 2.0 PROBLEM DEFINITION

Two areas of concern that Stealth CATs is targeting for the 2011 Clean Snowmobile Challenge are the reduction of exhaust noise and emissions. We hope to accomplish this by designing a new muffler and incorporation a catalytic converter.

In the 2010 competition the snowmobile did not pass the noise event. This year our team goal is to not only to reach the competition requirement of 78 dBA, set by the International Snowmobile Manufacturers Association [2], but also record a sound pressure that is below the National Park Services (NPS) Best Available Technology (BAT) level of 73.4 dBA [3]. A snowmobile must meet NPS BAT standards to be allowed in national parks such as Yellowstone [4].

Our next goal is to reduce the amount of emissions emitted by the engine. Last year the team easily passed the emissions portion of the competition without using a CAT. This year, however, the team’s goal is to reduce emissions far enough in order to also meet the National Park Standards.

The muffler design has several constraints and specifications that must be met and these are listed in Table 1.
Table 1: Product Specifications

<table>
<thead>
<tr>
<th>GENERAL REQUIREMENTS</th>
<th>SPECIFIC REQUIREMENTS</th>
<th>ACCEPTABLE PERFORMANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUIET</td>
<td>Reduces the sound emissions of the sled</td>
<td>78 dBA or less in J-192 Sound test (goal of 73 dBA)</td>
</tr>
<tr>
<td>REDUCE EMISSIONS</td>
<td>Incorporate a catalyst to reduce emissions</td>
<td>(HC+NOx)≤90g/KW-hr, CO≤275g/KW-hr, Escore≥100</td>
</tr>
<tr>
<td>SIMPLE MAINTENANCE</td>
<td>Catalyst must be replaceable, no other maintenance needed</td>
<td>CAT replacement takes less than 15 Minutes</td>
</tr>
<tr>
<td>PERFORMANCE</td>
<td>Doesn't increase backpressure</td>
<td>Less than 110% of stock backpressure</td>
</tr>
<tr>
<td>COMPACT DESIGN</td>
<td>Fits in sled without modification</td>
<td>Approximately 9&quot; Deep, 18&quot; Tall, 13&quot; Wide</td>
</tr>
<tr>
<td>LIGHT WEIGHT</td>
<td>Doesn't increase weight</td>
<td>Less than 16.76lb (110% of stock muffler weight)</td>
</tr>
<tr>
<td>ECONOMICAL</td>
<td>Within the project budget</td>
<td>Costs team less than $300 MSRP less than $700</td>
</tr>
<tr>
<td>EASY TO BUILD</td>
<td>Can be built by the sled team</td>
<td>Build using the U of I machine shop and facilities</td>
</tr>
</tbody>
</table>

As you can see there are many requirements of the muffler for it to be considered successful. The most important are reduction in sound and emissions. The CAT will need replaced several times and possibly at competition so CAT replacement must be quick and simple. The muffler must fit inside the sled and manufacturing must be easy and affordable for the CSC team.

Stealth CATs will have to learn about muffler design for this project. Research will need to be done about different muffler types, acoustic tuning, and the effects of flow modification. The team can examine the stock muffler and the previously designed laminar flow muffler. Also the theory behind the Hushpower muffler will need to be studied.

As for catalytic converters, the team will need to look into which type is best for two-strokes and our space constraints. Also which pollutants are weighed more in the competition and the CAT to best reduce these pollutants. The team will need to contact our CAT sponsor, Aristo Catalytic Technologies to find the one that best fits our needs.

Another area of project learning is in the simulation and testing sector. Modeling software like Ricardo WAVE and Solidworks flow simulations need explored. Results from J-192 sound tests and emissions data will need to be analyzed. The team will need to do flow testing on the muffler components and this will require the design and construction of a flow bench.
The final deliverables of this project will be a muffler with a removable CAT; verification of the performance of said muffler via sound testing, emissions testing, and flow testing. Side deliverables are the construction of a flow bench and the acquisition of several CATs.

3.0 CONCEPT DEVELOPMENT

Concept development is sometimes defined as “the process used in search for feasible solutions.” For this project the University of Idaho CSC team conducted a great deal of research, simulations, and tests and then constructed a prototype. The prototype was then tested and more simulations ran to create the design for the final product.

3.1 MUFFLER DESIGN

Mufflers are designed to dampen the high intensity pressure pulse generated by the combustion process from an internal combustion engine. Muffler design is traditionally a trial and error process. This is due to the tricky nature of several different properties coming together in a way that they cannot be considered at once. Professor David Egolf explained that it is fairly easy to design acoustic chambers to cancel out certain sound frequencies \[5\]. But after you design a muffler acoustically you have to incorporate the effects of the flow of the exhaust gases. If you manage to account for acoustics and flow you then must add the effects of very high fluid temperatures. In most commercial applications you design a muffler acoustically and adjust for flow and temperature experimentally until you get the desired results.

Three common muffler designs are absorption, restrictive, and reflective. The absorption or dissipative muffler, shown in Figure 1, is generally constructed with a straight perforated tube or a combination of chambers and perforated tubing. Surrounding the perforated tube is sound absorbing material; acoustical energy pulses vibrate the particles of the material and the energy dissipates as heat.

![Figure 1: Cross Section of an Absorption Muffler](image-url)
The restrictive muffler restricts the flow of the engine’s pressure pulse with the use of baffles and deflector plates. Restrictive mufflers are cheap and easy to make and are found in most automotive vehicles.

A reflective muffler is the most effective for attenuating exhaust noise. This muffler uses resonator chambers to cancel out sound waves. The length and volume of the chamber is chosen so that the reflected wave collides with the next incoming wave creating destructive interference. Most reflective mufflers exhibit techniques from all of the muffler designs because resonator chambers only work at certain frequencies. Figure 2 displays the inside layout of a reflective muffler.

![Reflective Muffler](image)

**Figure 2: Reflective Muffler**

### 3.1.1 STOCK MUFFLER DESIGN

The stock snowmobile muffler for the team’s Ski-doo is a four-chamber series design consisting of two reflection chambers and two absorption chambers. Figure 3 shows a cutaway of the stock muffler. The first and third chambers are reflection chambers; the second and fourth chambers are absorption chambers. The stock muffler is constructed to fill all available space in the chassis for the greatest sound dampening.
3.1.2 LAMINAR FLOW MUFFLER

The CSC team has previously looked into the concept of putting a laminar flow muffler on the sled. This type of muffler can ideally be tuned to cancel out a certain frequency of sound. This would be beneficial to the team, as we would mainly like to reduce the sound created at wide-open throttle (WOT). The frequency at WOT from 8000 rpm is assumed to be at 266.67 Hz as described in the book “The Design and Simulation of Two-Stroke Engines” [6]. Currently two laminar flow mufflers have been constructed and tested on the sled designed to cancel out the desired frequency. Both mufflers are shown in Figure 4. Neither provided a significant enough reduction in noise level compared to the stock muffler. This is most likely due to the high temperatures and high fluid flow through the muffler [5].

Figure 3: Stock Muffler Cutaway

Figure 4: Laminar Flow Mufflers
### 3.1.3 Hushpower Muffler

Hushpower mufflers are single chamber absorption mufflers as shown in Figure 5. For this design hot exhaust gasses are accelerated through the cone section A, which reflects the sound energy back into itself and out into the thermal barrier at C. The thermal barrier is packed with a sound absorbing material called Silkasoft that absorbs sound energy and insulates the muffler to keep the shell cooler. The exhaust is allowed to expand in section B thus reducing the turbulence. The exit cone at D is much larger than the inlet cone in order to create an easy exit for the exhaust; the exit cone also reflects sound energy back toward itself and the thermal barrier [7].

![Figure 5: Hushpower Muffler](image)

### 3.2 Catalytic Converter (CAT)

A catalytic converter is basically a chemically reactive filter, transforming harmful exhaust gasses to less harmful gasses as they flow through. Sled team has used CATs before with success and would like to be able to easily add and remove a CAT from the new muffler.

#### 3.2.1 CAT Research

A catalytic converter consists of three main parts: the core, the wash coat, and the catalyst. The core consists of a ceramic or stainless steel honeycomb that creates a vast surface area. The wash coat is usually a mixture of alumina and silica coating the core to make it rough and irregular. This creates the most surface area for the catalyst to be applied to and also encourages mixing in the flow. Lastly, the catalysts are generally various precious metals (typically platinum and rhodium) coating the honeycomb core. The flow of the gasses across
the precious metals causes a chemical reaction resulting in the oxidation of carbon monoxide and unburned hydrocarbons as well as the reduction of nitrogen oxides to nitrogen and oxygen [8]. Figure 6 shows a typical CAT.

![Figure 6: Catalytic Converter]

### 3.2.2 EMISSIONS RESEARCH AND SCORING

We will be targeting hydrocarbons (HC) and carbon monoxide (CO) because these are typically higher in two-stroke engines.

Extra HC emissions are due to the design of a two-stroke where both the intake and exhaust ports are open at the same time [9]. This means that when fuel is added to the combustion chamber part of it leaks out through the exhaust port. Also having lower engine temperatures relative to a 4-stroke, increases CO emissions. The lower temperatures do not allow the various emissions in the exhaust to be oxidized as efficiently. The upside to a 2-stroke is that very low levels of nitrogen oxide (NOx) are emitted due to the same reason [6].

Our goal is to reach the National Park Standard emission levels for both HC and CO. Table 2 shows last year’s results, the Clean Snowmobile Challenge limit, and the NPS limits.

<table>
<thead>
<tr>
<th>Table 2: Emission Data</th>
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<tbody>
<tr>
<td><strong>Emissions</strong></td>
</tr>
<tr>
<td><strong>CO</strong></td>
</tr>
<tr>
<td><strong>HC</strong></td>
</tr>
<tr>
<td><strong>NOx</strong></td>
</tr>
<tr>
<td><strong>HC+NOx</strong></td>
</tr>
<tr>
<td><strong>E-Score</strong></td>
</tr>
</tbody>
</table>
All pollutants shown are measured in g/kW-hr. For the competition, all teams must achieve an emissions score or an E-score over 100 [1]. This score is determined by the equation in Figure 7, which limits the total emissions allowed.

\[
E = \left(1 - \frac{(HC+NO_x)-15}{150}\right) \times 100 + \left(1 - \frac{CO}{400}\right) \times 100 \geq 100
\]

Figure 7: E Score Equation

### 3.3 FLOW BENCH

A side deliverable of this project is the design and construction of a flow bench. It will be used to flow test our mufflers and can be used by the CSC team on many other projects in the future.

#### 3.3.1 WHAT IS A FLOW BENCH?

A flow bench is a tool used for testing the aerodynamic performance of engine components. Its main use is for testing flow restriction of intake and exhaust ports on internal combustion engines. From these tests, designers are able to effectively shave ports to ideal sizes and geometries for maximizing flow efficiency which in turn increases the power output of the engine.

The device can also test the air passage qualities of air filters, manifolds, carburetors, and mufflers. The ability to flow test components outside of the vehicle gives designers a controlled environment for predicting component performance for any application. However, this is not just a test apparatus for the engine enthusiast; it can be used to test any component that channels a flowing gas or one that produces the flow of a gas.

The design of a flow bench can be as simple as a Shop-Vac, a homemade manometer, a flow meter, and miscellaneous plumbing. Or it can be as complicated as an electronically intensive and expensive piece of ordered equipment.

#### 3.3.2 FLOW BENCH RESEARCH

Flow bench design varies widely depending on what you will be using it for and as a result many manufactures offer kits for putting your own flow bench together. One such manufacturer is Flow Performance LLC out of Novato, California [10]. They do not sell completed benches, only kits with the needed electronics, plumbing, and software. Two such kits are pictured in Figure 8. On the Flow Performance website you can find free technical information on flow bench
assembly including complete plumbing diagrams and several ideas for housing for the systems. Also included are several set-ups for air supplies including shop-vacs and vacuum motors.

![Flow Performance Flow Bench Kits](image)

**Figure 8: Flow Performance Flow Bench Kits**

Flow benches that can be built using Flow Performance Kits range from high performance racing industry applications all the way to the home-shop enthusiast’s garage. Figure 9 shows a small, basic flow bench and bench used by JDF Performance INC to design engines [11].

![Flow Bench Examples](image)

**Figure 9: Flow Bench Examples**

As you can see one bench uses a household shop-vac as the air supply while the other uses vacuum motors shown in Figure 10.
3.3.3 FLOW BENCH REQUIREMENTS

We will be using the flow bench to test the difference in backpressures between our concept mufflers and the stock muffler. From this test we will be able to compare the restrictive qualities between each design. The prototype mufflers must express a backpressure similar to the stock muffler to ensure proper exhaust gas evacuation from the engine. Too much of an increase or decrease in backpressure can cause a decrease in engine performance.

The team does not have the funds to purchase a flow bench or flow bench kit. Stealth CATs will be designing one using components that the engineering department has been gathering for the construction of a flow bench.

Our team will need much more airflow than can be provided by a shop-vac. Stealth CATs will design a system using vacuum motors similar to the JDF Performance design to provide the necessary flow.

Some basic flow bench specifications are:

- Flow up to 500 cubic feet per min (cfm)
- Variable flow rates
- Easy to transport
- Student designed and built

3.3.4 FLOW BENCH CONSTRUCTION
The flow bench was entirely constructed on the U of I campus. Both the woodworking shop and the engineering machine shop were used. The detailed flow bench construction and assembly is included in Appendix H. The complete drawing package is included in Appendix J.

### 3.3.5 FLOW BENCH COMPONENTS

Figure 11 shows a diagram of Stealth CAT’s completed flow bench. The major parts are noted on the diagram as well as the flow direction.

![Flow Bench Diagram](image)

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**Figure 11: Flow Bench Diagram**
A test component is attached to the test stand with an adapter plate, which creates a seal with the settling chamber. Six axial flow vacuum motors are housed inside the flow box, which creates a vacuum in the forward system. A pressure gauge is used to measure the pressure drop at a given mass airflow rate determined by adjusting the number of motors in service.

There are six vacuum motors and five one way valves housed in the flow box. The one way valves are needed to keep the air from flowing backwards through motors not in use. One motor doesn’t have a valve because it is the variable power motor and will be used in all experiments.

3.4 SIMULATION SOFTWARE

Simulations of the snowmobile components can give insights on why existing components perform the way they do and give estimates of how theoretical components will perform. This is an extremely valuable tool as it can replace the time and expense of making prototypes as well as illustrate ways to improve existing parts.

3.4.1 RICARDO WAVE SIMULATION

WAVE is a leading engine and gas dynamics simulation software package from Ricardo Software used worldwide in industry sectors including passenger car, motorcycle, truck, locomotive, motor sport, marine, and power generation. WAVE enables performance simulations to be carried out based on virtually any intake, combustion, and exhaust system configuration. Ricardo is used by Idaho’s Formula SAE Hybrid Car to simulate their engine. This program’s direct application to this project and the CSC team is the ability to produce acoustic and emissions data for any given configuration of snowmobile engine components.

Stealth CATs started learning Ricardo by going through the manufacture’s tutorials. The first set, building a one cylinder engine, was very simple and straightforward. The team had high hopes as they started the second set of tutorials: a four-stroke engine with complete intake and exhaust manifolds, air filter, CAT, and a muffler. The completed engine is shown in Figure 12.
Upon completion of the four-stroke simulation, the team realized that finding all of the information needed for an accurate model of the snowmobile was going to be much more challenging than anticipated. The tutorials explained what some of the parameters were and how to find them on your own but many were just listed to be entered and then had to be changed to random numbers for the simulations to be runnable. Ricardo is an amazing tool that would bring a great deal of benefit to the UI CSC team but learning to use it is beyond the scope and capabilities of this project.

3.4.2 SOLIDWORKS FLOW SIMULATION

While the flow bench can give us the backpressure of constructed items Solidworks can give us flow data for configurations that are still in the modeling stages. Flow Simulation is a Solidworks add-in and comes standard with Solidworks.

To simulate flow through a part or assembly you need to open it in Solidworks and start the flow wizard. It will guide you through the needed steps to gather flow data. A basic tutorial of the teams flow simulation procedure can be found in Appendix I and Figure 13 shows a muffler at various stages throughout the simulation.
The simulation outputs a plot of the pressure drop over the part, shown on the far right of Figure BLANK, at a given flow rate. From a series of runs the pressure drop across the muffler was graphed as a function of the flow rate. The simulated data was compared against flow bench data for existing mufflers to check for accuracy. This comparison is discussed further in Section 3.6.5.

### 3.5 TESTING PROCEDURES

Several tests will be performed to determine the performance of the muffler and CAT. This section covers the testing procedures for each

#### 3.5.1 SAE J-192 SOUND TESTING PROCEDURE

Sound testing at the Clean Snowmobile Challenge competition is done using the SAE J-192 procedure [12]. For this test the sled enters the start gate at 15 mph then the rider goes to WOT to achieve maximum speed and noise level. The course is straight and 150 feet in length. After 150 feet the sled slows down and turns around for a pass in the other direction. The sound measurement microphones are located 50 feet to the side of the midpoint where a maximum A-weighted sound pressure level (dBA) is recorded. The final score is an average of six passes, three of each side. A diagram of the SAE J-192 test is shown below in Figure 14.
3.5.2 EMISSIONS TESTING

At the CSC competition there are two separate emissions testing events: laboratory emissions and in-service emissions. They are judged separately and each team is compared against the other team’s performance. Each team will receive a pass/fail and if they passed they receive points based on their rank compared to other teams.

The lab emissions are measured in g/kW-hr using laboratory-grade instrumentation with the engine loading on a Land & Sea dynamometer. The dynamometer directly mounts to the engine primary clutch shaft. The testing consists of a five-mode test procedure approved by EPA for snowmobile emissions measurement. The five-modes cycle is detailed in Table 3. The measured emissions are detailed in the emissions research section and they include CO, HC, and NOx.

<table>
<thead>
<tr>
<th>Mode</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Speed</td>
<td>100</td>
<td>85</td>
<td>75</td>
<td>65</td>
<td>IDLE</td>
</tr>
<tr>
<td>% Torque</td>
<td>100</td>
<td>51</td>
<td>33</td>
<td>19</td>
<td>0</td>
</tr>
<tr>
<td>% Wt. Factor</td>
<td>12</td>
<td>27</td>
<td>25</td>
<td>31</td>
<td>5</td>
</tr>
</tbody>
</table>

A pull behind emissions analyzer will be used for in-service emissions portion. Snowmobiles will be driven by competition organizers on a three-mile course reaching speeds up to 45 mph. Each snowmobile will be ridden in as consistent manner as possible to ensure fair comparisons. The measured emissions include HC, CO, and NOx—all equally weighted.

3.5.3 FLOW BENCH TESTING PROCEDURE
The test element is attached to the test stand using an adapter plate. Clamps can be used to secure the plate to the test stand and a gasket material, such as sticky tape, applied between the components. Figure 15 shows a muffler set-up to be flow tested on the test stand.

![Figure 15: Flow Bench Testing of a Hushpower Muffler](image)

The mass airflow sensor is powered by a 12-volt power source and a multimeter is used to read its voltage output. The digital pressure gauge is turned on and zeroed before testing. The flow bench needs plugged into a 220-volt three phase power outlet which can be found in the Senior Design Lab and the Engine Bay. Take precautions as the vacuum motors are very loud.

The vacuum motors are turned on starting with the variable flow motor set to full power. Next additional motors are turned on until the pressure gauge reads just over the pressure that will be tested. Then power supplied to the variable motor is reduced until the pressure gauge reads exactly the pressure you would like to test. The output voltage from the mass airflow sensor is converted to cfm using a MatLab code.

For each muffler being flow tested we did a sweep over several different pressures and plotted pressure drop versus flow rate.

### 3.6 DEVELOPMENT OF PROTOTYPE

With the Clean Snowmobile Challenge competition March 7th thought the 11th the team had very early deadlines. We had to build our first prototype around winter break and launch
directly into a final muffler configuration to allow time for tuning the engine and working the bugs out before we left for Michigan.

### 3.6.1 J-192 TEST RESULTS OF MUFFLERS

To begin gathering ideas for a new snowmobile muffler using Hushpower technology Stealth CATs preformed sound testing on Hushpower mufflers and previously built laminar flow muffler. All sound testing was performed according to the SAE J-192 procedure.

Adapters were made for mounting Hushpowers and the laminar flow muffler to the sled. The Hushpower mufflers were arranged in three different configurations: two in parallel, two in series, and three in series. Figure 16 shows each of the Hushpower arrangements.

![Figure 16: Hushpower Muffler Configurations](image)

All tests, including stock, were done with the exhaust-side side panel removed as it did not fit around the adaptors and would make the data more comparable to stock. The results from this experiment are displayed in Figure 17 and the complete testing data can be found in Appendix B.
This experiment was not very precise but its purpose was only to see if the idea may be feasible. The results show that two Hushpower mufflers in series are comparable to the stock muffler. Both are still much louder than the 78 dBA needed for competition but it is a place for the design to start.

It was discussed that the two Hushpowers in series may be louder than the stock muffler because the test setup hung outside of the chassis and was therefore less muffled. To test this theory the team constructed a mount which placed the stock muffler outside the sled body. The sound data was analyzed but the results were inconclusive. The testing data is included in Appendix C.

### 3.6.2 Prototype Design

The team brainstormed several muffler configurations that included two Hushpowers and a CAT. The two main ideas are picture below in Figure 18.
One was a linear configuration while the other was triangular. The team chose to construct the linear model; it was closer to the shape of the stock muffler and would fit in the chassis better. Also it would be easier to build than the triangular idea. A more thorough diagram of this design is pictured in Figure 19.

The basic idea is that the flow enters the muffler at the inlet; the inlet was placed to connect to the tuning pipe without any modifications. Then it flows through the two Hushpowers in series which are connected with welded chambers. Lastly the flow passes through a shell which houses the CAT and exits the muffler out of the bottom of the sled.
The CAT is inserted by sliding it into the shell where it hits a stop ring. Then a removable end cap is bolted to the shell which holds the CAT in place. To change the CAT you simply need to take the muffler out of the sled and remove four bolts. A full CAT replacement can be done in about five minutes. As a CAT is much shorter than a Hushpower muffler, there is room in the design for extra sound material or a flow chamber. The team decided to leave the shell opening accessible so different mediums can be placed inside and tested.

### 3.6.3 Prototype Construction

The muffler was constructed using sheet metal, two fully assembled Hushpowers, and a cylindrical shell provided by Hushpower. Five parts had to be machined on the mill and the assembly was welded together. The piece over the shell opening was secured using clamps. Figure 20 show the prototype muffler being constructed.

![Figure 20: Building the Prototype](image)

The muffler took about four days to manufacture and was finished on January 28th.
3.6.4 SOUND TESTING OF PROTOTYPE MUFFLER

With the muffler built and competition coming up quickly, the team took the sled and muffler out sound testing right away. The team tested with the space above the CAT empty and with part of a Hushpower perforated cone. Figure 21 shows the muffler mounted to the sled during a sound pass.

![Muffler on Sled](image)

Figure 21: Muffler on Sled

The sound data came back very positive with the Stealth CAT muffler being 2.5 dBA quieter than the stock muffler without panels. This included a Hushpower cone in the extra space. The sound data can be found in Appendix D.

For a true evaluation of performance more than just the sound pressure level must be examined. The reason the new muffler was quieter than stock was because it limited the performance of the engine. The engine could only rev to 6000 revolutions per minute (RPM) instead of the normal 8000 RPM so much less noise was produced resulting in a quieter run. Also the sled only created 55 horsepower (hp) compared to the stock horsepower of 105.

3.6.5 FLOW TESTING RESULTS OF INITIAL COMPONENTS AND PROTOTYPE MUFFLER

To determine why the engine performance was limited the team turned to flow testing. The team used both the newly constructed flow bench as well as Solidworks flow simulation.
Both mufflers were flow tested on the flow bench and the results compared. Figure 22 shows their pressure drops over a range of flow rates.

![Flow Testing Results](image)

**Figure 22: Flow bench Results of Stock and Team Muffler**

From this data the team learned that the new muffler had much higher back pressure than the stock muffler. As the flow rate increased across the team’s muffler the pressure drop becomes a near vertical line meaning that the muffler will only allow up to a certain flow rate through it. As RPM increases the engine needs to flow more air out the exhaust. Because the muffler could only flow up to a certain rate the engine could only rev up to 6000 RPM.

Next the team looked for ways to increase the muffler’s flow rate. Hushpower had provided the team with three mufflers; two with a cylindrical shell and one with an oval shell. The two cylindrical Hushpowers were used for the prototype. The team examined the third muffler and found that its inner cone diameter was 2.5 inches while the other Hushpowers were only 1.5 inches in diameter. The larger inner diameter could possibly provide the necessary flow to lower the backpressure of the muffler. The following figure, Figure 23, shows the two different sized cones.

![1.5" and 2.5" Hushpower Cones](image)

**Figure 23: 1.5" and 2.5" Hushpower Cones**
The team turned to Solidworks flow simulation so see if this idea could produce around stock backpressure. Both Hushpower mufflers where modeled in Solidworks as well as both muffler configurations. Figures 24 and 25 show the flow simulation being run at 90 and 100 cfm and the resulting back pressure.

![Image of Solidworks Flow Simulation](image1)

**Figure 24: Solidworks Flow Simulation of 1.5” and 2.5” Hushpowers**

**1.5” Cone Diameter Hushpower and 2.5” Cone Diameter Hushpower**
At 90 cfm – backpressure of 0.22 psi and 0.01 psi

![Image of Solidworks Flow Simulation](image2)

**Figure 25: Solidworks Flow Simulation of 1.5” and 2.5” Mufflers**

**1.5” Cone Diameter Muffler and 2.5” Cone Diameter Muffler**
At 100 cfm – backpressure of 0.7 psi and 0.14 psi
To verify that the Solidworks data was applicable to the real world, the Solidworks results were compared with flow bench data. The Hushpowers used to make the prototype had been flow tested on the flow bench prior to being welded into the muffler. Figure 26 shows the data comparison for the 1.5 inch muffler.

The dashed lines are from Solidworks and the solid lines are from the flow bench. As you can see the square line (Solidworks: 1.5” Hushpower) and the diamond line (Flow bench: 1.5” Hushpower) are very similar showing that Solidworks can accurately represent a single Hushpower muffler. Also the triangle line (Solidworks: Team Muffler 1.5”) and the X line (Flow bench: Team Muffler 1.5”) are close but not as close as the single muffler. This is because it is harder to model the exact geometry’s of the muffler chambers resulting in small differences.

Now that Solidworks was verified with the 1.5 inch mufflers the team moved to the 2.5 inch mufflers. The results are shown in Figure 27.
The triangle line (Flow bench” 2.5” Hushpower) is not comparable because the muffler came with an inlet diameter of 2 inches even though the cone diameter is 2.5 inches. The team will be removing the inlet to put it in the muffler configuration so the Solidworks flow simulation was done with a 2.5 inch inlet. Also the muffler will be placed in a cylindrical shell and it was tested in the oval shell it came in. It wasn’t practical for the team to put the 2.5 inch Hushpower in a new shell and weld in a bigger inlet just for flow testing.

The square line (Solidworks: Team Muffler 2.5”) is just less than the circle line (Flow bench: Stock Muffler). This proves that a muffler using two 2.5 inch Hushpowers will have comparable backpressure to the stock muffler. The backpressure will most likely be higher than the simulation as it was with the 1.5 inch muffler. Flow bench data for all tests can be found in Appendix F and the Solidworks flow simulation data can be found in Appendix G.

### 3.6.6 PROTOTYPE CONCLUSIONS

The Stealth CAT prototype muffler had too much back pressure for the sled to run correctly. Building the same muffler with larger inner cone diameter Hushpowers will decrease the backpressure and allow more flow.

### 3.7 FINAL SELECTIONS
Unfortunately the prototype proved that we needed to manufacture another muffler before it would meet the CSC requirements. Deadlines were approaching and with only a few weeks to acquire materials, assemble a new muffler, mount it in the sled, preform testing, and re-tune the engine, the team decided that they would run the stock muffler at the 2011 CSC. It was not worth the risk of testing a new muffler too close to completion and having the sled breakdown without adequate time to repair it. Also we did not want to get the sled setup and tuned with the new muffler, find out it didn’t work as well as stock, and then not have time to switch back.

The new muffler will be built, tested, and presented to the U of I CSC team for consideration in the 2012 competition. It will be constructed by removing the 1.5 inch Hushpowers from the prototype muffler and inserting 2.5 inch Hushpowers. We know that this will give us a backpressure that is closer to stock but we do not have any predictions of its sound dampening performance.

Stealth CATs is being sponsored by Aristo Catalytic Technologies, who will select a CAT specifically tailored to our specifications. Appendix A lists the different specifications of our size preference, our engine, and our target emissions.

### 4.0 PRODUCT DESCRIPTION

#### 4.1 FINAL MUFFLER

The final Stealth CAT muffler for the University of Idaho Clean Snowmobile Challenge Team is picture below in Figure 28. The complete drawing package is included in Appendix K. All parts were welded together except for the CAT cap which is bolted on.
The diagram below in Figure 29 highlights some of the features of the muffler. As you see the team added half of a Hushpower cone section above the CAT. From testing this was found to be the quietest arrangement.

4.2 CAT INTEGRATION

The CAT was integrated into the muffler keeping in mind space, heat, and need to be removed easily. The team received an extra Hushpower cylindrical shell to mount the CAT in. This kept construction simple as all three tubes of the muffler would be the same diameter and the team did not have to find someone to roll sheet metal. Figure 30 shows how the CAT is mounted and removed from the shell.
The CAT can freely slide in and out of the shell and machined rings on the caps keep the CAT centered. Changing the CAT requires only the removal of four bolts.

### 4.3 CAT SELECTION

Aristo has chosen a CAT to best fit our uses and it will be placed in the final muffler. It is 3.5 inches in diameter and 4 inches long with 200 cells per square inch. It is picture below in Figure 31.
4.4 FLOW BENCH

Figure 32 shows a picture of the completed flow bench.

![Flow Bench](image)

It was used to measure the backpressure of our mufflers. The flow bench is able to flow up to 500 cfm and was designed and built entirely by Stealth CAT’s.

5.0 DESIGN EVALUATION

The muffler was run through all the tests to see how well it preformed and met the project specifications. The CAT was also tested to see how well it worked in the sled.

5.1 PROJECT SPECIFICATIONS

The two main goals of this project were to make the snowmobile cleaner and quieter than it currently was. The team succeeded on both of these fronts. Adding a CAT reduced sled emissions and the Stealth CAT muffler reduced the noise of the sled by 2.27 dBA. Even with this
success the team did not meet the project specifications for sound and emissions. The detailed specifications along with the resulting performance are listed in Table 4.

Table 4: Project Specifications

<table>
<thead>
<tr>
<th>REQUIREMENTS</th>
<th>ACHIEVEMENTS</th>
<th>Pass/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sled less than 78 dBA with a goal of 73 dBA</td>
<td>2.27 dBA less than the stock muffler coming in at 82 dBA</td>
<td>Fail</td>
</tr>
<tr>
<td>Pass competition emissions with a goal of less than NPS emissions</td>
<td>Detailed in section 5.2.2. Passed competition and failed NPS</td>
<td>Fail</td>
</tr>
<tr>
<td>CAT replacement takes less than 15 minutes</td>
<td>CAT replacement takes around 5 minutes</td>
<td>Pass</td>
</tr>
<tr>
<td>Less than 110% of stock backpressure</td>
<td>Stealth Cat muffler has ≈ 140% stock back pressure</td>
<td>Fail</td>
</tr>
<tr>
<td>Approximately 9&quot; Deep, 18&quot; Tall, 13&quot; Wide</td>
<td>Final dimensions: 6&quot; X 16&quot; X 12&quot;</td>
<td>Pass</td>
</tr>
<tr>
<td>Less than 18 lbs or 110% of stock muffler weight</td>
<td>Final muffler weighs 22 lbs or 140% of stock weight</td>
<td>Fail</td>
</tr>
<tr>
<td>Costs team less than $300 MSRP less than $700</td>
<td>Cost about $150 MSRP of $568</td>
<td>Pass</td>
</tr>
<tr>
<td>Can build using the U of I machine shop and facilities</td>
<td>Built using only the U of I machine shop and facilities</td>
<td>Pass</td>
</tr>
</tbody>
</table>

The team did not reduce the noise of the sled as much as was planned but it is the first muffler ever made by the CSC team to be quieter than the stock muffler. A group of college students successfully produced a muffler that had greater dampening than a professionally designed muffler. That is a large accomplishment despite the fact that the goals were not met.

The final muffler fit within the chassis and did not hinder the performance of the sled. It was economical and easy to manufacture. The CAT helped with emissions but our sled, like most sleds being used today, did not meet the strict NPS emissions standards.

5.2 PROJECT TESTING RESULTS

Sound testing, emissions testing and flow bench testing were done to evaluate the performance of the muffler and CAT.

5.2.1 SOUND TESTING RESULTS

The final muffler was mounted in the sled and ran through the J-192 sound testing procedure. The Stealth CAT muffler was tested with and without a CAT and compared to the stock muffler. Sound data can be found in Appendix E and Figure 32 shows the results.
Changing out the mufflers and running six sound passes takes time and conditions often change. This team compensated for this by running a control sled, a sled that not is not changed during testing so it produces the same sound level every time it is ran, in between a few of the tests. On the testing day the control sound increased by 2.5 dBA. The scores on the graph were normalized with respect to the control sled in order to account for the changing conditions.

5.2.2 EMISSION TESTING RESULTS

The Stealth CAT muffler may not have made it to the 2011 competition, but the CAT the team received did. Table 5 shows the performance results compared to CSC and NPS limits and the 2010 results.
Table 5: Emission Results*

<table>
<thead>
<tr>
<th></th>
<th>CSC Limit</th>
<th>NPS Limit</th>
<th>2011 Results</th>
<th>2010 Results</th>
<th>% reduction</th>
<th>Pass/Fail CSC</th>
<th>Pass/Fail NPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>≤ 275</td>
<td>≤ 120</td>
<td>272.98</td>
<td>209.94</td>
<td>-23%</td>
<td>Pass</td>
<td>Fail</td>
</tr>
<tr>
<td>HC</td>
<td>≤ 15</td>
<td></td>
<td>36.87</td>
<td>41.6</td>
<td>13%</td>
<td>-</td>
<td>Fail</td>
</tr>
<tr>
<td>NOx</td>
<td></td>
<td></td>
<td>3.91</td>
<td>5.8</td>
<td>48%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HC + NOx</td>
<td>≤ 90</td>
<td></td>
<td>40.78</td>
<td>47.36</td>
<td>16%</td>
<td>Pass</td>
<td>-</td>
</tr>
<tr>
<td>Escore</td>
<td>≥ 100</td>
<td></td>
<td>114.57</td>
<td>125.9</td>
<td>-10%</td>
<td>Pass</td>
<td>-</td>
</tr>
</tbody>
</table>

*all units in g/kW-hr

As you can see the U of I CSC teamed passed all of the competition requirements but they still have a lot of work to do to meet National Park Standards. This year the team was lower in every category but CO which also hurt the Escore.

The team did well compared to the other teams at competition. The University of Idaho sled had the second lowest in-service emissions and the fourth lowest laboratory emissions.

### 5.2.3 FLOW TESTING RESULTS

The final muffler was flow tested and the results recorded. Figure 34 shows the data versus the prototype muffler and the stock muffler.

![Flow Test: Muffler Comparison](Figure 34: Muffler Flow Comparison)
As you can see the Stealth CAT muffler has about 140% of the backpressure of the stock muffler. This reduced the sled performance to 85 hp without tuning but more testing will be done before the 2012 competition. The stock muffler’s backpressure fits somewhere within a range of pressures that the sled will operate within and the final muffler is close enough to fall in the upper pressure range.

The final muffler had more backpressure than predicted because of two reasons. First the team knew from the 1.5 inch simulation that Solidworks under predicted backpressure in full muffler runs due to getting the exact muffler geometry correct. Second the team added half of a Hushpower cone to the space above the CAT. This increased backpressure very slightly but decreased sound. The team evaluated the engine performance with and without the extra cone and decided that the extra backpressure was worth the increased sound reduction.

5.3 DESIGN FAILURE MODE AND EFFECT ANALYSIS (DFMEA)

The purpose for creating a design failure mode effects analysis (DFMEA) spread sheet is to reduce the risk of failure for a proposed design project. With a well-developed spread sheet, a design team can easily identify and quantify possible areas of risk and determine possible design controls in order to effectively reduce and/or eliminate potential design flaws. The outcome of this type of analysis should result with an improved product with a reduction in functioning risk and increased usability. The teams DFMEA table is included in Appendix L.

Our DFMEA analysis covers two main categories of possible failures: the muffler components and the catalytic converter. The results of the spread sheet analysis deemed that excess heat production from the catalytic converter as our highest risk for component failure with three categories receiving a 20 point score for the risk priority number (RPN). RPN is the product of the severity, occurrence and detection numbers. Items with high RPN numbers should be taken as the most critical for analyzing failure but the severity, occurrence and detection numbers should also be taken into account individually when determining solutions for possible component failures. Possible solutions for our team are: designing an cooling system for the catalyst chamber and using welds for heat shrinking the muffler end caps in order to stiffen the chamber walls.

5.4 ESTIMATED COSTS

The estimated cost of producing the final muffler as design and constructed by the Stealth CAT team is detailed in Table 6.
The estimated MSRP (manufactured suggested retail price) is detailed in Table 7. This will be used by the team in the CSC design report.

The team cost for making the muffler and the final MSRP are below the project specifications of $300 and $700. Our muffler would be cheaper than buying a stock muffler which costs $547 and with a CAT $707 [13].

### 6.0 RECOMMENDATIONS AND FUTURE WORK

This project successfully reduced the noise and emissions of the sled as compared to the stock muffler. Some recommendations for continued development are running the Stealth CAT muffler on the dynamometer and tuning the engine for emissions, fuel economy, and performance. Then more sound testing needs done with the re-tuned engine. At that point a
A comparison of engine horsepower and noise level can be made between the stock system and the Stealth CAT design. The CSC team will be able to choose between the two systems based on the need to pass sound without sacrificing performance.

Minor modifications need to be made to the sled to implement the Stealth CAT muffler. A new exhaust hole was cut in the bottom of sled and the old hole covered up with an aluminum plate. The aluminum also added extra strength and heat shielding.

Adding this muffler will decrease the MSRP of the sled as our muffler is cheaper than stock. It would take the CSC team about a week to construct another Stealth CAT muffler given all of the needed materials have been gathered.

This project showed through that Hushpower mufflers are very applicable to this branch of the motor sports industry. The CSC team and the muffler manufacturing industry should continue looking at how Hushpowers can help quiet snowmobiles.

Future work for making the sled cleaner and quieter includes:
- Create an aluminum outer shell lined with insulation to wrap muffler. This is for heat management and possibly sound reduction.
- Using a spectrum analyzer to measure exact engine output frequencies to be targeted by the muffler
- Sizing the top and bottom chambers of the muffler for acoustic benefit (small Helmholtz chambers)
- Preform more CAT research and test different CATs on the sled to determine which best fits out needs, possibly looking into CATs from various vendors
- Set up several projects working on modeling the snowmobile in Ricardo and use WAVE to run simulated sound, performance, and emissions testing

Future work for the flow bench includes:
- Putting together a simple users guide pamphlet so students with limited background can run flow tests
- Make a binder with the drawing package, instructions, troubleshooting guide, hard copy of the MatLab code, etc. for future students to reference
- Design MatLab code using Simulink to directly measure and display the flow rate in real time
- Design a calibration test to check the accuracy of the pressure tap and mass airflow meter
7.0 ACKNOWLEDGMENTS

The Stealth CAT team would like to thank Hushpower for their support of this project in the form of time, knowledge, and materials. Without them and their initial input this project would not have been possible. We would like to thank Aristo for sponsoring us and their help in selecting a CAT that best fit our needs.

We appreciate the National Institute of Advanced Technology and Transportation (NIATT) for funding this project and the CSC team. It provides students with hands on experience and real world learning to advance their education and career opportunities.

Many people contributed time, knowledge, skill, and support to this project, and we are pleased to acknowledge their contributions. This includes the University of Idaho Clean Snowmobile Challenge team, Steve Beyerlein, Dan Cordon, Russ Porter, Austin Welch, and David Egolf.

8.0 REFERENCES


APPENDIX A – ARISTO CAT SPECIFICATIONS

Physical Package:

- Preferred catalyst location
- Photos or measurements showing the space envelope available for the catalyst
- Preferred exhaust pipe diameter and catalyst diameter and length: exhaust diameter of 2.15 to 2.5 inches
- Silencer requirements

Engine Data:

- Using a REV 600
- Air/Fuel Ratio: at wide open throttle AFR is 10-12, at cruise speed 13-15, and very lean at idle
- Fuel composition, and fuel consumption
- Engine oil - manufacturer, type, composition, and consumption/hour: Skidoo XPS full synthetic, don't know exact composition, consumption of 120:1
- Engine outlet temperature: maximum of 1100 °F
- Engine outlet mass flow: around 600 cfm
- Engine out gas concentrations

Catalyst targets:

- Desired percentage reduction of each component: want to meet National Park Standards
- Maximum acceptable backpressure due to catalyst: preferred 2-3 psi but could go up to 4-5 psi
# APPENDIX B – J-192 RESULTS OF INITIAL COMPONENTS

Testing date: 10/1/2010

**SOUND TESTING**

<table>
<thead>
<tr>
<th>Configuration</th>
<th>dBA</th>
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<tbody>
<tr>
<td>Stock W/ Panels</td>
<td>83.93</td>
</tr>
<tr>
<td>Stock W/O Panels</td>
<td>85.52</td>
</tr>
<tr>
<td>2 Hushpower (Parallel)</td>
<td>88.97</td>
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<tr>
<td>2 Hushpower (Series)</td>
<td>86.47</td>
</tr>
<tr>
<td>3 Hushpower (Series)</td>
<td>86.99</td>
</tr>
<tr>
<td>1 Hushpower</td>
<td>89.13</td>
</tr>
<tr>
<td>Laminar Flow</td>
<td>90.25</td>
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# APPENDIX C – J-192 RESULTS OF MUFFLER LOCATION

Testing date: 1/19/2011

**SOUND TESTING**

<table>
<thead>
<tr>
<th>Configuration</th>
<th>dBA</th>
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</thead>
<tbody>
<tr>
<td>Stock external</td>
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<tr>
<td>Stock</td>
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<tr>
<td>2 Hushpower in series</td>
<td>85.90</td>
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</table>

# APPENDIX D – J-192 RESULTS OF PROTOTYPE MUFFLER

Testing date: 1/29/2011

**SOUND TESTING**

<table>
<thead>
<tr>
<th>Configuration</th>
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</thead>
<tbody>
<tr>
<td>Team Muffler, extra cone, no CAT</td>
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</tr>
<tr>
<td>Control Sled</td>
<td>84.33</td>
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<tr>
<td>Team Muffler, extra cone, CAT</td>
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<td>Team Muffler, no extra cone, CAT</td>
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<tr>
<td>Stock Muffler w/o panel</td>
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<tr>
<td>Control Sled</td>
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**APPENDIX E – J-192 RESULTS OF FINAL MUFFLER**

Testing date: 4/6/2011

**SOUND TESTING**

<table>
<thead>
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<th>Configuration</th>
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<tbody>
<tr>
<td>Team Muffler, no CAT</td>
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<td>85.37</td>
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<td>Stock Muffler</td>
<td>84.70</td>
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<td>Control Sled</td>
<td>87.78</td>
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<td>Team Muffler, CAT</td>
<td>83.63</td>
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**APPENDIX F – FLOW BENCH DATA**

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<thead>
<tr>
<th>1.5&quot; Hushpower</th>
<th>Team Muffler 1.5&quot;</th>
<th>Stock Muffler</th>
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</thead>
<tbody>
<tr>
<td>Pressure Drop (psi)</td>
<td>Flow Rate (cfm)</td>
<td>Pressure Drop (psi)</td>
</tr>
<tr>
<td>0.2</td>
<td>72.41</td>
<td>0.2</td>
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<tr>
<td>0.4</td>
<td>114.79</td>
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<td>0.6</td>
<td>133.18</td>
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<td>2</td>
<td>-</td>
<td>2.32</td>
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<table>
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<td>Pressure Drop (psi)</td>
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<td>1.6</td>
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<td>1.8</td>
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<tr>
<td>2</td>
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<table>
<thead>
<tr>
<th>Team Muffler 2.5&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Drop (psi)</td>
</tr>
<tr>
<td>0.2</td>
</tr>
<tr>
<td>0.4</td>
</tr>
<tr>
<td>0.6</td>
</tr>
<tr>
<td>0.8</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
</tr>
<tr>
<td>1.4</td>
</tr>
<tr>
<td>1.6</td>
</tr>
<tr>
<td>1.8</td>
</tr>
<tr>
<td>2.32</td>
</tr>
<tr>
<td>Pressure Drop (psi)</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
</tbody>
</table>

### 1.5" Hushpower

<table>
<thead>
<tr>
<th>Pressure Drop (psi)</th>
<th>Flow Rate (cfm)</th>
<th>Pressure Drop (psi)</th>
<th>Flow Rate (cfm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.22</td>
<td>90</td>
<td>0.17</td>
<td>50</td>
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<tr>
<td>0.4</td>
<td>120</td>
<td>0.7</td>
<td>100</td>
</tr>
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</table>

### Team Muffler 1.5"

<table>
<thead>
<tr>
<th>Pressure Drop (psi)</th>
<th>Flow Rate (cfm)</th>
<th>Pressure Drop (psi)</th>
<th>Flow Rate (cfm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.14</td>
<td>100</td>
<td>0.01</td>
<td>90</td>
</tr>
<tr>
<td>0.31</td>
<td>150</td>
<td>0.02</td>
<td>120</td>
</tr>
<tr>
<td>0.55</td>
<td>200</td>
<td>0.04</td>
<td>180</td>
</tr>
</tbody>
</table>

### Team Muffler 2.5"

<table>
<thead>
<tr>
<th>Pressure Drop (psi)</th>
<th>Flow Rate (cfm)</th>
<th>Pressure Drop (psi)</th>
<th>Flow Rate (cfm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>250</td>
<td>0.08</td>
<td>240</td>
</tr>
<tr>
<td>1.3</td>
<td>300</td>
<td>0.13</td>
<td>300</td>
</tr>
</tbody>
</table>

### 2.5" Hushpower
APPENDIX H – FLOW BENCH CONSTRUCTION

Stage 1: Box Construction

a) A ¾”- 4’x8’ sheet of melamine coated particle board was cut using a large table saw to the dimensions given in the drawing package.

b) The intake and exhaust ports were cut using a skill saw and sanded to the appropriate dimensions using a reciprocating cylinder sander.

c) A CNC wood mill was used to cut the patterns for the two center inserts. The code for the CNC wood mill was developed using a solid works drawing.

d) 2-½” #8 drywall screws were used to assemble the box. A silicon adhesive was used to seal the inner box joints.

e) One 3” schedule 40 and 2 - 4” schedule 40 PVC pipe couplers were installed into the intake and exhaust ports using an all-purpose epoxy. The ports were also sealed with a silicon adhesive.

Stage 2: Gate-valve Construction

a) 3- 3” polystyrene pipe couplers were cut down the center with a vertical band saw to create the valve couplers.

b) The valve tubes were cut using a horizontal band saw to the correct dimensions expressed in the drawing package.

c) The 1/16”- 1-¼”x 2” polystyrene gate stiffener were cut from a sheet measuring 1’x 1’.

d) The sealing flaps were cut from a 1-¾” wide rubber strap purchased from McMaster Carr.

e) The valve base plate was cut from a ¼”–5”x 24” piece of polystyrene.

f) The valve flaps were attached to the base using two ¼” bolts with nylon lock nuts and a ¼” polystyrene backing plate.
Stage 3: Test Pipe Assembly

a) All PVC pipe sections were cut using the horizontal band saw to dimensions called out in the drawing package.
b) A rubber pipe coupler was cut in half for sealing the connections between the PVC pipe inserts and the mass air flow sensor.
c) The black ABS toilet flange slips tightly over the 4” PVC settling chamber for attachment to the bottom side of the flow bench top.

Stage 4: Test Stand Construction

a) Left over ¾” melamine coated particle board from the box construction was cut to the dimensions specified in the drawing package.
b) The pieces were cut using a large table saw.
c) The holes were cut using a skill saw and sanded to the desired size using a reciprocating cylinder sander.
d) 2-½" #8 drywall screws were used to assemble the test stand.
e) 6 - 5/16” holes were drilled in the base of the testing stand to match the pattern of the ABS flange.

Stage 5: Valve Attachment

a) A two part epoxy was used to attach the valve couplers to the valve housing board.
b) The valve tubes were glued into the couplers using the same epoxy.
Stage 6: Mating of Valve and Motor Housings

a) The two inner housing boards were mated together using 4- 1” #8 drywall screws in each of the corners

Stage 7: Vacuum Motor Attachment

a) The vacuum motors are attached to the motor housing board using six steel straps.
b) A ¼”- 1-¼”x 84” piece of steel strap was cut into 6- 13.9” lengths. The 5/16” bolt holes were drilled using a drill press with appropriate tolerances.
c) The vacuum motor brackets were bolted through both housing boards using 18 – 4 ½“-5/16” bolts.

Stage 8: Housing Board Installation

a) The housing board was inserted into the box slightly off center. The distance measured for the inside of the intake side board of the box to the front of the valve housing board is 6-½”.
b) The housing board was attached using 2-½” #8 drywall screws. The screws were driven from the outside of the box into both housing boards on either side of the box.
c) The top of the box was also secured using 2½” #8 drywall screws.
Stage 9: Bench Assembly

a) The flow bench box was wired up prior to box insertion. See the wiring diagram provided in the flow bench user manual.
b) The pipe assembly was installed into the flow bench frame and connected to the airflow supply box.
c) The test stand was inserted over the settling chamber and attached to the bench top along with the ABS flange below the bottom with 6- 5/16” bolts.

Stage 10: Switch and Fuse Box Installation

a) 14- 5/8” through holes were drilled in the top of the bench for installing the fuse and switch box wiring.
b) The boxes were attached to the surface of the bench with dimensions shown in the drawing package.

Stage 11: Mass Air Flow Sensor Wiring

a) Three leads are needed for the operation of the mass air flow sensor.
   1. Positive (12 volt)
   2. Negative
   3. Feedback
APPENDIX I – SOLIDWORKS FLOW SIMULATION PROCEDURE

1) Open the part or assembly to be analyzed.

2) Click: tools - add ins - flow simulation

3) For internal flow you need to create lids over the openings.
   - The area that’s to be analyzed must be a closed body and cannot have any areas of zero thickness (where two corners meet).
   - To automatically create the lids, click create lids, then select the faces of the openings of your part, then click ok.

4) Create a section view for the remainder of the analysis.

5) Click the wizard button, and follow the instructions.
   - This is where you will set all the parameters; unit system (USA...), internal or external flow, fluid type, and others such as the results resolution.

6) After you click finish, it will create a Flow Simulation Analysis Tree.
7) It will also automatically create a computational domain, which must encompass the entire cavity to be analyzed. You can modify the computational domain by dragging the arrows in or out.

8) Next you need to create boundary conditions (you have to create boundary conditions on every lid)

- Right click Boundary Conditions, and select Insert Boundary Conditions.
- Select the face of the lid and what type of boundary it is (flow, pressure, or wall) and enter its value. Shown below is an example with an inlet flow of 100 cfm and an environmental pressure outlet.
9) To change the Calculation Control Options select , and edit as needed.

- Note: we had to check the “Maximum calculation time” box and set it to 1200s (20 min) to reduce the calculation time.

10) To run the Flow Simulation click run , set the options and click run .

- It then opens the calculation window, as shown below, and loads the results automatically when finished.
11) There are several ways of viewing the results.

- To insert a cut plot of pressure, temp., or velocity. Right click cut plots and select insert. You can then edit the cut plot properties if needed. Click ok.

- The default cut plot is pressure as shown below.
• You can change the type of plot by clicking pressure at the bottom of the scale and selecting a different plot from the list. You can also create a different plot by clicking display parameters and enabling another parameter.

• Note: We found the relative pressure to be the most informative, since it gives the pressure difference from environmental (gauge pressure), which we could then compare with the flow bench.

NOTE: This program is capable of doing much more with flow simulation, but for this project this is all that was needed. There is also several videos online demonstrating how to use Solidworks flow simulation that can be found with a simple search.
APPENDIX J – FLOW BENCH DRAWING PACKAGE
Exhaust Assembly

<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>PART NUMBER</th>
<th>QTY.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Insert Large holes</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Blower</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>Metal Strap</td>
<td>6</td>
</tr>
</tbody>
</table>

Flow Bench

UNIVERSITY OF IDAHO ME DEPARTMENT

Scale: 1:6 SHEET 1 OF 4
Gate Valve Assembly

<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>PART NUMBER</th>
<th>QTY.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gate valve base</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Valve tube</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Gate valve</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>3&quot; polystyrene coupler</td>
<td>1</td>
</tr>
</tbody>
</table>

Flow Bench
Flow Bench

UNIVERSITY OF IDAHO
ME DEPARTMENT

Descrip.
Flow Bench
Part #:
4/20/2011
QTY:

Propr. valve tube
Scale: 1:2
SHEET 3 OF 5

DIMENSIONS ARE IN METERS
THIRD ANGLE PROJECTION

MATERIAL: 3" Polyethylene pipe

DEFAULT TOLERANCES:

LINEAR:
X: ± 0.25
Y: ± 0.125
Z: ± 0.5

ANGULAR:
± 5°
± 3°
± 15°

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PROPRIET.

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APPENDIX K – FINAL MUFFLER DRAWING PACKAGE
<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>PART NAME</th>
<th>QTY.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hushpower</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Cat SubAssembly</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Top SubAssembly</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Bottom SubAssembly</td>
<td>1</td>
</tr>
</tbody>
</table>

**Dimensions are in inches**

**Third Angle Projection**

**Material:** Steel

**Stamp:** StealthCat™

**University of Idaho ME Department**

**EPIC BUDDRIUS**  
**4/14/2011**  
**Part #:**  
**QTY:** 1

**Scale:** 1:4  
**Sheet 2 of 2**
CAT SUB-ASSEMBLY

<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>PART NAME</th>
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<tbody>
<tr>
<td>1</td>
<td>Catalyst</td>
<td>Aristo Donation</td>
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</tr>
<tr>
<td>2</td>
<td>Extra Chamber</td>
<td>Hushpower Donation</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Cat Upper Ring</td>
<td>Machined Part</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Cat chamber</td>
<td>Hushpower Donation</td>
<td>1</td>
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<tr>
<td>5</td>
<td>Cat Bottom ring</td>
<td>Machined Part</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>Cat cap</td>
<td>Machined Part</td>
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<td>7</td>
<td>Exit pipe</td>
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<tr>
<td>8</td>
<td>Cone Ring</td>
<td>Machined Part</td>
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<tr>
<td>9</td>
<td>Hushpower Cone</td>
<td>Hushpower Donation</td>
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</tbody>
</table>

DIMENSIONS ARE IN INCHES
THIRD ANGLE PROJECTION

StealthCat
NOTE: EXPANDED EXHAUST PIPE
NOTE: Thickness 1/16"
NOTE: STOCK 2" X 4" OD PIPE (CUT IN HALF LENGTHWISE)
### DFMEA Scales

<table>
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<tr>
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<td></td>
<td>3</td>
<td>operation seriously compromised</td>
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<tr>
<td></td>
<td>2</td>
<td>operation somewhat compromised</td>
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<tr>
<td></td>
<td>1</td>
<td>cosmetic damage/operational</td>
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<td></td>
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<td>i</td>
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<td>i</td>
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<td>easily predictable</td>
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<td>ITEM AND FUNCTION</td>
<td>POTENTIAL FAILURE MODES</td>
<td>POTENTIAL EFFECTS OF FAILURE</td>
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<td>---------------------------</td>
<td>----------------------------------</td>
<td>---------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Muffler</td>
<td>Poor sound reduction</td>
<td>the sled does not pass sound testing</td>
</tr>
<tr>
<td>Muffler</td>
<td>Produces excess heat</td>
<td>melting of oil tank</td>
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<tr>
<td>Muffler chambers</td>
<td>Welds break</td>
<td>loud sled, poor performance</td>
</tr>
<tr>
<td>Muffler cones</td>
<td>Flow restriction</td>
<td>increased backpressure, poor sound attenuation</td>
</tr>
<tr>
<td>Muffler packing material</td>
<td>Heat expulsion, increased sound</td>
<td>reduced sound attenuation, excess heat in engine compartment</td>
</tr>
<tr>
<td>CAT end cap</td>
<td>bolts loosen</td>
<td>increased vibration, reduced catalyst performance</td>
</tr>
<tr>
<td>CAT</td>
<td>Producing excess heat</td>
<td>engine over heats</td>
</tr>
<tr>
<td>CAT</td>
<td>Poor emissions</td>
<td>the sled does not pass emissions</td>
</tr>
</tbody>
</table>