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MECH 4860

MacDon Industries Ltd.

Windrower Cab Leakage Testing System to Confirm Integrity of Seals

Group 11 – MDKB Consulting

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Executive Summary

The client for this project, MacDon Industries Ltd., requested a leakage testing system be developed for MacDon windrower cabs. The current leak testing system is to spray the cab with a garden hose, and manually check for wet areas in the interior of the cab. This method does not align with the company's goal of continuous improvement, and MacDon desired a more repeatable solution.

The design team met with the client and carefully defined the requirements and constraints of the problem. The problem was broken down into five functional groups including location, medium supply, delivery method, detection method, and medium removal. Considering all possible options for each functional group, over 200 concepts were generated. The top concepts were presented to MacDon, and ultrasonic leak detection was selected as the design concept best suited to achieve the design requirements.

The design team contacted multiple companies in order to receive quotes and information regarding commercially available products. Products found to meet the design objectives were scored, allowing the top choice to be found, namely the SDT200 ultrasonic receiver with SDT8 ultrasonic emitter. Ultrasonic leak testing products were demonstrated at MacDon, validating the emitter location in the cab and that ultrasonic leak detection achieved all customer requirements.

The cost to implement ultrasonic testing is , with an annual cost of . As compared to the current water testing method, MacDon will save per year. Additional value-added uses include detecting leaks in buildings and tractor components, as well as serviceable components. Ultrasonic testing has a net present value of , indicating that MacDon will benefit financially by implementing the SDT200 and SDT8.

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1. Background and Problem Statement

The client for this project is MacDon Industries Ltd. MacDon is a worldwide leader in the design and manufacturing of harvesting and agricultural equipment. The company operates around the globe with offices in Canada, the United States, Germany, and Australia.

A major product line that MacDon offers is the self-propelled (SP) windrower. A windrower features a cab where the farmer can sit to operate the machine. The primary purpose of the SP windrower is to attach to a cutting implement (a header) and cut crop during a harvest. The cut crop is cut by the header, and lies in a line (a windrow) behind the windrower and is left in the field to dry, as seen in Fig. 1.

Fig. 1. A MacDon SP windrower using a header attachment in order to cut crop in a field of canola [1].

A combine collects crop after it has dried. Allowing the crop to sit and dry reduces the amount of shelling, meaning less seeds are lost during the harvest and more revenue can be achieved.

Through normal operation, a windrower becomes dirty due to crop build-up, debris, and oil spills and requires periodic cleaning. The most common method of cleaning a windrower is for the farmer to bring the machine to his or her farm and use a pressure washer to clean the exterior. It is important to keep the machine clean and to keep the interior dry. It is necessary to keep the cab clean to ensure good visibility. Good visibility is not only safer for the operator but also leads to fewer cutting mistakes.

A variety of issues arise if the interior of the cab becomes wet. The cab is where the farmer spends multiple hours a day during a harvest, guiding the windrower manually. Therefore, the cab interior must be a comfortable environment. If the cab interior becomes wet, time originally spent cutting may be lost waiting for it to dry. Additional wait time means that crop conditions may change and revenue could be lost. Therefore, MacDon wants cabs to be tested for leaks during the manufacturing stage to ensure that they will not leak when washed in the field.

the team was tasked with designing a solution for cab leak testing. Fig. 2 shows a current MacDon windrower cab. The cabs are fully contained and feature curved glass on all four sides, metal supports at the door, and a metal roof and base.

Fig. 2. A MacDon windrower cab model, as provided by Sean Hakansson [2].

MacDon's Winnipeg manufacturing plant currently produces all components of the windrower, including cabs and windrower bodies. The cabs are assembled in their own assembly line, separate from the windrower body. The windrower body is assembled on its own assembly line. The cab is transported through the line on a wagon that has four casters and follows a track from station to station down the assembly line. The throughput of the cab line is six cabs per day. Seals are located at the edges of all glass panels and silicon is used to adhere the front window seal to the roof of the cab. The areas of focus for leak testing include all seals where glass interfaces with any other component.

The current testing procedure requires one cab to be tested at the beginning of the shift to determine if the process is yielding waterproof cabs. The last cab produced during the previous day is the cab that is tested. Testing a previously made cab ensures that the silicon seals on the glass panels have dried sufficiently to allow for water based leak testing. Fig. 3 shows the current floor plan of the manufacturing building, highlighting both the cab line and the windrower line. To test a cab, it must be wheeled from location A to location B at the opposite corner of the facility.

Fig. 3. Top down view of the cab and windrower vehicle assembly as provided by Sean Hakansson [2].

A garden hose and a drain are located at location B. The cab is hosed down and inspected for leaks around the seals by a worker physically touching areas around the seals while inside the cab. If no leaks are present, it is assumed that the line is producing waterproof cabs and production continues for the current day. Conversely, when a cab is found to be leaking, the assembly stations are examined to find the cause of the leak and where the leak originated. Additionally, cabs that have been previously installed on windrowers the day before need to be checked for leaks.

The current testing process relies heavily on the individual inspecting the cab, and therefore is not a repeatable process. Having to re-examine previously produced cabs is time consuming and expensive. Therefore, MacDon requested the development of a more consistent leak testing method for the current windrower cabs.

1.1 Project Objectives

As per MacDon's request, the goal of this project is to create a repeatable procedure for MacDon windrower cabs to be tested for water leakage. This report includes a standard testing procedure for the client to follow and details the leak testing device. The device is evaluated in terms of cost, feasibility, and effectiveness. A final assembly CAD file and engineering drawing are also supplied. The project began on September 21, 2015 and concluded on December 9, 2015, as shown in Appendix A.

1.2 Design Expectations

Design expectations were identified by meeting with our contact at MacDon, Sean Hakansson, and discussing the project while on site. The design problem was originally open ended and flexible, but key expectations of the design were defined. Thus, the design of the testing procedure and device must meet the following expectations:

- The procedure must be easy to conduct for any MacDon employee, and require as little human interaction as possible to increase repeatability.
- The device must be able to test for leaks that would occur if the cab were pressure washed by a person.
- The device must be able to test the cab without causing the cab to fail.
- The area of leak testing must cover the same regions of the cab as if it were pressure washed by a person.
- The device must be able to be easily manufactured in-house or obtained from a supplier company.
- The test procedure and device must be integrated into the assembly process so that up to twelve cabs can be tested per day.
- The device must function properly in order to conduct leak tests.
- The design must not exceed the allocated budget.
- The testing procedure must not excessively corrode the cab or testing device.

This project also features a design exclusion. The silicon currently used to seal the cab has a long drying time. Throughout this project, the team did not attempt to find a better sealing method by analyzing different silicon compounds. This problem is being investigated in-house at MacDon and was considered outside the scope of this project.

1.3 Customer Needs

The design must also meet various needs identified by MacDon. After speaking with Sean Hakansson and Eric Hornby of MacDon Industries, the following customer needs were identified:

1. The device must be able to test for leaks that would occur if the cab were pressure washed by a person.
2. The design must be able to be manufactured or purchased within the allocated budget.
3. The design must conduct the testing procedure within the allocated time.
4. The design must limit human interaction and be repeatable.
5. The design must fit within the allowable footprint.
6. The design must continue to function for the entirety of the projected production life span of the current and next generation windrower cabs.
7. The design accommodates testing of both current and next generation windrower cabs.
8. The design provides a measured indication of the size of the leak.
9. The design complies with the Manitoba Workplace Safety and Health Regulation Act, which require that new processes and machinery be within the allowable legislated limits for continuous noise exposure level [3].

The customer needs were ranked, allowing the team to understand their relative importance. TABLE I contains the customer needs and the relative importance of that need, with a score of ‘1’ being low importance, while a score of ‘5’ shows a high importance.

TABLE I. CUSTOMER NEEDS WITH CORRESPONDING LEVELS OF IMPORTANCE [4]

Number	Description	Importance
1	The device must be able to test for leaks that would occur if the cab were pressure washed by a person.	5
2	The design must be able to be manufactured or purchased within the allocated budget.	3
3	The design must conduct the testing procedure within the allocated time.	5
4	The design must limit human interaction and be repeatable.	4
5	The design must fit within the allowable footprint.	4
6	The design must continue to function for the entirety of the projected production life span of the current and next generation windrower cabs.	4
7	The design accommodates testing of both current and next generation windrower cabs.	4
8	The design provides a measured indication of the size of the leak.	4
9	The design complies with the Manitoba Workplace Safety and Health Regulation Act, which require that new processes and machinery be within the allowable legislated limits for continuous noise exposure level **[3]**.	5

As TABLE I shows, all the needs were very important to MacDon as they all show high importance values.

1.4 Technical Specifications

The customer needs that were defined in TABLE I were assigned quantifiable values in order to help the team gain a better understanding of how to achieve each need. Quantitative target specifications that correspond to the customer needs were given marginal and ideal values. TABLE II shows the required values for each target specification.

TABLE II. TARGET SPECIFICATIONS WITH MARGINAL AND IDEAL VALUES [4]

Number	Metric	Units	Marginal Value	Ideal Value
1	Testing water pressure	Psi	2000 - 4000	3250
2	Manufacturing cost	$	10,000 – 20,000	15,000
3	Process time	Minutes	< 60	< 30
4	Number of process steps	Tasks	5 - 10	7
5	Maximum footprint	Sq. ft.	< 121	< 100
6	Useful life of test apparatus	Years	6 - 10	8
7	Compatibility with current and next generation windrower models	Pass/fail	None	Pass
8	Measured indication of leak	Pass/fail	None	Pass
9	Noise exposure level	dBA	< 85	< 80

The ideal values shown in TABLE II represent the results that are most favoured by MacDon. The ideal value for the testing water pressure of 3250 psi comes from the standard power washer available at MacDon. Therefore, when the cabs are tested, pressure washing at this pressure can be used as a way to benchmark what size of leaks are unacceptable.

MacDon gave the team a maximum budget of $20,000 for this design project. Minimizing the amount of money required for the design will make the project more viable and attractive to MacDon. Selecting an ideal value of $15,000 allows the team $5,000 worth of adjustments once cost estimates are formed.

The ideal value for process time was selected as 30 minutes. 30 minutes will allow MacDon to test 12 cabs per day. MacDon currently tests six cabs per day, resulting in a process time of 60 minutes. The client stated that the best solution would allow each cab to be tested during a high volume run, meaning only 30 minutes would be available per station per cab. The team will attempt to meet this mark so that the cab testing system will integrate seamlessly into MacDon's assembly line during a high volume assembly run.

The design must be easy to use and simple to operate. The team felt that a fairly general design would require ten process steps in order to test for leaks, while a very refined design could use only five. The team wants to keep the number of process steps low, as it will inevitably affect the throughput time. As such, seven process steps were taken as the ideal value.

MacDon specified that an assembly station in the cab assembly line is 11 feet by 11 feet, resulting in 121 square feet of available space. The cab itself has smaller dimensions, measuring approximately nine feet by nine feet. The team decided to choose an area of ten feet by ten feet (100 square feet) as the ideal value, as it would give ample clearance space of one foot on any side of the cab. It is assumed that future cab designs will also require approximately the same amount of space. Additionally, the team wants to focus on minimizing the footprint, as a larger footprint will yield a larger total cost in terms of potentially unutilized space.

MacDon's current line of windrowers (5 Series) has been produced for a few years. MacDon desires that the testing apparatus be useful for the duration of the current product. At this point, it is difficult to estimate an exact value for the amount of years that the current product will be produced for, with estimates ranging from six to ten years.

Therefore, the team took the nominal value of eight years as the length of time that the testing device should be operable.

The time will come when MacDon introduces a new product and ends current production. As these times may overlap, MacDon wishes that the testing device and procedure be applicable to both the current and future generation windrower cabs. General guidelines were given to the team regarding the size of future designs. The ideal footprint value was selected with these values in mind.

In order to increase the repeatability of the leak testing process, a measured indication of a leak is preferred. The current method is subjective and prone to error as it relies on an individual’s interpretation of what is wet or not. A measured indication would eliminate any subjectivity and give a reliable pass or fail value. If the indicator shows a leak, the cab has failed. If the indicator shows no leak, the cab attains the ideal value of “pass”.

MacDon has also voiced concerns on the safety of the apparatus. One area the team must consider is the audible range of the device. The Manitoba Workplace Safety and Health Act have strict rules regarding noise levels in employee workspaces [3]. The maximum allowable value of noise perceived by a human ear for a workplace is listed as 85 dBA (A-weighted decibels) [3]. Any design that exceeds this value cannot be legally implemented into a workplace. Therefore, in order to ensure that the design is safe for MacDon employees, the ideal value for noise exposure level was selected to be 80 dBA.

1.5 Constraints and Limitations

The project also has various constraints and limitations. After conversing with the associates at MacDon, several constraints were identified:

1. The testing apparatus must be located within the production area of the MacDon Windrower Manufacturing Facility.
2. Only one drain is located within the production area of the MacDon Windrower Manufacturing Facility and no additional drains can be installed.
3. The windrower cabs are to remain on the small wagon used on the cab assembly line.
4. The maximum footprint of the device is limited to 121 sq. ft. [4].
5. The noise level of the device must not exceed 85 dBA [3].
6. The testing device is not to exceed a manufacturing cost of $20,000.

The aforementioned constraints restrict the designs of the project physically, acoustically, and financially. Again, all constraints must be met for the project to be considered a success.

2. Concept Generation

The team made sure that as many concepts were generated as possible in order to consider all solutions to the design problem. Therefore, various internal and external concept generation techniques were used. Additionally, the problem was decomposed into five functional groups, and 202 initial concepts were generated. Internal search result methodology is included in Appendix B, while external search methodology is included in Appendix C.

A significant portion of concepts dealt with ultrasonic products. Many of the external search results showed that ultrasonic leak detection methods were viable solutions for MacDon's design problem. The team researched ultrasonic leak detection theory to become more familiar with the subject, and the theory is explained in Section 2.1. Information from applicable patents and comparable competitor's products are available in Appendix C.

2.1 Ultrasonic Leak Detection Theory

Ultrasonic leak testing is based on the simple principle that when air escapes from a source it creates a sound. Everyday examples include air escaping from a balloon, a tire, or an inflatable bed. When a leak is large enough, the sound can be heard by the human ear and the location identified. As a hole gets smaller, the sound becomes higher pitched (higher frequency) making it inaudible to the human ear.

However, air is still escaping and making a sound. If the higher frequency sound could be heard, the leak could be located as one finds a leak on an ordinary balloon. Ultrasonic detectors provide the detection solution by using the Heterodyne Principle [5].

Heterodyning helps to transfer a signal from its given frequency to an intermediate frequency. It accomplishes this frequency transfer with a mixer as shown in Fig. 4.

Fig. 4. Heterodyne principle showing mixing between two sound waves to create a lower frequency beat [6].

A modulated carrier wave at frequency f_1 is mixed with a local oscillator sine wave at frequency f_2, shown in Fig. 4. The result of the mixed wave is that the new frequency is lower than the original modulated wave, assuming f_2 is larger than f_1. Thus, with the Heterodyne Principle, it is possible to take a very high frequency leak, which was previously in the inaudible frequency range, and lower it to a range that is within human hearing limits [6]. Therefore, it is possible to create an ultrasonic detector that is capable of collecting a high frequency noise, lower it to an audible frequency, and outputting the same sound but at a lower frequency noise, which the operator can hear via headphones or a quantify via digital display. The response is instantaneous, allowing the user to search for leaks in real time.

3. Concept Analysis and Selection

All concepts that were generated were screened for feasibility, and the top concepts were compared using a scoring matrix. The top scoring concept was found to be ultrasonic leak testing and is discussed in further detail in Section 3.1. All screening matrices, scoring matrices, weighting matrices, the House of Quality, and other designs presented to the MacDon team during the concept analysis stage are included in Appendix D.

3.1 Ultrasonic Emitter and Receiver Concept

The design concept using sound was one of the simplest designs the team considered. Testing can be conducted in essentially any location, as the source of sound is produced from a very small ultrasonic emitter. Possible ultrasonic emitters are shown in Fig. 5.

Fig. 5. Various ultrasonic air transducers as provided by Massa Product Corporation, highlighting the small footprint required by such a device [7].

The emitter could be placed inside the cab at the most convenient location, and does not require additional infrastructure or barriers in order to be used. Fig. 6 shows an example setup of the emitter in the cab.

Fig. 6. Example placement of the ultrasonic emitter inside the windrower cab, the detector used to search for leaks, and the headphones to notify the operator [2].

It is important to note that the sound range at which the test would take place would be outside of the range of human hearing, meaning additional safety equipment would not be required.

In order to conduct the leak test, a worker would use a handheld air condensing microphone and display unit to receive the emitted sound waves. An example microphone recommended in patent EP0260818A2 is the Bruel and Kjaer model number 4135 air condenser microphone. Such a microphone can be attached to a visual detector (such as the Olympus EPOCH 650) in order to see where leaks exist while scanning the seals. As described in EP0260818A2 [8], leakage areas will allow more sound waves to travel through, producing a noticeably higher voltage recorded by the microphone.

The main advantages of ultrasonic leak detection are the versatility of use and speed of results. As previously mentioned, the emitter can be placed in the cab at any location, and tested by a single worker. Furthermore, the leaks can be identified as soon as silicon is applied to the cab, regardless of drying time, meaning all cabs can be tested each day. Any leak prone features or assembly methods can be identified and dealt with immediately.

3.2 Decision of Conceptual Design to Pursue

The client was also involved in concept analysis and selection. The team met with Sean, Eric, and Mark at MacDon on October 27, 2015. All final designs that the team had modeled were presented to receive their feedback. The MacDon team was especially interested in the ultrasonic design due to key advantages such as space requirements, ease of use, versatility, and ability to be implemented into the cab line. MacDon's positive response was justified considering that the ultrasonic idea scored the highest in the scoring matrix. The design concept is summarized in TABLE III.

TABLE III. PRELIMINARY DESIGN INFORMATION

Design Name	**Ultrasonic Leak Test**
Location	Any (preferred in the cab line)
Medium Supply	Ultrasonic emitter
Delivery Method	Through air
Detection Method	Handheld ultrasonic detection
Medium Removal	Current hearing protection (additional not required)
Scoring Matrix Value	486.3
Scoring Matrix Finishing Place	First
MacDon Selection	Yes
Estimated Cost	$5,000.00

Having identified the top design concept, detailed design work could be conducted. Section 4 shows the final design recommended to MacDon and details the justification and selection procedure for each component.

4. Final Design Details

The final design recommended to MacDon is ultrasonic leak detection using the SDT8 ultrasonic emitter and SDT200 ultrasonic receiver. The final design considers all aspects of operation, including the method of applying the ultrasonic sound, comparing commercially available emitters and receivers, process engineering, and economic analysis. Each component of the final design is described in greater detail in Section 4.1 to Section 4.5. The final model of the ultrasonic leak testing setup is shown in Fig. 7.

Fig. 7. CAD model of final ultrasonic leak test including SDT8 emitter and SDT200 receiver [2].

The operator places the SDT8 emitter on the seat of the cab while the SDT200 detector and head set is handheld. An engineering drawing was created in order to ensure consistent placement of the emitter in the windrower cab for optimal results. The drawing is shown in Fig. 8.

Fig. 8. Drawing identifying SDT8 emi

itter placement in windrower cab [2].

The drawing in Fig. 8 shows the placement of the SDT8 emitter in the cab. Ideally the emitter will be placed in the middle of the cab seat. However, large tolerances (+/- 50 mm) are allowed as the emitter can sufficiently fill the cab with ultrasonic sound from essentially any location. The method of filling the cab with ultrasonic sound is described in Section 4.1.

4.1 Ultrasonic Application Method

The team identified two possible methods in order to use ultrasonic technology to test the seal integrity on a windrower cab. The first method would be to pressurize the cab with some gas, and detect the sound of the gas leaking out. The pressurized method is commonly used in industry (for example, to detect leaks from gas pipes) [**27]**. However, due to the design intent of the windrower cab, pressurizing the cab to acceptable leak testing levels (approximately 150 psi) is not feasible and was not further considered.

The second method is to place an emitter inside the cab and follow the principles described in patent EP0260818A2. A detector would be used on the outside of the cab to detect any sound waves that are escaping through gaps in the seal.

The emitter method works similarly to the pressurized gas method. The key difference is that the emitter is used to simulate a pressurized vessel. Therefore, this method is useful when looking for leaks in seals where a vessel is not air tight, since the detector is not detecting the flow of gas from the leak but rather the amount of ultrasonic sound escaping the cab.

There are many positives with using the ultrasonic detector and emitter. A few of the positive aspect to ultrasonic detection is that it can be used in a cab that is not airtight, the size of the leaks can be quantified, and there is very little setup time required to use this test in the windrower cab.

4.2 Selection of Emitter and Receiver Devices

Having identified the most appropriate ultrasonic leak testing method in Section 4.1, various devices from various suppliers had to be compared in order to find the best product. Each team member researched potential products and contacted various companies in order to obtain quotes and additional information about the product. Only companies that the team was able to contact and receive quotes from were considered. Quotes that were received are included in Appendix E. The information received from the contacted companies is included in TABLE IV.

TABLE IV. SUMMARY OF POTENTIAL FINAL DESIGN PRODUCTS AS RECEIVED FROM SUPPLIERS

Metric	Company			
		Robinair Sound Generator 16451 [10],		Bacharach Tru Pointe Ultra HD [13]
Purchase Cost [$ CAD]				
Operating Frequency [kHz]		40.0 +/- 2.5		34.0 to 42.0
Volume [cm]		11.4 x 8.6 x 1.9		10.5 x 6.1 x 2.2
Unit Mass [kg]		0.14		0.30
Required Employees		1		1
Battery Type		9-volt Cell		9-volt Alkaline
Indicators		audible via headphones, LED visual indicator		Audio (0 Hz to 4 kHz), visual (10 element LED bar graph)
Warranty		One year with proof of purchase		One year manufacturing defects
Sensitivity		+/- 50 parts per million		0.005” diameter leak @ 5 psi @ distance of 20-30 ft
Device Type		Handheld		Handheld

Information that the team felt was important to determining which product should be used for the final design was included for each product. These metrics include:

- Cost of the device.
- Operating frequency; the frequency, in Hertz (KHz), that the sound is emitted at.
- Volume of the device.
- Unit mass of the device.
- Required employees; the number of employees required to successfully operate the device and conduct a leak test.
- Battery type; the type of battery the ultrasonic emitter device uses, such as rechargeable or single use.
- Indicators; how the device signals that a leak has been found to the operator.
- Warranty; the length of time that the device is insured, and which components have warranty coverage.
- Sensitivity; how small of a leak can be identified.
- Device type; the type of device that the product is, such as handheld or stationary.

With possible alternatives to the design solution identified, the best product had to be determined. In order to evaluate the products against each other, a variety of selection criteria were defined and scored against each other in a metric scoring matrix. TABLE V shows the results of the scoring matrix.

TABLE V. METRIC SCORING MATRIX TO DECIDE ON FINAL PRODUCT

Selection Criteria		Cost	Operating Frequency	Sound Level	Volume	Mass	Required Employees	Battery Type	Battery Life	Operating Temp [deg C]	Indicators	Warranty	Sensitivity	Margin of Error	Serviceability
		a	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**	**j**	**k**	**l**	**m**	**n**
Cost [$ CAD]	**a**	x	b	c	a	a	f	a	a	a	j	k	l	m	n
Operating Frequency [kHz]	**b**		x	b	b	b	b	b	b	b	b	b	b	b	b
Sound Level [dB]	**c**			x	c	c	f	c	c	c	j	c	l	c	n
Volume [cm]	**d**				x	e	f	g	h	i	j	k	l	m	n
Mass [kg]	**e**					x	f	g	h	i	j	k	l	m	n
Required Employees	**f**						x	f	f	f	f	f	f	f	f
Battery Type	**g**							x	h	g	j	k	l	m	n
Battery Life	**h**								x	h	j	k	l	m	n
Operating Temp [deg C]	**i**									x	j	k	l	m	n
Indicators	**j**										x	j	j	j	j
Warranty	**k**											x	l	m	n
Sensitivity	**l**												x	l	l
Margin of Error	**m**													x	m
Serviceability	**n**														x
Metric Amount		5	13	8	0	1	12	3	4	2	11	6	10	8	8
Total Amount		83	83	83	83	83	83	83	83	83	83	83	83	83	83
Weight		0.06	0.16	0.10	0.00	0.01	0.14	0.04	0.05	0.02	0.13	0.07	0.12	0.10	0.10

The possible final products as identified in TABLE IV were then scored against each other using the metric weightings found in TABLE V. The final results are shown in TABLE VI.

TABLE VI. WEIGHTED SCORES OF POTENTIAL FINAL PRODUCTS

		Products									
Selection Criteria	Weight	UE 10000		Robinair 16451		SDT270		SDT200		Bacharach Tru Pointe	
		Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Cost [$ CAD]	0 06	1 00	0 06	5 00	0 30	2 00	0 12	4 00	0 24	4 00	0 24
Operating Frequency [kHz]	0 16	5 00	0 78	4 00	0 63	4 00	0 63	4 00	0 63	4 00	0 63
Sound Level [dB]	0 10	3 00	0 29	3 00	0 29	3 00	0 29	3 00	0 29	3 00	0 29
Volume [cm]	0 00	2 00	0 00	5 00	0 00	4 00	0 00	4 00	0 00	5 00	0 00
Mass [kg]	0 01	2 00	0 02	5 00	0 06	4 00	0 05	4 00	0 05	5 00	0 06
Required Employees	0 14	5 00	0 72	5 00	0 72	5 00	0 72	5 00	0 72	5 00	0 72
Battery Type	0 04	5 00	0 18	1 00	0 04	5 00	0 18	5 00	0 18	1 00	0 04
Battery Life [hrs]	0 05	2 00	0 10	4 00	0 19	3 00	0 14	3 00	0 14	5 00	0 24
Operating Temp [deg C]	0 02	3 00	0 07	3 00	0 07	5 00	0 12	5 00	0 12	3 00	0 07
Indicators	0 13	3 00	0 40	1 00	0 13	5 00	0 66	5 00	0 66	1 00	0 13
Warranty	0 07	4 00	0 29	1 00	0 07	5 00	0 36	4 00	0 29	1 00	0 07
Sensitivity	0 12	4 00	0 48	4 00	0 48	5 00	0 60	5 00	0 60	4 00	0 48
Margin of Error	0 10	4 00	0 39	1 00	0 10	5 00	0 48	5 00	0 48	4 00	0 39
Serviceability	0 10	2 00	0 19	1 00	0 10	5 00	0 48	5 00	0 48	2 00	0 19
Total	**1.00**		**3.98**		**3.18**		**4.84**		**4.89**		**3.55**

The potential ultrasonic emitters were given ratings for each metric described in Section 4.2. Ratings were multiplied by the metric weights determined in TABLE V to give scores for each metric for each design. Finally, the scores of all metrics were summed for each design. As TABLE VI shows, the two products from SDT scored the highest (SDT 270, 4.84 and SDT200, 4.89), with the second closest competitor being from UE Systems at 3.98. As the scored results are nearly an entire point apart, only the top two concepts will be considered, and a sensitivity analysis is not required.

The SDT200 scored slightly higher than the SDT270 (4.89 versus 4.84). The SDT200 is the "economy" class detector offered by SDT, while the SDT270 is the "premium" offering. While both units perform the same fundamental operations such as leak detection and tightness testing, the SDT270 contains additional but unrequired features.

It is also important to consider the cost of the devices. Considering that both the SDT270 and SDT200 scored similarly and perform the same fundamental functions, the higher scoring SDT200 was selected as the final design as the initial purchase cost was approximately half of the purchase cost of the SDT270

4.2.1 Validation of SDT Devices

Having selected the final design choice for the ultrasonic leak testing device, all relevant information regarding the SDT200 and SDT8 is tabulated in TABLE VII.

TABLE VII. SDT200 METRICS

In order to ensure that the SDT200 ultrasonic receiver and SDT8 ultrasonic emitter chosen by the team were viable for future implementation at MacDon, they were compared directly with the customer requirements. In this way, the team ensured that the final design recommendation would meet the project requirements originally outlined in Section 1.3, Customer Needs. The customer need verification is shown in TABLE VIII.

TABLE VIII. CUSTOMER NEEDS ADDRESSED FOR THE FINAL DESIGN

Customer Need	Need Met?
The device must be able to test for leaks that would occur if the cab were pressure washed by a person.	Yes – leaks with diameters as small as three micrometers can be identified.
The design must be able to be manufactured or purchased within the allocated budget.	Yes – the receiver and emitter are available for a purchase cost within the specified budget shown in Section 4.4, Economic Analysis.
The design must conduct the testing procedure within the allocated time.	Yes – the testing time required fits within the specified takt time shown in Section 4.3, Process Engineering and Product Integration.
The design must limit human interaction and be repeatable.	Yes – the new leak testing process is simpler than before, and physically touching the cab has been replaced with a quantifiable measuring tool.
The design must fit within the allowable footprint.	Yes – the emitter is small enough to fit within the cab itself, requiring no additional footprint space.
The design must continue to function for the entirety of the projected production life span of the current and next generation windrower cabs.	Yes – the receiver and emitter feature manufacturer warranty, manufacturer serviceability, and can be replaced when their useful life expires.
The design accommodates testing of both current and next generation windrower cabs.	Yes – the receiver and emitter do not depend on the cab shape and size to function and can accommodate virtually any shape.
The design provides a measured indication of the size of the leak.	Yes – the design features quantifiable outputs that are visual, digital, and audible to the user.
The design complies with the Manitoba Workplace Safety and Health Regulation Act, which require that new processes and machinery be within the allowable legislated limits for continuous noise exposure level **[3]**.	Yes – the operating frequency of the emitter is outside of the range of human hearing, and additional considerations are described in Section 4.3.1, Safety Considerations.

As TABLE VIII shows, all customer requirements are met by the SDT200 and SDT8.

Following the selection of the SDT200 as the final design choice, the team remained in contact with the company. SDT recommended the use of the SDT8 ultrasonic emitter as the device to be paired with the SDT200 ultrasonic receiver. The two products function together and provide an advantage for service and maintenance, as only one company is required for ultrasonic testing needs. Thus, the final ultrasonic testing unit recommended for MacDon is the SDT200 ultrasonic receiver with accompanying SDT8 ultrasonic emitter.

4.3 Process Engineering and Product Integration

The ultrasonic leak testing process will be integrated into the MacDon windrower cab line. In order to best decide where and when in the assembly line the leak testing process should take place, a series of observations at the MacDon windrower factory were conducted. The testing process is required to take place after the installation of the front window, rear window, right door, left door and roof as all of the seals within the windrower cab need to be tested. TABLE IX is a list of the basic tasks occurring at each windrower cab assembly stations one through ten.

TABLE IX: INSTALLATION TASK AT EACH CAB STATION

Cab Station	Installation Task
1	Cab silicone and prep
2	Upholstery 1
3	Upholstery 2
4	Windows
5	Window sealing
6	Trainer seat
7	Operator station
8	Doors
9	Roof and mirrors
10	Cab onto windrower frame

Based on the observations, it is clear that there is only one possible station (cab station 10) where the front window, rear window, right door, left door and roof have all been installed on the windrower cab. Therefore, the ultrasonic leak testing process will take place at cab station 10 within the MacDon cab assembly line as shown in Fig. 9.

Fig. 9. Layout of cab line stations [2].

While at the MacDon facility conducting observations of the cab line, pictures were taken of the surrounding area of cab station 10 in order to ensure that there was ample room exists around the station to conduct the ultrasonic leak test at the station. Fig. 10 and Fig. 11 show the normal layout of cab station 10A with a view of both sides of the windrower cab prior to being lifted onto the fixture rack at station 10B. It is visually confirmed that there is enough room around the windrower cab at station 10A to facilitate the ultrasonic leak test prior to lifting of the cab onto the fixture rack.

Fig. 10. Cab station 10 – right hand side.

Fig. 11. Cab station 10 – left hand side.

A full study of the tasks occurring at station 10 was conducted in order to determine the most efficient addition of the leak testing process. The current cab station 10 tasks are displayed in TABLE X.

TABLE X: CAB STATION 10 TASKS

	Tasks	TASK TIME (MINUTES)
Operator 1	Place cab on the rack	2
	Gather parts and place into cab	1
	Install bulk head nut onto wiring harness	1
	File and hammer steering arm into position	3
	Bolt and pin steering arm to secure	1
	Install pre-assembled speed arm assembly	2
	Install shock bracket and control arm bracket	1
	Lift cab over frame and install control arm and shocks	2
	Gather tools and bring them to the frame	1
	Install speed arm assembly to servo	4
	Gather more tools	2
	Tighten and torque all bolts	2
	Connect and complete installation of ECM	5
	Subassembly speed arm	4
Operator 2	Place cab on the rack	2
	Gather parts & install shocks	3
	Route harness at rear edge of cab	3
	Tighten brackets on frame	1
	Wait for other operator to complete activities	5
	Lift the cab onto the frame	2
	Install shock bolts and control arm bolts	1
	Route wiring harness and A/C hose through frame	1
	Install control arm bolt	1
	Complete installation of harnesses and HVAC	8
	Torque bolts	2

Current activities at cab station 10 begin by lifting the windrower cab onto a rack fixture to facilitate the installation of various components. After the components are installed onto the cab, the cab is lifted and placed onto the windrower frame, followed by the torqueing of numerous joints connecting the cab and windrower frame. The current process time for cab station 10 totals 32 minutes. The ultrasonic leak testing procedure will be integrated into cab station 10A by conducting the leak test as the first step in the stations processes, prior to placing the cab onto the fixture rack. The leak testing procedure is estimated to take 10 minutes for one operator to complete, thereby adjusting the overall station takt time to 42 minutes, which is well within the cab lines current takt time of 60 minutes. While one operator at cab station 10 is conducting the leak test, the second operator at cab station 10 will be available as a floater on the cab assembly line to assist any cab stations requiring rework assistance in order to keep the assembly line on takt.

4.3.1 Safety Considerations

Ultrasonic detectors are sensitive devices capable of identifying extremely low energy high frequency sound pressure waves. In some cases the ultrasonic source is weak and requires amplification of the signal to be detectable. When utilizing the SDT200 ultrasonic receiver the tendency is to continually increase the gain of the detector so that even the smallest of leaks are discovered. In order to prevent possible harmful audible signals heard in the headset due to sudden bursts of high-energy ultrasound, the ultrasonic headset volume is to be kept at a low volume and gradually increased to a comfortable auditory level for the operator as per ASTM standards E413, E90, and E 336 (outlined in detail in Appendix B). As stated in the SDT8 user manual in regards to the use of the SDT8 ultrasonic transmitter, “There is no likelihood of direct consequences for the hearing capacities of the operator [19].”

Based on the American Conference of Governmental Industrial Hygienists (ACGIH) standards for ultrasonic exposure limits, the maximum sound exposure at 40 kHz frequency is 145 dB [20]. The SDT8 ultrasonic transmitter poses no direct consequences for the hearing capacities of the operator as the sound output is well below the threshold value of 145 dB. Operator safety during ultrasonic leak testing will be ensured through on the job operator training described in Section 4.3.2.

4.3.2 Testing Procedure

The testing procedure will be utilized to facilitate reliable leak testing results. Operator training will promote operator confidence in the leak testing process and ensure operators properly conduct the standardized ultrasonic leak test. All operators of the ultrasound leak detector must receive practical hands on training pertaining to the use of the SDT200 handheld ultrasonic receiver, SDT8 ultrasonic transmitter and ultrasonic leak testing procedure from the Cab Line Lead Hand prior to conducting an ultrasonic leak test.

The three fundamental areas of practical training as covered in the Standardized Ultrasonic Testing Process are:

1. Operation of the SDT8 ultrasonic transmitter
2. Operation of the SDT200 handheld ultrasonic receiver
3. How to conduct a standardized ultrasonic leak test

The standardized leak testing procedure will describe how the operator is required to: operate the ultrasonic devices, locate a leak, quantify the results, and re-check the repaired leak. The leak test procedure also describes how the operator must follow each step and record information about a leak.

The ultrasonic leak test procedure is outlined in TABLE XI. The procedure describes the process of testing the cab from start to finish and follows a standard MacDon template. The steps are numbered from 1 – 9, with an accompanying description in the “process” column. To further clarify the instructions, each step has a descriptive picture correlating to the step number in the bottom row of the table.

TABLE XI: STANDARDIZEI

O LEAK TEST PROCEDURE

MacDon has indicated that the current windrower cabs are not designed to be functionally air tight, but rather completely water tight. The SDT200 device measures the acoustic ultrasonic energy strength measured in units of dBuV. While ultrasonic leak testing the windrower cabs using the SDT200, categorizing all registered leak measurements over 0 dBuV as a failed leak test would non-discriminately associate air and water leaks alike. However, the process design requirements stipulate that the testing procedure must identify water leaks within the windrower cab. Considering that air penetrates smaller holes in an imperfect seal than water, and that the dBuV measurement taken by the SDT200 is directly proportional to the size of a hole in a seal, it stands to reason that the dBuV measurement of a water leak versus an air leak can be quantified. Therefore, it is necessary to establish a Threshold Failure Value (TFV), which stipulates an unacceptable leak that will allow water into the cab.

Once MacDon purchases the SDT ultrasonic testing devices, the Threshold Failure Value (TFV) will need to be determined. In order to facilitate establishing the TFV, the Manufacturing Engineer overseeing the Windrower Line should utilize the following procedure to determine the TFV for cabs that have failed and leaked water during the current water testing procedure.

The following procedure must be completed prior to any rework of the leaking cab seal(s):

1. Once a windrower cab has failed the current water leak test, mark the location of the failed cab seal using a wax pencil, and then thoroughly dry the inside and outside of the seal.
2. Conduct a standardized ultrasonic leak test on the leaking cab, and record the dBuV reading measured by the SDT200 device at the previously marked leak location.

3. Repeat steps one and two for five or more separate leaking cabs that have failed the current water leak test.
4. Determine the TFV by taking the average of the dBuV measurements recorded from the location of the water leak from each discrete cab tested.

Conducting this process for more than five leaking windrower cabs will ultimately increase the statistical reliability of the calculated TFV, and in turn increase the overall reliability of the standardized ultrasonic leak test.

4.3.3 Process Failure Modes and Effects Analysis (PFMEA)

A Process Failure Modes and Effects Analysis (PFMEA) is a structured analytical tool used in industry to identify and evaluate the potential failures of a process. PFMEA helps to establish the impact of the failure, and identify and prioritize the action items with the goal of alleviating risk. PFMEA evaluates each process step and assigns a score on a scale of 1 to 10 for the following variables [21]:

1. Severity — Assesses the impact of the failure mode (the error in the process), with 1 representing the least impact concern to the process and 10 representing the largest impact on the testing process.
2. Occurrence — Assesses the chance of a failure happening, with 1 representing the lowest occurrence and 10 representing the highest occurrence. For example, a score of 1 may be assigned to a failure that happens once in every 5 years, while a score of 10 may be assigned to a failure that occurs once per hour, once per minute, etc.
3. Detection — Assesses the chance of a failure being detected, with 1 representing the highest chance of detection and 10 representing the lowest chance of detection.
4. RPN — Risk priority number = severity X occurrence X detection. By rule of thumb, any RPN value exceeding 80 requires corrective action. The corrective action ideally leads to a lower RPN number. [21]

The required steps followed to conduct a PFMEA on the Standardized Ultrasonic Leak Testing Procedure are as follows:

- Identify key process characteristics as potential sources of failure.
- Describe the potential failure modes for each process step.
- Identify the impact of each potential failure mode on downstream processes/product functionality.
- Identify the process causes for the failure modes.

The PFMEA conducted on the ultrasonic leak testing procedure is displayed in TABLE XII.

TABLE XII: PFMEA (PROCESS FA

Project:	Cab Ultrasonic Leak Testing		
Date:	December 7, 2015		
Function / Item	**Requirements**	**Potential Failure Mode**	**Potential Effect(s) of Failure**
SDT8 Ultrasonic Transmitter	Transmit ultrasonic frequencies	Improper placement in cab	Inaccurate leak test results
		Will not transmit	Cannot conduct leak test
		Will not transmit	Cannot conduct leak test
SDT200 Ultrasonic Receiver	Receive ultrasonic frequencies	Will not receive	Cannot conduct leak test
		Will not receive	Cannot conduct leak test
	Provide accurate ultrasonic measurements	Inaccurate measurements	Misleading leak test results
		Inaccurate measurements	Misleading leak test results

ILURE MODE EFFECT ANALYSIS)

	Facilitator:	Kevin Nikkel					

	Severity	Potential Causes(s) of Failure	Occurrence	Current Process: Controls Prevention	Current Process: Controls Detection	Detection	RPN
	7	Equipment not set up properly	3	Operator training & standardized work instructions	Monthly Process Audit	3	63
	10	Water in the sensor	1	Keep transmitter indoors and away from water - Operator Training	Process integrated into Cab station 10 indoor	1	10
	10	Dead Battery - Tools improperly prepared	7	Purchase spare battery	Operator is to check daily at end of shift, that battery is charging	1	70
	10	Dead Battery - Tools improperly prepared	7	Purchase spare battery	Operator is to charge the battery at the end of every second shift	1	70
	10	Flexible sensor is not attached - Equipment not set up properly	3	Operator training	Standard work procedures	2	60
	7	Improper equipment maintenance	2	Yearly calibration - preventative maintenance	Place device on Tool crib yearly calibration schedule for August	1	14
	7	Improver operation	3	Operator training & standardized work instructions	Monthly Process Audit	3	63

Based on the PFMEA conducted on the ultrasonic leak testing procedure, it is evident that two of the failure modes, a dead SDT200 battery and a dead SDT8 battery, are the highest potential failure modes with a risk priority number of 70. As previously stated, a risk priority number exceeding the threshold value of 80 requires implementation of additional corrective actions to mitigate the potential risks inherit in the process. Since the PFMEA conducted on the ultrasonic leak testing procedure indicated that the risk priority number for all identified risks present in the ultrasonic testing process are below the threshold risk priority number, no further corrective actions are required. However, a simple solution exists to mitigate both failure modes. Both the SDT200 and SDT8 feature replaceable rechargeable batteries, and therefore extra batteries can be obtained and charged before use. Additionally, properly charging the units between tests or when they are not in use will mitigate the failure mode.

4.4 Economic Analysis

The proposed ultrasonic leak testing devices and procedure will be analyzed taking into consideration the associated costs with using the devices during a useful eight-year lifespan. The cost breakdown for the initial purchase of the ultrasonic leak testing products is listed in TABLE XIII.

TABLE XIII: ULTRASONIC EQUIPMENT COST

The dollar amount required per year of operation of the current water testing procedure (over and above the cost of operation of the proposed ultrasonic leak testing) will be compared to the initial cost of the proposed ultrasonic leak testing in order to determine the most cost effective procedure. As requested by MacDon, the cost of operation is limited to the direct labour cost billed at per hour associated with the testing processes. The new ultrasonic leak testing procedure will be compared to the current water testing procedure based on the equivalent annual cost and the payback period on the purchase of the ultrasonic leak testing devices.

TABLE XIV shows the tabulation of annual operating costs with the current method, and the operating costs that would be associated with the proposed ultrasonic leak testing procedure. Each section of the table outlines the quantity of material (or time) and associated cost required per leak test and per year. According to this method of analysis, the annual operating cost for the current water testing method is ; this cost includes the cost of the water, dedicated factory floor space and labour. The annual operating cost of the proposed ultrasonic testing alternative is including yearly calibration and labour. MacDon will save annually on operating costs by moving to ultrasonic leak testing.

TABLE XIV: ANNUAL COST OF OPERATION

Two economic evaluation methods were used to determine if the proposed ultrasonic leak testing process should be chosen over the current water testing method, over an eight-year period assuming a 10% interest rate, common for MacDon projects. The net present value (NPV) of the proposed ultrasonic testing method is shown in TABLE XV. Since there are no cash inflows associated with this analysis, the savings that occur annually by moving to the proposed ultrasonic testing method (the annual water testing operating cost less the proposed annual ultrasonic testing operating cost) will be used to represent the annual cash inflows. When analyzed over an eight-year period the proposed ultrasonic leak testing is favoured as a result of the high annual operating cost of the current method. Since the NPV of the ultrasonic leak testing process is positive, the ultrasonic leak testing process is economically viable, and should be implemented.

TABLE XV: NET PRESENT VALUE OF ULTRASONIC PROCESS - EIGHT YEAR ANALYSIS

The payback period on the initial purchase of the ultrasonic testing equipment was also considered. The payback period is considered the initial investment divided by the annual cash inflows. The cash inflows associated with the payback period analysis are the savings that occur annually by moving to the proposed ultrasonic leak testing. The payback period was found to be 1.47 years based on an initial cost for the ultrasonic testing equipment of and an annual savings of

4.5 Additional Uses for Ultrasonic Testing at MacDon

While the main body of this report has focused on the ability of ultrasonic devices to locate leaks in the seals of the windrower cabs, the functionality can be applied to other uses as well. In order to avoid gold plating, it is important to note that the key requirements of the project have been met. However, the chosen device is capable of performing additional actions alongside leak testing. Section 4.5.1 to Section 4.5.3 discusses how the device can be used to detect building leaks, gas leaks on tractor components and air fittings, and how it can be used to check wear on various serviceable components such as bearings.

4.5.1 Detecting Building Leaks

The SDT200 in conjunction with the SDT8 is capable of filling a volume of 125,000 m^2 [19]. With this functionality, it is possible for MacDon to pinpoint leaks in various locations such as in the roof or walls. Doing so will not only prevent future water damage but will also help reduce energy used to heat and cool the facility in yearly operation.

4.5.2 Gas Leaks Around the Facility

Another advantage of ultrasonic testing is that all gas leaks can be detected, as the technology does not depend on chemical composition as gas sniffers do. As long as the gas is moving or escaping through a leak, the ultrasonic receiver can identify the sound. This feature means a gas leak in air-conditioning lines can be spotted without the use of specialty equipment. In such a case, it would not be necessary to use the SDT8 as escaping gas would already be audible to the SDT200. Thus, only the SDT200 ultrasonic receiver would be necessary to detect any leaks in gas lines anywhere in the MacDon plant.

Another application for ultrasonic leak technology is to find leaks in compressed air lines. Leaks can be identified and marked for repair by starting the air compressor and scanning the lines and connectors with the SDT200 [22]. It should be noted that once all leaks are repaired, it is important to go over the system again to ensure more leaks have not formed as a result of the repair. If more leaks are found, they should be repaired and another system check performed.

UE Systems has created estimates of the potential monetary losses a company can expect if leaks of a given diameter are unrepaired in compressed air lines. These findings are presented in TABLE XVI.

TABLE XVI. EXPECTED AIR LEAK COST (REPRODUCED BASED UPON UE SYSTEMS INC. "COMPRESSED AIR ULTRASONIC LEAK DETECTION GUIDE" [22])

TABLE XVI shows the correlation between the size of leak found in a compressed air system and corresponding cost based on the compressor having to continually run to keep the system at the ideal operating pressure. As the size of the leak increases, the amount of money required compensating for the leak increases. Therefore, there is a significant financial advantage to be attained if other compressed air systems are also tested for leaks at MacDon using ultrasonic technology.

4.5.3 Detection of Wear on Serviceable Components

The ultrasonic detector is also able to measure the minute differences between a well working bearing and one that is on the verge of breaking through the use of a probe (sold separately) which senses the sounds the vibration makes. This new method of preventative maintenance is at the forefront of lean manufacturing, and helps ensure that machine down time and costly repairs are reduced.

The system is able to detect wear over and under lubrication by first obtaining a baseline measurement from a well lubricated bearing. An operator then takes ultrasonic readings. A rise of 8 dB indicates under lubricated bearings, while a drop of 8 dB indicates over lubricated bearings. Results are then examined via a comparative analysis or referring to historical data [23].

For the comparative analysis, measurements are taken between two or more bearings to check to see if the values agree with another. By comparing values, it can be decided as to whether or not a bearing may need to be replaced [23].

The other bearing examination method is through the use of historical data. In this method, the bearing is continuously checked and the data compared from test to test to identify whether or not a trend of larger output sound exists. If a larger sound reading is consistently obtained, it indicates that the bearing is starting to wear and may succumb to fatigue failure, brinelling of bearing surfaces, or incorrect amounts of lubricant [23].

5. Conclusions

The team was presented with the task of developing a device which is capable of detecting leaks in the seals of the SP windrower cabs as the current methods do not align with MacDon's goals of continues improvement. Furthermore, MacDon wants to ensure that any cab which is pressure washed by the owner during routine maintenance will not leak due to poor seal integrity at the time of manufacture.

The current method for cab leak testing requires the last cab from the previous shift being transported from the end of the windrower line to a location on the opposite side of the factory. At this location, an individual uses a garden hose to soak around all the seals of the windrower cabs while another worker inside of the cab touches around the sealed areas to check for water penetration. Any leaks found must be dealt with for cabs currently in the line as well as cabs produced between testing segments.

The team was able to develop design considerations as well as customer needs and rank their importance to the design by speaking with the client. The team also listed any limiting constraints to the design, including physical and financial limitations.

While considering customer needs and constraints, the team generated over 200 possible solutions to the cab leak-testing problem. A screening matrix was used to eliminate ideas that were not as feasible as the current solution. After screening the concepts, the team constructed a weighting matrix to determine the weight attributed to each of the devised selection criteria. Metric weightings were confirmed with the MacDon team before proceeding to concept scoring.

After the final scoring was complete, ultrasonic leak testing was found to be the top scoring design. Due to the large score differences between concepts a sensitivity analysis was unnecessary. However, the team decided to present the top three designs to the MacDon team during the concept review meeting in order to get more feedback.

The top scoring concepts were modeled in SolidWorks and brought to MacDon where they were judged by a panel of three engineers. It was unanimously decided that the team should move forward with ultrasonic leak detection, confirming the results found from the team's scoring matrix.

The team began the final phase of the design project by finding that the most feasible method of supplying ultrasonic sound to the cab is by using an ultrasonic emitter. The team then focused on comparing available options of emitter and detector couples. After speaking with various ultrasonic companies and receiving expert opinions from employees, the team was able to make an informed decision on which product would best suite MacDon's needs by using a scoring matrix. Following the discussions with the manufacturers and the results of the scoring matrix, the team unanimously agreed that the SDT200 detector and the SDT8 emitter is the best long-term solution for MacDon because of its leak testing capabilities, serviceability, cost, and warranty options.

Process engineering was conducted in order to integrate the device into MacDon's current cab assembly line. The team modeled the emitter and detector in SolidWorks and created a drawing to show where to locate the emitter inside the cab. The best option for implementing the leak testing procedure was found to be when the cab is finished assembly, with all components including seat and control module attached (cab stage 10).

MacDon personnel received a demonstration model of a Bacharach "SoundBlaster" emitter and "Tru Pointe 2100 Ultrasonic Detector" receiver. Using the devices and conducting a leak test verified the concept of ultrasonic leak detection with the MacDon team, and it was discovered that the obstructions in place in the cab did not hinder the results of the detector. Thus, it was confirmed that the cab could be tested completely with the emitter placed on the seat.

Also considered was the training and safety of the MacDon employees. The team found that the device operated in a range that would not warrant any health or safety risks to the operator. A standard testing procedure was created with step-by-step instructions for the operators to follow to ensure accurate results when conducting the leak test. The testing plan will be provided to MacDon, and it can be adjusted to their exact specifications.

The team also conducted Process Failure Modes and Effect Analysis (PFMEA) on the ultrasonic leak detection process. The biggest potential for process failure is if the SDT200 or SDT8 battery runs out of power, causing tests to stop. To circumvent this issue, the team has recommended that the units be charged when not in use, and to keep additional batteries charged as spares to allow for quick changes and minimal interruptions to the process.

The team also conducted an economic analysis of using the ultrasonic detector. The first cost of the unit was found to be . The team also found that the payback period of the ultrasonic testing equipment would be 1.47 years based on the initial and annual savings of over the current water testing method. The net present value of the system was found to be , suggesting that the MacDon will benefit financially from implementing the process.

The solution selected is able to test every cab that MacDon produces and is not limited by cab design or location of apparatus. The solution is repeatable, quantifiable, below budget, saves money and time over the current system, and requires a low takt time. Furthermore, all customer needs were met by the design. Additional uses that result in financial benefit were also identified, including leak testing buildings, pressurized tractor components, compressed air gas lines, and serviceable parts. Considering that the designed solution meets all customer needs and can be used for additional benefits, the team recommends that MacDon move forward with the implementation of the SDT200 ultrasonic receiver and SDT8 ultrasonic emitter.

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Appendix A:
Supplemental Material

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1. Supplementary Material

1.1 Project Schedule

The project schedule allows for achieving the end goal of developing a standard leak testing procedure for the client to follow and a leak-testing device to be fabricated. This includes a final CAD model, cost analysis, and testing procedure for the design. The schedule is broken into three phases. Phase one includes the problem definition report and initial oral presentation, which has already been completed. The second phase of this project includes the phase two report. Phase three includes the final report, final oral presentation, and the final presentation poster. In this final phase the detailed analysis and design will be completed, along with CAD models, detailed drawings, and a test procedure. To visualize the work required to complete the project, a work breakdown structure (WBS) was created and is displayed in Fig. 1.

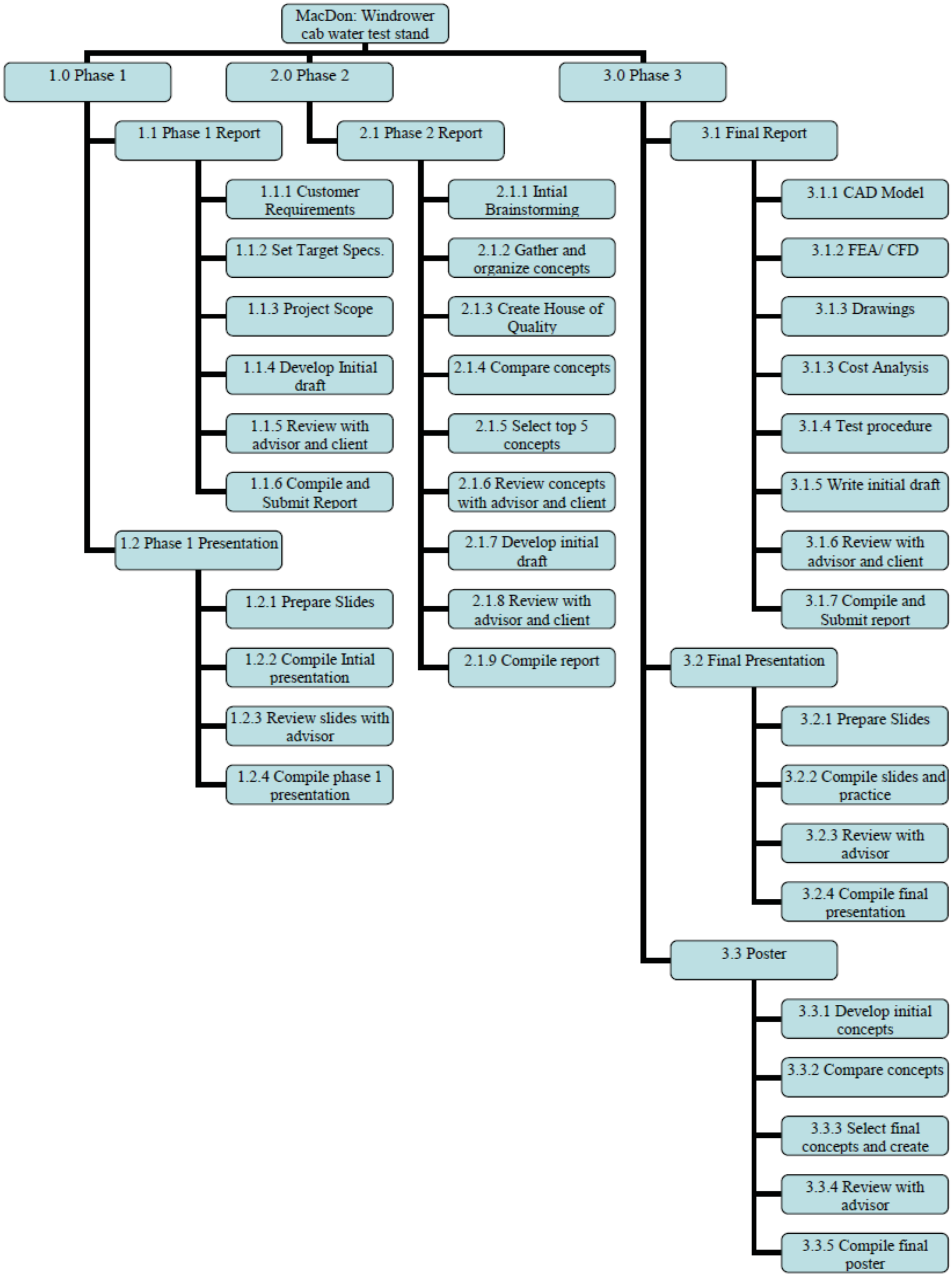

Fig. 1. The work breakdown structure outlining project tasks

At this point, all work tasks and work packages required for the successful completion of the project has been completed.

1.1.1 Gantt Chart

Using the work break down structure shown in Fig. 1 in conjunction with internal and external deadlines, a Gantt chart was created. The Gantt chart is displayed in Fig. 2, with timelines and interdependencies shown between deliverables.

WBS	Tasks	Task Lead	Start	End	Duration (Days)	% Complete	Working Days	Days Complete	Days Remaining
1	**Phase 1**		9/14/15	10/9/15	26	100%	20	26	0
1 1	Phase 1 Report		9/14/15	10/5/15	22	100%	16	22	0
1 1 1	Customer Requirements		9/14/15	9/17/15	4	100%	4	4	0
1 1 2	Set Target specs		9/18/15	9/24/15	7	100%	5	7	0
1 1 3	Complete Project Charter		9/14/15	9/24/15	11	100%	9	11	0
1 1 4	Develop Intial draft		9/25/15	9/29/15	5	100%	3	5	0
1 1 5	Review with advisor and client		9/30/15	10/2/15	3	100%	3	3	0
1 1 6	Compile report		10/3/15	10/5/15	3	100%	1	3	0
1 2	Phase 1 Presentation		9/25/15	10/9/15	15	100%	11	15	0
1 2 1	Prepare slides		9/25/15	10/1/15	7	100%	5	7	0
1 2 2	Compile Intial presentation		10/2/15	10/3/15	2	100%	1	2	0
1 2 3	Review slides with advisor		10/4/15	10/5/15	2	100%	1	2	0
1 2 4	Compile phase 1 presentation		10/6/15	10/9/15	4	100%	4	4	0
2	**Phase 2**		10/5/15	10/30/15	26	100%	20	26	0
2 1	Phase 2 report		10/5/15	10/30/15	26	100%	20	26	0
2 1 1	Initial Brainstorming		10/5/15	10/11/15	7	100%	5	7	0
2 1 2	Gather and organize concepts		10/12/15	10/14/15	3	100%	3	3	0
2 1 3	Create House of Quality		10/12/15	10/14/15	3	100%	3	3	0
2 1 4	Compare concepts		10/15/15	10/16/15	2	100%	2	2	0
2 1 5	Select top five concepts		10/17/15	10/18/15	2	100%	0	2	0
2 1 6	Review concepts with advisor and client		10/19/15	10/21/15	3	100%	3	3	0
2 1 7	Develop Initial draft		10/18/15	10/21/15	4	100%	3	4	0
2 1 8	Review with advisor and client		10/22/15	10/24/15	3	100%	2	3	0
2 1 9	Compile Report		10/25/15	10/30/15	6	100%	5	6	0
3	**Phase 3**		10/31/15	12/9/15	40	100%	28	40	0
3 1	Phase 3 report		10/31/15	12/7/15	38	100%	26	38	0
3 1 1	Research and contact companies		10/31/15	11/6/15	7	100%	5	7	0
3 1 2	CAD Model		11/5/15	11/9/15	5	100%	3	5	0
3 1 3	Drawings		11/4/15	11/13/15	10	100%	8	10	0
3 1 4	Test Procedure		11/4/15	11/13/15	10	100%	8	10	0
3 1 5	Develop Initial draft		11/14/15	11/22/15	9	100%	5	9	0
3 1 6	Review with advisor and client		11/23/15	11/29/15	7	100%	5	7	0
3 1 7	Compile report		11/30/15	12/7/15	8	100%	6	8	0
3 2	Final Presentation		11/25/15	12/8/15	14	100%	10	14	0
3 2 1	Prepare slides		11/25/15	11/28/15	4	100%	3	4	0
3 2 2	Compile slides and practice		11/29/15	12/2/15	4	100%	3	4	0
3 2 3	Review with advisor		12/3/15	12/5/15	3	100%	2	3	0
3 2 4	Compile final presentation		12/6/15	12/8/15	3	100%	2	3	0
3 3	Poster		11/25/15	12/8/15	14	100%	10	14	0
3 3 1	Develop Initial concepts		11/25/15	11/28/15	4	100%	3	4	0
3 3 2	Compare concepts		11/29/15	12/1/15	3	100%	2	3	0
3 3 3	Select final concepts and create poster		12/2/15	12/4/15	3	100%	3	3	0
3 3 4	Review with advisor		12/5/15	12/7/15	3	100%	1	3	0
3 3 5	Compile final poster		12/7/15	12/8/15	2	100%	2	2	0

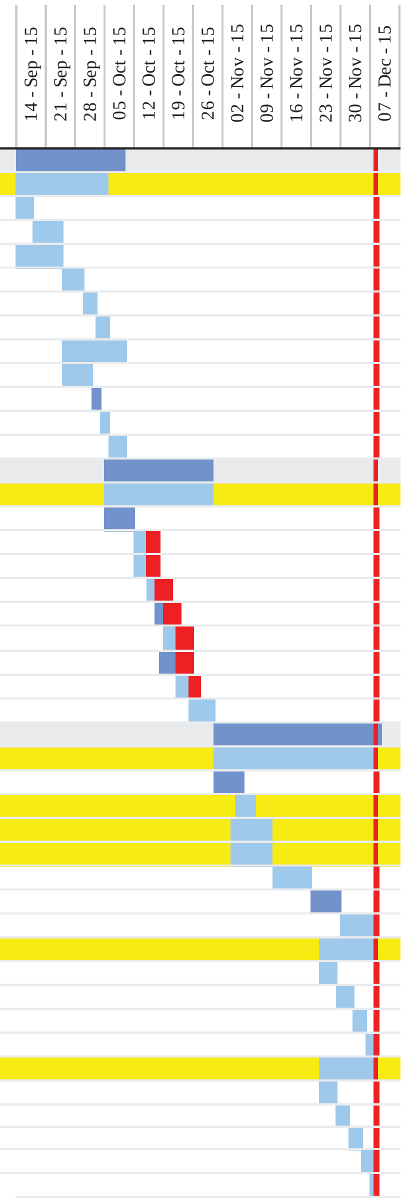

Fig. 2. Current Gantt chart with milestones marked in yellow, and project deviations marked in red.

The team fell behind schedule during the second phase of the project. Red bars on the Gantt chart indicate how long it took to actually complete a task. Some tasks in the concept generation phase took longer than expected because group members were busy with other class commitments, such as midterms and presentations. The project was also slowed down because the team realized during initial brainstorming that the problem definition and customer requirements focused too much on water testing solutions. The team took a step back and redefined the customer requirements and problem to broaden the possible solutions. Subsequently, the extra time required for this step pushed back all the tasks after the initial brainstorming. The slack time at the end of phase two, allowing nine days between a complete initial draft and submission date for the final report, allowed the group to complete the report on time. The team managed to stay on task for the entirety of phase three.

The milestones for the project are identified on the Gantt chart (Fig. 2) as yellow coloured cells. Milestones include major tasks that are required for the class portion of the course, as well as critical deliverables that MacDon Industries has required. The milestones are included in TABLE I, where all start and end dates are identified. Completed milestones are highlighted in green.

TABLE I. MILESTONES FOR THE PROJECT AS IDENTIFIED BY THE GANTT CHART

Milestone	Start Date	End Date
1.1 Phase 1 Report	9/14/15	10/5/15
2.1 Phase 2 Report	10/5/15	10/30/15
3.1 Phase 3 Report	10/31/15	12/7/15
3.1.1 CAD Models	10/31/15	11/4/15
3.1.3 Drawings	11/4/15	11/13/15
3.1.4 Test Procedure	11/4/15	11/13/15
3.2 Final Presentation	11/25/15	12/8/15
3.3 Poster	11/25/15	12/8/15

As TABLE I shows, the all phases and milestones have been completed.

Appendix B:
Internal Search Result Methodology

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List of Tables

1. Internal Search Results

General brainstorming and using the TRIZ problem solving method were the internal search methods used in order to generate as many concepts as possible. Brainstorming was conducted used to develop various initial concepts, while the TRIZ problem solving method was used to complement the brainstorming.

1.1.1 Brainstorming Method

Initially, the team was focusing too greatly on using water as the testing medium, making it difficult to break down designs into coherent categories to be screened and scored. Initially, the five main categories that the design was broken down into were water delivery, structure idea, drainage method, water supply, and detection method, as shown in TABLE I.

TABLE I. INITIAL TOP LEVEL DESIGN AND FUNCTIONAL GROUPS

Top Level Design	Functional Group
Windrower Cab Water Testing System	Water Delivery
	Structure Idea
	Drainage Method
	Water Supply
	Detection Method

As the names of the functional groups suggest, the solution was already heavily favoured towards using water as the testing medium. Therefore, the functional groups of the design had to be redefined. TABLE II contains the redefined functional groups for the project.

TABLE II. REDEFINED TOP LEVEL DESIGN AND FUNCTIONAL GROUPS

Top Level Design	Functional Groups
Windrower Cab Leakage Testing System	Location
	Medium Supply
	Delivery Method
	Detection Method
	Medium Removal

The team redefined the problem by making the major components of the design more general to ensure that the final design would not be biased toward a water based solution. The redefined major components of the design included:

- Location; where the device/testing would take place.
- Medium supply; how the medium used would be supplied.
- Delivery method; how the medium used would be delivered to the cab.
- Detection method; how the cab would be detected for leaks.
- Medium removal; how the medium would be removed once the test has been completed.

Once the five main functional groups were determined, various ideas were brainstormed for each group. TABLE III shows the ideas brainstormed for the functional group of location.

TABLE III. BRAINSTORMED IDEAS FOR THE LOCATION FUNCTIONAL GROUP

Functional Group	Top Level Category	Brainstormed Ideas
Location	Drain Vicinity	Overtop the Drain
		Trenched to Drain/Grate
		Beside the Drain
		Self Contained
	In the Assembly Line	In the Cab Line
		In the Windrower Line
		Self Contained Platform
		End of the Cab Line
		End of Windrower Line
	Outside	Shipping Yard
		Outside of Building 590

Similarly, TABLE III shows the ideas that were brainstormed for the medium supply functional group.

TABLE IV. BRAINSTORMED IDEAS FOR THE MEDIUM SUPPLY FUNCTIONAL GROUP

Functional Group	Top Level Category	Brainstormed Ideas
Medium Supply	Liquid	Garden Hose
		Pre Filled Tank
		Tapping Into Existing Water Line
		Rainwater Collection
		Water Truck
		Re-purified Water
	Sound	Emitter
		Speaker
		Manual
		Laser
		Vibration
	Gas	Pre Filled Tank
		Vacuum
		Compressor

TABLE V shows the ideas brainstormed for the delivery method functional group.

TABLE V. BRAINSTORMED IDEAS FOR THE DELIVERY METHOD FUNCTIONAL GROUP

Functional Group	Top Level Category	Brainstormed Ideas
Delivery Method	Liquid	Garden Hose Nozzle
		Pressure Jet/Nozzle
		Pump
		Physical
	Sound	Through Air
	Gas	Nozzle
		Pressurized

Ideas for the detection method were also brainstormed, and are included in TABLE V.

TABLE VI. BRAINSTORMED IDEAS FOR THE DETECTION METHOD FUNCTIONAL GROUP

Functional Group	Top Level Category	Brainstormed Ideas
Detection Method	Liquid	Manual Touch
		Foam/Bubble
		Fluorescent/UV
		Physical Change/Color Change
		Chemical Reaction
		Thermal Scan
		Sensor
	Sound	Ultra Sonic Detection
		Manual Hearing
		Microphone
		Sensor/Accelerometer
	Gas	Pressure Decay
		Trace Gas
		Visual
		Airflow Detector
		Smell
		Chemical Reaction

Finally, ideas were brainstormed for the medium removal functional group, and are contained in TABLE VII.

TABLE VII. BRAINSTORMED IDEAS FOR THE MEDIUM REMOVAL FUNCTIONAL GROUP

Functional Group	Top Level Category	Brainstormed Ideas
Delivery Method	Liquid	Garden Hose Nozzle
		Pressure Jet/Nozzle
		Pump
		Physical
	Sound	Through Air
	Gas	Nozzle
		Pressurized

The aforementioned ideas formed the basis of concepts that were considered for this design project. As the project continued, these basic ideas were combined together to create a list of higher level ideas achieving each function as described by the functional groups.

A similar re-definition process was required for the project's selection criteria. The selection criteria at the beginning of the concept development phase were too specific, and included criteria that only applied to water in some cases, even though other mediums were considered.

TABLE VIII. INITIAL SELECTION CRITERIA CORRESPONDING TO THE INITIAL FUNCTIONAL GROUPS

Functional Group	Selection Criteria
Water Delivery **Structure Idea** **Drainage Method** **Water Supply** **Detection Method**	Available Pressure
	Cost
	Takt Time
	Limited Human Interaction
	Footprint
	Functions for the Cab Production Life
	Usable for Testing Current and Next Generation Cabs
	Measure Output Water Pressure
	Sound Level of Device
	Inflow Does Not Exceed Outflow
	Process Repeatability

As TABLE VIII shows, the 11 selection criteria were the same for every functional group. However, the selection criteria were found to favour water as the design solution. Subsequently, the team began having difficulty applying these selection criteria to all ideas in the functional groups. Some ideas in the functional groups simply did not make sense when judged against these selection criteria. For example, "UV detection" was listed in the detection method category, but could not be judged against "ability to measure output water pressure" in any way. New selection criteria were required. The re-defined selection criteria are listed in TABLE IX.

TABLE IX. RE-DEFINED SELECTION CRITERIA CORRESPONDING TO THE NEW FUNCTIONAL GROUPS

Functional Group	Selection Criteria
Location	Footprint
	Cost
	Throughput
	Usability
Medium Supply	Footprint
	Cost
	Maintenance
	Throughput
	Usability
	Operator Safety
Delivery Method	Cost
	Maintenance
	Throughput
	Usability
	Operator Safety
	Repeatability
Detection Method	Cost
	Maintenance
	Throughput
	Usability
	Operator Safety
	Repeatability
Medium Removal	Cost
	Maintenance
	Throughput
	Usability
	Operator Safety
	Efficiency
	Footprint

As TABLE IX shows, the selection criteria are better suited and organized to match with their specific functional group. Some selection criteria (such as footprint) are important to multiple functional groups, and therefore are listed for each group. Selection criteria that are listed multiple times will have their weights adjusted for accordingly during concept screening and scoring.

1.1.2 TRIZ Problem Solving Method

TRIZ was used to complement the brainstorming procedure and results. TRIZ is a problem solving method developed by Genrich Saulovich Altshuller in the 1950's, known as the Theory of Inventive Problem Solving (TIPS) in English. Altshuller searched through numerous patents and noticed that inventors used patterns without realizing it. Altshuller concluded that innovation could be organized in a systematic view [**1**].

1.1.2.1 Methodology

The first step in using the TRIZ problem solving method is to develop ideal conditions for the problem, assuming there are no limitations or constraints. For our problem of developing a cab leakage testing system for MacDon Industries, the following list of ideal conditions were found:

- The test stand will have a small footprint.
- The test procedure will be repeatable from cab to cab.
- Tests will yield accurate results.
- If a test stand is required, it will be fully automated.
- If a test stand is required, it will be easy to manufacture.
- If a test stand is required, it will be durable.
- If a test stand is required, it will be cheap to produce and operate.
- If a test stand is required, it will be reliable.
- If a test stand is required, it will be quiet while operating.
- The test will be safe to operate.
- The test will be able to test all cabs produced daily.
- The test and potentially required test stand will be as simple as possible.
- The test stand and/or equipment required will be easy to maintain.

The actual solution cannot have all the aforementioned ideal conditions, since having one condition met will negatively affect another condition. These contradictions can be written in terms of engineering parameters using the TRIZ method. The TRIZ method lists 40 engineering parameters [**1**]. The contradictory statements, along with the associated engineering parameters, are listed are described in TABLE X.

TABLE X. CONTRADICTION STATEMENTS WITH CORRESPONDING ENGINEERING PARAMETERS USING THE TRIZ METHOD

Contradiction Statement	Engineering Parameters	
	Good	**Bad**
1. The test stand will be fully automated (good), but will require an increase in complexity to achieve (bad)	Level of Automation	Complexity of Device
2. The test stand will be reliable (good), but will be more complex due to the automation required (bad)	Reliability	Complexity of Device
3. The test stand will be easy to maintain (good), but will be more complex due to automation required (bad)	Reparability	Complexity of Device
4. The test stand will test all cabs (good), but testing will use more of testing medium (bad)	Productivity	Amount of Substance
5. The test stand will yield accurate results (good), but must not be too complex to control (bad)	Accuracy of Measurements	Complexity of Control

With the contradiction statements and engineering parameters determined, solutions could be found. The TRIZ method has a matrix outlining which design principles can be used to solve any contradiction between engineering parameters. The design principles that will solve the contradictions laid out in TABLE X are included in TABLE XI.

TABLE XI. DESIGN PRINCIPLES THAT SOLVE CONTRADICTING ENGINEERING PARAMETERS FOR THE TRIZ METHOD [2]

Contradictions of Engineering Parameters		Design Principles to Solve
Good	**Bad**	
Level of Automation	Complexity of Device	10, 15, 24
Reliability	Complexity of Device	13, 35, 1
Reparability	Complexity of Device	1, 35, 11, 10
Productivity	Amount of Substance	35, 38
Accuracy of Measurements	Complexity of Control	26, 24, 32, 28

A specific design principle is able to solve each contradiction. The design principles listed in TABLE XI include principle 1, 10, 11, 13, 15, 24, 26, 28, 32, 35, and 38. These specific design principles are defined, and solutions are explained relating to our problem:

1. Segmentation – Separate an object or process in simpler parts [**2**]. This principle could be used to improve the reliability and the reparability of the test stand while reducing the complexity. A modular test stand could be constructed, allowing complex parts to be broken down into simpler parts that will be easier to repair.

10. Preliminary Action – Take action on an object before it is needed [**2**]. This principle can be used to maintain the automation while reducing device complexity by setting up components of the test stand before the testing starts. It can also be used to increase reparability, while reducing device complexity, by introducing a preventive maintenance strategy for the test stand. This principle shows that it will be easier to perform routine maintenance instead of major repairs.

11. Beforehand Cushioning – Prepare in advance for a failure to compensate for object with low reliability [**2**]. This principle could be used to increase reparability while not increasing the complexity of the device by providing machine fail-safes. Fail-safes will keep the machine operating if a breakdown occurs. Repairs will be easier to conduct since failures will be easier to detect.

13. The Other Way Round – Try a different way to solve a problem such as heating a part instead of cooling it; flip the fixed with the moveable parts [**2**]. This principle can be used to increase reliability while decreasing the complexity of the test device by rotating the base of the test stand instead of moving the testing medium applicator.

15. Dynamics – Allow adjustability in an object to allow it to meet an ideal place or characteristics [**2**]. This principle can be used to maintain the automation while reducing device complexity by allowing for mechanical adjustments in the test stand instead of adding electrical control complexity.

24. Intermediary – Use an intermediate step or process [**2**]. This principle can be used to maintain the automation while reducing device complexity by creating an intermediate process such as mixing in a dye into the medium supply before it is applied to the cab. The principle can also be used to maintain the accuracy of the measurement while reducing the complexity by introducing an intermediate process for the detection method after the medium is applied to the cab.

26. Copying – Use a simpler copy of an object instead of an unavailable, expensive, and fragile object [**2**]. This principle can be used to maintain the accuracy of the measurement while reducing the complexity of the device. An example would be to use an infrared sensor to detect the temperature of any water that made leaked into the cab, rather than manually feeling for the leak.

28. Mechanics Substitution – Replace a mechanical means with a sensory means, such as an optical, acoustic sensor [**2**]. This principle can be used to maintain the accuracy of the measurements while reducing the complexity of device. For example, sensors can be used to detect leaks through the cab seal instead of manual detection.

32. Colour Changes – Change the color of an object or its environment [**2**]. This principle can be used to maintain the accuracy of the cab leak detection system measurements while reducing the complexity of the device. The color of the testing medium could be changed if it leaks through the cab seals, allowing it to be visible rather than being a clear medium.

35. Parameter Changes – Change an object's physical state, change the concentration or consistency, or change the degree of flexibility [**2**]. This principle can be used to improve the reliability of the test stand while reducing its complexity. For example, using adjustable stops in the test stand would allow for easier alignment of the cab. The principle can also be used to improve the reparability of the test stand while reducing the complexity by introducing flexible components that will not wear out as quickly as fixed components. Additionally, the principle can be used to maintain the same level of production while reducing the amount of testing medium used. For example, using sound as the testing medium instead of water removes the constraint of water supply.

38. Strong Oxidants – Replace air with oxygen-enriched air or expose air to oxygen to ionizing radiation [**2**]. This principle can be used to maintain the same level of productivity while reducing the amount of testing medium used. For example, using ionized oxygen in the cab would quickly dissipate another gas initially used for the leak test through a strong chemical reaction.

The solutions found using the TRIZ problem solving method will not be used directly, as they are meant to stimulate idea generation. Therefore, the solutions identified by TRIZ will be considered as additional brainstorming is conducted later on the in the concept generation stage, and throughout the detailed design phase.

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considered as additional brainstorming is conducted later on the in the concept generation stage, and throughout the detailed design phase.

2. References

[1] "Presentation 6 TRIZ," class notes for MECH 4860, Mechanical and Manufacturing Engineering, Univeristy of Manitoba, Fall 2015.

[2] SolidCreativity, (2014). "*The 40 TRIZ Principles,"* [Online]. Available: http://www.triz40.com/aff_Principles_TRIZ.php#&ui-state=dialog. [October 25, 2015].

Appendix C:
Internal Search Result Methodology

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List of Figures

1. External Search Results

To increase the potential ideas for this project, the team conducted external searches. Various external resources were used, such as discussions with lead users and experts, researching competitor's products, researching applicable patents/literature, and searching for applicable codes and standards. Each area that was investigated yielded unique results and considerations.

1.1 Discussions with Experts and Lead Users

In order to gain a greater understanding of how a cab is washed in the field, and what the cab seals would be subjected to, MacDon's Field Test Technician Leader, Jeffrey Leachman, was contacted. Jeff informed the group of some key points to consider during the lifecycle of the cab.

Specifically, farmers generally give the cab a quick wash when cleaning, but focus the water on the windshield and side doors. The farmer will also spray inside the windrower hood. Additionally, every windrower sold by MacDon contains a sign in the window instructing the purchaser to pressure wash it on delivery to the dealership. Pressure washing cleans any salt that has built up on the windrower during the manufacturing and shipping processes. Thus, each cab is washed thoroughly by the dealership to ensure that all salt is cleared from the cab. At this point, the cab and windrower are not attached to a header, meaning that the dealers wash the cab at close proximity with a powerful pressure washer [**1**]. Knowing how the cab is washed will help the group have a better understanding of how to test seals for leakage.

1.2 Comparable Competitor's Products

Since MacDon tests their products for leakage, the team reasoned that other agricultural companies would also test their products for leakage. Research was conducted to find competitor's methods for leak testing cabs. However, it found that most agricultural processes for waterproofing equipment are kept as trade secrets, and are not documented through patents or other means. The team decided to broaden their research to include other industries that may give public access to their waterproofing methods.

1.2.1 Automobile Industry

Leakage testing methods employed by the automobile industry were found to be applicable for this project. One method used in the past to leak test automobiles was to pressurize the vessel and submerge it in a water bath. The water bath would be monitored to see if the vessel being tested allowed bubbles to come to the surface. This method, however, is not widely used. Some automobile components may not be submerged in water, or may have leaks so small that bubbles are unable to be made due to the water's surface tension [**2**].

Another method, which automobile manufacturers are starting to avoid, is the pressure decay method. This method requires a vessel to be pressurized to some known pressure. The vessel is then monitored with a pressure sensor and the leak rate can then be calculated [**3**]. However, some automobile components are not designed to handle various higher pressures for specific durations of time, causing the industry to move away from pressure decay testing.

Another testing method is the helium leak test. The helium leak test methodology is similar to the method used in the pressure decay test, but with a small difference. Rather than measuring the pressure difference, a mass spectrometer is used to find the change in the amount of helium atoms inside the vessel. Subsequently, large amounts of helium gas are required to test vehicles. While this method is common practice for many automotive companies, many are starting to shy away from it due to its high costs of helium gas, and often unnecessarily accurate results [**2**].

1.2.2 Shipping Industry

One of the leak testing methods used in the shipping industry that stood out to the team was the use of ultrasonic testing. A generator is placed inside the vessel to be tested, and an operator scans the sealed areas using a handheld device. If a leak is detected, it will result in a blip in the ultrasonic signature shown on the device, as well as an audible signal provided to the operator [**4**].

1.3 Patents and Literature

Having discussed washing methodology with experts and lead users, and researching leakage-testing methods in other industries, the team attempted to follow up on ideas by searching various patents and literature. The United States Patent and Trademark Office was the main source for patents regarding information for vehicle leakage testing devices and procedures. Multiple applicable patents were found, and they allowed the team to think about solving the design problem for MacDon in different ways than what was originally conceived.

Design solutions originally focused on using water as the testing medium. Thus, various patents concerned with ways to wash vehicles were found, including US2950492A [**5**], CA2124310A1 [**6**] , US3961983, and US6354139 [**7**]. Fig. 1 shows art from US6354139, detailing a leakage testing setup that includes an adjustable water spraying station that is automatically controlled to function for nearly any vehicle volume.

Fig. 1. An adjustable water spraying station in US6354139 that can be automatically controlled to conduct leak tests on bodies of varying volumes [7].

US2950492 details a portable vehicle washing machine [**5**], CA2124310A1 details a vehicle washing system [**6**], and US3961983 deals with providing a method for washing interiors of truck and trailer bodies [**7**]. It was helpful for the team to look through these patents, as they showed that considerable thought has already been put into how to supply and apply water to vehicles. If water were chosen as the testing medium, these patents would allow the team to think of feasible ways to apply the water to the cab.

The team also investigated ways that other industries clean their products, in order to see if any leakage testing procedure were established. Patents relating to other industries were US8381747 [**8**], US5718382 [**9**], and US3878857 [**10**]. Fig. 2 shows art from Boeing's patent, US8381747, which details a method for washing fuselage interiors.

Fig. 2. A cutaway view of the interior of a plane fuselage, displaying the automated cleaning system claimed by The Boeing Company in US8381747 [8]

US5718382 describes an apparatus for cleaning vessels [**9**], and US3878857 describes an apparatus for cleaning tanks [**10**]. These patents were useful as they described various ways to set up cleaning apparatuses, and provided visual inspiration for future designs. These patents may be able to provide new ideas to the design team when the ideas brainstormed for locations are considered. Depending on where the cab testing system is placed at MacDon, a different testing apparatus may be required.

The previous patent searches led the team to patents concerned with waterproof testing devices and methods, such as EP2455738A2 [**11**] and US7904259 [**12**]. Fig. 3 shows the waterproof testing device described in EP2455738A2, which can supply gas or water to the product being tested [**11**].

Fig. 3. A waterproof test device as described in EP2455738A2, featuring water supplying units (30) and gas supplying unit (40) in order to check for leakages [11]**.**

EP2455738A2 outlines plans for a waterproof testing device for smaller products, such as cell phones [**11**]. However, the design idea could potentially be scaled up to a larger version to fit a cab. US7904259 details a waterproof testing method described by a flow chart, outlining steps to use to check a device for leaks by using air flow rates [**12**]. These two previously listed patents began to help the team think outside the box for additional design solutions, and not be overly fixated with only using and detecting water.

Solutions dealing with mediums other than water were found, expanding the collection of feasible solutions available to the team. Patents concerning leakage testing and methods are US7353692 [**13**], US8297109 [**14**], WO2011124611A2 [**15**], and US5398543 [**16**]. US7353692 focuses primarily on detecting leakages by measuring pressure changes [**13**], while US8297109, WO2011124611A2 and US5398543 describe a method and device used to detect leaks through the use of a tracer gas. Fig. 4 shows a sketch made for patent US8297109, showing that helium gas can be transferred to a test surface by being transported in small soap bubbles.

Fig. 4. A handheld blower device described in USE8297109 used to discharge a tracer gas in soap bubbles to various seals of interest during a leak test [14]

The above ideas found in patents allowed the team to consider gas as a viable alternative testing medium. Gas testing offers the distinct advantage of being more repeatable and yielding quantifiable results than water testing with air flow meters or mass spectrometers.

An interesting patent the team found was patent EP0260818A2 this patent uses ultrasonic detection along with an emitter to find a leak EP0260818A2 details a sound detection device and testing method [17]. Fig. 5 shows a sketch from patent EP0260818A2, showing an emitter (82) releasing sound waves towards a seal of interest that is monitored by a microphone (88), and the expected voltage spike expected if the seal is not closed.

Fig. 5. An emitter and detecting microphone (left) as described in EP0260818A2 used to detect sound level changes as compared to ambient background noise to detect a leak (right) [17].

Thus, the time spent searching patents yielded many results for the team. Firstly, ideas were generated for how to make a testing system work depending on the location. Secondly, new and alternative ways were found to apply the testing medium. Thirdly, other unique testing mediums that had been brainstormed and found in competitor's products, including gas and sound, were identified and verified as possible alternatives to water. Finally, the ideas in the patents also included model numbers and information as to where to obtain specific parts.

1.4 Applicable Standards and Codes

Having found various ways to conduct leakage tests, the team wants to ensure that the chosen process used to test the cab follows internal specifications, as well as environmental, operational, and safety standards. The team found several standards that may be applicable depending on the design chosen. These standards, as well as applicable MacDon specifications, are divided into environmental, operational, and safety sections. Each applicable standard is briefly summarized as well as discussed as to how it may be applicable to this project.

1.4.1 Environmental Standards

The team considered that if water is used to test the cab in some location other than the location containing a floor drain, provisions must be made to deal with the excess water. The following buildings codes help establish some guidelines as to how to deal with the water:

Division B: 5.6.1 Protection from Precipitation: States that where a building or component is exposed to water it must minimize the exposure and try to prevent over exposure to the precipitation. This code is invalid if the precipitation will not affect occupant's health, the intended use of the building, or the operation of the building service [**18**].

Division B: 5.6.2 Sealing, Drainage, Accumulation and Disposal: Components exposed to precipitation should be sealed to prevent penetration of said precipitation or precipitation drained to the exterior. This code is invalid if the precipitation will not affect occupant's health, the intended use of the building, or the operation of the building service [**18**].

Division B: 5.8.1 Foundation and Floor Drainage: Drainage shall be specified and installed to accommodate the drainage load [**18**].

Division B: 9.14.5 Drainage Disposal: Foundation drains shall drain to a sewer, drainage ditch or dry well [**18**].

Division B: 9.31.5 Sewage Disposal: Waste from every plumbing fixture should be drained into the public sewage system (where available). Where not available, the building shall discharge into a private disposal system [**18**].

1.4.2 Operational Standards

An operational standard was found for the proper use of pressure water jet cleaning and cutting:

ASTM E1575: Discusses operator training, pressure ranges, as well as safety concerns with pressure water jets [**19**].

1.4.3 Safety Standards

If a sound emitter option is chosen, it is important to ensure workers are adequately protected from noise. The following code from the National Building Code of Canada helps ensure that the goal of worker safety is met:

Division B: 5.9.1. Protection from Noise: Sound transmission class ratings shall be determined in accordance with:

- ASTM E 413: Classification for Rating Sound Insulation.
- ASTM E 90: Laboratory Measurement of Airborne Sound Transmission Loss of Buildings Partitions and Elements.
- ASTM E 336: Measurement of Airborne Sound Attenuation between Rooms in Buildings [**18**].

The aforementioned codes and standards will become extremely important to consider once a design is chosen at the end of phase two, and detailed design begins at the start of phase three. Having identified various applicable codes and standards will help the team stay on schedule following the conclusion of phase two.

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Appendix D:
Concept Analysis and Selection

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1. Concept Analysis Phase

Ideas from these five functional groups discussed in Appendix A during the brainstorming phase were first screened for feasibility, then scored to see which ideas were most favourable for the design problem at hand. The following sections show the screening, scoring, House of Quality, and a cost analysis of the top concepts.

1.1 Screening Matrices

Multiple screening matrices were used in order to rate ideas and integrated design concepts. TABLE I to TABLE V shows the results of the screening matrices for the ideas generated for each of the five functional groups.

TABLE I. SCREENING MATRIX FOR LOCATION

	Location										
TOP LEVEL	**Drain Vicinity**				**In the Assembly Line**					**Outside**	
Ideas	**Overtop the Drain Trenched to Drain/Grate Beside the Drain Self Contained**				**In the Cab Line In the Windrower Line Self Contained Platform End of the Cab Line End of Windrower Line**					**Shipping Yard Just Outside of Bldg 590**	
	REF										
Selection Criteria	Overtop the Drain	Trenched to Drain/Grate	Beside the Drain	Self Contained	In the Cab Line	In the Windrower Line	Self Contained Platform	End of the Cab Line	End of Windrower Line	Shipping Yard	Just Outside of Bldg 590
Footprint	0	-	-	-	+	-	-	+	+	-	-
Cost	0	-	-	-	0	0	-	0	0	-	-
Throughput	0	0	0	+	+	+	+	+	+	-	0
Usability	0	+	+	+	+	-	+	+	-	0	0
Number of Pluses	0	1	1	2	3	1	2	3	2	0	0
Number of Minuses	0	2	2	2	0	2	2	0	1	3	2
Number of Sames	4	1	1	0	1	1	0	1	1	1	2
Net	**0**	**-1**	**-1**	**0**	**3**	**-1**	**0**	**3**	**1**	**-3**	**-2**

TABLE II. SCREENING MATRIX FOR MEDIUM SUPPLY

	Medium Supply													
TOP LEVEL	**Liquid**						**Sound**					**Gas**		
Ideas	**Garden Hose Pre Filled Tank Tapping Existing Water Line Rainwater Collection Water Truck Repurified Water**						**Emitter Speaker Manual Laser Vibration**					**Pre Filled Tank Vacuum Compressor**		
	REF													
Selection Criteria	Garden Hose	Pre Filled Tank	Tapping Existing Water Line	Rainwater Collection	Water Truck	Repurified Water	Emitter	Speaker	Manual	Laser	Vibration	Pre Filled Tank	Vacuum	Compressor
Footprint	0	-	0	+	0	-	+	+	-	0	+	-	0	-
Cost	0	-	-	+	-	-	-	-	-	-	-	-	0	-
Maintenence	0	0	0	-	-	-	0	0	-	-	-	-	0	0
Throughput	0	+	+	-	0	0	+	+	+	+	+	-	+	+
Usability	0	+	+	-	-	-	-	-	-	-	-	-	+	+
Operator Safety	0	0	0	0	-	0	+	+	-	-	-	0	0	0
Number of Pluses	0	2	2	2	0	0	3	3	1	1	2	0	2	2
Number of Minuses	0	2	1	3	4	4	2	2	5	4	4	5	0	2
Number of Sames	6	2	3	1	2	2	1	1	0	1	0	1	4	2
Net	**0**	**0**	**1**	**-1**	**-4**	**-4**	**1**	**1**	**-4**	**-3**	**-2**	**-5**	**2**	**0**

TABLE III. SCREENING MATRIX FOR DELIVERY METHOD

	Delivery Method					
TOP LEVEL	Liquid			Sound	Gas	
Ideas	Garden Hose Nozzle			Through Air	Nozzle	
	Pressure Jet/Nozzle				Pressurized	
	Pump					
	Physical					
Selection Criteria	Garden Hose Nozzle	Pressure Jet/Nozzle	Pump	Through Air	Nozzle	Pressurized
Cost	0	-	-	+	-	-
Maintenence	0	0	-	+	0	0
Throughput	0	+	0	+	+	0
Usability	0	0	0	+	+	-
Operator Safety	0	0	0	-	0	-
Repeatability	0	+	+	+	+	+
Number of Pluses	0	2	1	5	3	1
Number of Minuses	0	1	2	1	1	3
Number of Sames	6	3	3	0	2	2
Net	**0**	**1**	**-1**	**4**	**2**	**-2**

TABLE IV. SCREENING MATRIX FOR DETECTION METHOD

	Detection Method											
TOP LEVEL	Liquid						Sound	Gas				
Ideas	Manual Touch						Ultra Sonic Detector	Pressure Decay				
	Foam/Bubble						Manual Hearing	Trace Gas				
	Flourescent/UV						Microphone	Visual				
	Physical Change/ Color Change						Sensor/Accelerometer	Airflow Detector				
	Chemical Reaction							Smell				
	Thermal Scan							Chemical Reaction				
	Sensor											
	REF											
Selection Criteria	Manual Touch	Foam/Bubble	Flourescent/UV	Physical Change/ Color Change	Chemical Reaction	Thermal Scan	Ultra Sonic Detector	Pressure Decay	Trace Gas	Visual	Airflow Detector	Chemical Reaction
Cost	0	0	-	-	-	-	-	-	-	0	-	-
Maintenence	0	0	0	-	-	0	0	0	0	0	0	--
Throughput	0	+	+	-	+	+	+	-	+	+	+	+
Usability	0	0	+	-	-	+	+	-	+	+	+	-
Operator Safety	0	0	0	0	-	0	0	0	0	0	0	-
Repeatability	0	+	+	+	+	+	+	+	+	+	+	+
Number of Pluses	0	2	3	1	2	3	3	1	3	3	3	2
Number of Minuses	0	0	1	4	4	1	1	3	1	0	1	3
Number of Sames	6	4	2	1	0	2	2	2	2	3	2	0
Net	**0**	**2**	**2**	**-3**	**-2**	**2**	**2**	**-2**	**2**	**3**	**2**	**-1**

TABLE V. SCREENING MATRIX FOR MEDIUM REMOVAL

	Medium Removal											
TOP LEVEL	**Liquid**						**Sound**			**Gas**		
Ideas	**Drain**						**Dampening Environment**			**Pressure**		
	Pump						**Hearing Protection**			**Purge**		
	Shop Vac						**Frequency Cancellation**			**Dilute**		
	Absorbant									**Chemical Reaction**		
	Reclamation/Repurify											
	Storage/Collection											
	REF											
Selection Criteria	Drain	Pump	Shop Vac	Absorbant	Reclamation/Repurify	Storage/Collection	Dampening Environment	Hearing Protection	Frequency Cancellation	Pressure	Dilute	Chemical Reaction
Cost	0	-	-	-	-	-	-	0	-	-	0	-
Maintenence	0	-	-	-	-	0	-	0	-	-	0	-
Throughput	0	0	-	-	0	-	0	+	0	0	0	0
Usability	0	-	-	-	-	0	0	+	-	-	0	-
Operator Safety	0	0	-	0	-	0	0	+	+	-	-	-
Efficiency	0	+	+	0	+	0	-	+	0	-	0	+
Footprint	0	-	0	0	-	-	-	+	-	-	+	0
Number of Pluses	0	1	1	0	1	0	0	5	1	0	1	1
Number of Minuses	0	4	5	4	5	3	4	0	4	6	1	4
Number of Sames	7	2	1	3	1	4	3	2	2	1	5	2
Net	**0**	**-3**	**-4**	**-4**	**-4**	**-3**	**-4**	**5**	**-3**	**-6**	**0**	**-3**

The screening matrices allowed the team to determine which ideas should be dropped, and which ideas should be kept as the design process continued. Columns in red are ideas that were deemed unfeasible and were dropped from subsequent designs.

The next stage involved screening all 202 designs that were generated by combining all feasible ideas together. TABLE VI contains the screening matrices used to screen all 202 concepts.

TABLE VI. SCREENED CONCEPTS

			Location	Over Drain
			Medium Supply	Existing Water Supply
			Delivery Supply	Garden Hose
			Detection Method	Manual Touch
		Liquid	Medium Removal	Drain
Brady	Footprint			0
	Throughput			0
	Usability			0
	Maintenance			0
	Operator Safety			0
	Repeatability			0
	Efficiency			0
Damon	Footprint			0
	Throughput			0
	Usability			0
	Maintenance			0
	Operator Safety			0
	Repeatability			0
	Efficiency			0
Kevin	Footprint			0
	Throughput			0
	Usability			0
	Maintenance			0
	Operator Safety			0
	Repeatability			0
	Efficiency			0
Matt	Footprint			0
	Throughput			0
	Usability			0
	Maintenance			0
	Operator Safety			0
	Repeatability			0
	Efficiency			0
			Plus	0
			Minus	0
			Zero	28
			Total	0
			Continue?	NA

Over Drain	Over Drain	Over Drain	Over Drain
Existing Water Supply	Existing Water Supply	Existing Water Supply	Existing Water Supply
Garden Hose	Garden Hose	Garden Hose	Garden Hose
Manual Touch	Manual Touch	Foam/Bubble	Foam/Bubble
Pump	Storage Collection	Drain	Pump
-	-	0	-
0	0	+	+
-	0	0	0
-	0	0	-
0	0	0	0
0	0	+	+
0	0	0	0
0	0	2	2
3	1	0	2
4	6	5	3
-3	-1	2	0
no	no	no	no

Over Drain	Over Drain	Over Drain	Over Drain
Existing Water Supply	Existing Water Supply	Existing Water Supply	Existing Water Supply
Garden Hose	Garden Hose	Garden Hose	Garden Hose
Foam/Bubble	Fluorescent/UV	Fluorescent/UV	Fluorescent/UV
Storage Collection	Drain	Pump	Storage Collection
-	0	-	-
+	+	+	+
0	+	+	+
0	0	-	0
0	0	0	0
+	+	+	+
0	+	+	+
2	4	4	4
1	0	2	1
4	3	1	2
1	4	2	3
no	no	no	no

Over Drain	Over Drain	Over Drain	Over Drain
Existing Water Supply	Existing Water Supply	Existing Water Supply	Existing Water Supply
Pressure Jet	Pressure Jet	Pressure Jet	Pressure Jet
Manual Touch	Manual Touch	Manual Touch	Foam/Bubble
Drain	Pump	Storage Collection	Drain
0	-	-	0
0	0	0	+
0	0	0	0
0	-	0	0
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	1
0	2	1	0
7	5	6	6
0	-2	-1	1
no	no	no	no

Over Drain	Over Drain	Over Drain	Over Drain
Existing Water Supply	Existing Water Supply	Existing Water Supply	Existing Water Supply
Pressure Jet	Pressure Jet	Pressure Jet	Pressure Jet
Foam/Bubble	Foam/Bubble	Fluorescent/UV	Fluorescent/UV
Pump	Storage Collection	Drain	Pump
-	-	0	-
+	+	+	+
0	0	+	+
-	0	0	-
0	0	0	0
0	0	+	+
0	0	+	+
1	1	4	4
2	1	0	2
4	5	3	1
-1	0	4	2
no	no	no	no

Over Drain	Over Drain	Over Drain
Existing Water Supply	Tee Into Existing Water Supply	Tee Into Existing Water Supply
Pressure Jet	Garden Hose	Garden Hose
Fluorescent/UV	Manual Touch	Manual Touch
Storage Collection	Drain	Pump
-	0	-
+	0	0
+	0	0
0	0	-
0	0	0
+	0	0
+	0	0
4	0	0
1	0	2
2	7	5
3	0	-2
no	no	no

Over Drain	Over Drain	Over Drain
Tee Into Existing Water Supply	Tee Into Existing Water Supply	Tee Into Existing Water Supply
Garden Hose	Garden Hose	Garden Hose
Manual Touch	Foam/Bubble	Foam/Bubble
Storage Collection	Drain	Pump
-	0	-
0	+	0
0	0	0
0	0	-
0	0	0
0	+	+
0	0	0
0	2	1
1	0	2
6	5	4
-1	2	-1
no	no	no

Over Drain	Over Drain	Over Drain
Tee Into Existing Water Supply	Tee Into Existing Water Supply	Tee Into Existing Water Supply
Garden Hose	Garden Hose	Garden Hose
Foam/Bubble	Fluorescent/UV	Fluorescent/UV
Storage Collection	Drain	Pump
-	0	-
+	+	+
0	+	+
0	0	-
0	0	0
+	+	+
0	+	+
2	4	4
1	0	2
4	3	1
1	4	2
no	no	no

Over Drain	Over Drain	Over Drain
Tee Into Existing Water Supply	Tee Into Existing Water Supply	Tee Into Existing Water Supply
Garden Hose	Pressure Jet	Pressure Jet
Fluorescent/UV	Manual Touch	Manual Touch
Storage Collection	Drain	Pump
-	0	-
+	0	0
+	0	0
0	0	-
0	0	0
+	0	0
+	0	0
4	0	0
1	0	2
2	7	5
3	0	-2
no	no	no

Over Drain	Over Drain	Over Drain
Tee Into Existing Water Supply	Tee Into Existing Water Supply	Tee Into Existing Water Supply
Pressure Jet	Pressure Jet	Pressure Jet
Manual Touch	Foam/Bubble	Foam/Bubble
Storage Collection	Drain	Pump
-	0	-
0	+	+
0	0	0
0	0	-
0	0	0
0	0	0
0	0	0
0	1	1
1	0	2
6	6	4
-1	1	-1
no	no	no

Over Drain	Over Drain	Over Drain
Tee Into Existing Water Supply	Tee Into Existing Water Supply	Tee Into Existing Water Supply
Pressure Jet	Pressure Jet	Pressure Jet
Foam/Bubble	Fluorescent/UV	Fluorescent/UV
Storage Collection	Drain	Pump
-	0	-
+	+	+
0	+	+
0	0	-
0	0	0
0	+	+
0	+	+
1	4	4
1	0	2
5	3	1
0	4	2
no	no	no

Over Drain	Over Drain	Over Drain	Over Drain
Tee Into Existing Water Supply	Prefilled Tank	Prefilled Tank	Prefilled Tank
Pressure Jet	Garden Hose	Garden Hose	Garden Hose
Fluorescent/UV	Manual Touch	Manual Touch	Manual Touch
Storage Collection	Drain	Pump	Storage Collection
-	0	-	-
+	0	0	0
+	0	-	0
0	0	-	0
0	0	0	0
+	0	0	0
+	0	0	0
4	0	0	0
1	0	3	1
2	7	4	6
3	0	-3	-1
no	no	no	no

Over Drain	Over Drain	Over Drain	Over Drain	Over Drain
Prefilled Tank	Prefilled Tank	Prefilled Tank	Prefilled Tank	Prefilled Tank
Garden Hose	Garden Hose	Garden Hose	Garden Hose	Garden Hose
Foam/ Bubble	Foam/ Bubble	Foam/ Bubble	Fluorescent/UV	Fluorescent/UV
Drain	Pump	Storage Collection	Drain	Pump
0	-	-	0	-
+	+	+	+	+
0	0	0	+	+
0	-	0	0	-
0	0	0	0	0
+	+	+	+	+
0	0	0	+	+
2	2	2	4	4
0	2	1	0	2
5	3	4	3	1
2	0	1	4	2
no	no	no	no	no

Over Drain	Over Drain	Over Drain	Over Drain	Over Drain
Prefilled Tank	Prefilled Tank	Prefilled Tank	Prefilled Tank	Prefilled Tank
Garden Hose	Pressure Jet	Pressure Jet	Pressure Jet	Pressure Jet
Fluorescent/UV	Manual Touch	Manual Touch	Manual Touch	Foam/Bubble
Storage Collection	Drain	Pump	Storage Collection	Drain
-	0			
+	0			
+	0			
0	0			
0	0			
+	0			
+	0			
		-	-	-
		0	0	0
		0	0	0
		-	-	-
		-	-	-
		0	0	+
		0	+	0
4	0	0	1	1
1	0	3	3	3
2	7	4	3	3
3	0	-3	-2	-2
no	no	no	no	no

Over Drain	Over Drain	Over Drain	Over Drain	Over Drain
Prefilled Tank	Prefilled Tank	Prefilled Tank	Prefilled Tank	Prefilled Tank
Pressure Jet	Pressure Jet	Pressure Jet	Pressure Jet	Pressure Jet
Foam/Bubble	Foam/Bubble	Fluorescent/UV	Fluorescent/UV	Fluorescent/UV
Pump	Storage Collection	Drain	Pump	Storage Collection
-	-	-	-	-
0	0	0	0	0
0	0	0	0	0
-	-	-	-	-
-	-	-	-	-
+	+	+	+	+
+	+	+	+	+
2	2	2	2	2
3	3	3	3	3
2	2	2	2	2
-1	-1	-1	-1	-1
no	no	no	no	no

Self Contained in Drain Area	Self Contained in Drain Area	Self Contained in Drain Area
Existing Water Supply	Existing Water Supply	Existing Water Supply
Garden Hose	Garden Hose	Garden Hose
Manual Touch	Manual Touch	Manual Touch
Drain	Pump	Storage Collection
-	-	-
-	-	-
0	0	0
-	-	-
0	0	0
0	0	0
0	+	+
0	1	1
3	3	3
4	3	3
-3	-2	-2
no	no	no

Self Contained in Drain Area	Self Contained in Drain Area	Self Contained in Drain Area
Existing Water Supply	Existing Water Supply	Existing Water Supply
Garden Hose	Garden Hose	Garden Hose
Foam/Bubble	Foam/Bubble	Foam/Bubble
Drain	Pump	Storage Collection
-	-	-
+	+	+
0	0	0
-	-	-
0	0	0
+	+	+
0	+	+
2	3	3
2	2	2
3	2	2
0	1	1
no	no	no

Self Contained in Drain Area	Self Contained in Drain Area	Self Contained in Drain Area
Existing Water Supply	Existing Water Supply	Existing Water Supply
Garden Hose	Garden Hose	Garden Hose
Fluorescent/UV	Fluorescent/UV	Fluorescent/UV
Drain	Pump	Storage Collection
-	-	-
+	+	+
0	0	0
-	-	-
0	0	0
+	+	+
0	+	+
2	3	3
2	2	2
3	2	2
0	1	1
no	no	no

Self Contained in Drain Area	Self Contained in Drain Area	Self Contained in Drain Area
Existing Water Supply	Existing Water Supply	Existing Water Supply
Pressure Jet	Pressure Jet	Pressure Jet
Manual Touch	Manual Touch	Manual Touch
Drain	Pump	Storage Collection
-	-	-
-	-	-
0	0	0
-	-	-
-	-	-
0	0	0
0	+	+
0	1	1
4	4	4
3	2	2
-4	-3	-3
no	no	no

Self Contained in Drain Area	Self Contained in Drain Area	Self Contained in Drain Area
Existing Water Supply	Existing Water Supply	Existing Water Supply
Pressure Jet	Pressure Jet	Pressure Jet
Foam/Bubble	Foam/Bubble	Foam/Bubble
Drain	Pump	Storage Collection
-	-	-
+	+	+
0	0	0
-	-	-
-	-	-
+	+	+
0	+	+
2	3	3
3	3	3
2	1	1
-1	0	0
no	no	no

Self Contained in Drain Area	Self Contained in Drain Area	Self Contained in Drain Area
Existing Water Supply	Existing Water Supply	Existing Water Supply
Pressure Jet	Pressure Jet	Pressure Jet
Fluorescent/UV	Fluorescent/UV	Fluorescent/UV
Drain	Pump	Storage Collection
-	-	-
+	+	+
0	0	0
-	-	-
-	-	-
+	+	+
0	+	+
2	3	3
3	3	3
2	1	1
-1	0	0
no	no	no

Self Contained in Drain Area	Self Contained in Drain Area	Self Contained in Drain Area
Tee Into Existing Water Supply	Tee Into Existing Water Supply	Tee Into Existing Water Supply
Garden Hose	Garden Hose	Garden Hose
Manual Touch	Manual Touch	Manual Touch
Drain	Pump	Storage Collection
-	-	-
0	0	0
+	+	+
-	-	-
0	0	0
0	0	0
+	+	+
2	2	2
2	2	2
3	3	3
0	0	0
no	no	no

Self Contained in Drain Area	Self Contained in Drain Area	Self Contained in Drain Area
Tee Into Existing Water Supply	Tee Into Existing Water Supply	Tee Into Existing Water Supply
Garden Hose	Garden Hose	Garden Hose
Foam/Bubble	Foam/Bubble	Foam/Bubble
Drain	Pump	Storage Collection
-	-	-
+	+	+
+	+	+
-	-	-
0	0	0
+	+	+
0	+	+
3	4	4
2	2	2
2	1	1
1	2	2
no	no	no

Self Contained in Drain Area	Self Contained in Drain Area	Self Contained in Drain Area
Tee Into Existing Water Supply	Tee Into Existing Water Supply	Tee Into Existing Water Supply
Garden Hose	Garden Hose	Garden Hose
Fluorescent/UV	Fluorescent/UV	Fluorescent/UV
Drain	Pump	Storage Collection
-	-	-
+	+	+
+	+	+
-	-	-
0	0	0
+	+	+
0	+	+
3	4	4
2	2	2
2	1	1
1	2	2
no	no	no

Self Contained in Drain Area	Self Contained in Drain Area	Self Contained in Drain Area
Tee Into Existing Water Supply	Tee Into Existing Water Supply	Tee Into Existing Water Supply
Pressure Jet	Pressure Jet	Pressure Jet
Manual Touch	Manual Touch	Manual Touch
Drain	Pump	Storage Collection
-	-	-
0	0	0
+	+	+
-	-	-
-	-	-
0	0	0
0	+	+
1	2	2
3	3	3
3	2	2
-2	-1	-1
no	no	no

Self Contained in Drain Area	Self Contained in Drain Area	Self Contained in Drain Area
Tee Into Existing Water Supply	Tee Into Existing Water Supply	Tee Into Existing Water Supply
Pressure Jet	Pressure Jet	Pressure Jet
Foam/Bubble	Foam/Bubble	Foam/Bubble
Drain	Pump	Storage Collection
-	-	-
+	+	+
+	+	+
-	-	-
-	-	-
0	+	+
0	+	+
2	4	4
3	3	3
2	0	0
-1	1	1
no	no	no

Self Contained in Drain Area	Self Contained in Drain Area	Self Contained in Drain Area
Tee Into Existing Water Supply	Tee Into Existing Water Supply	Tee Into Existing Water Supply
Pressure Jet	Pressure Jet	Pressure Jet
Fluorescent/UV	Fluorescent/UV	Fluorescent/UV
Drain	Pump	Storage Collection
-	-	-
+	+	+
+	+	+
-	-	-
-	-	-
+	+	+
0	+	+
3	4	4
3	3	3
1	0	0
0	1	1
no	no	no

Self Contained in Drain Area	Self Contained in Drain Area	Self Contained in Drain Area
Prefilled Tank	Prefilled Tank	Prefilled Tank
Garden Hose	Garden Hose	Garden Hose
Manual Touch	Manual Touch	Manual Touch
Drain	Pump	Storage Collection
-	-	-
0	0	0
0	0	0
-	-	-
0	0	0
0	0	0
0	+	+
0	1	1
2	2	2
5	4	4
-2	-1	-1
no	no	no

Self Contained in Drain Area	Self Contained in Drain Area	Self Contained in Drain Area
Prefilled Tank	Prefilled Tank	Prefilled Tank
Garden Hose	Garden Hose	Garden Hose
Foam/Bubble	Foam/Bubble	Foam/Bubble
Drain	Pump	Storage Collection
-	-	-
+	+	+
0	0	0
-	-	-
0	0	0
+	+	+
0	+	+
2	3	3
2	2	2
3	2	2
0	1	1
no	no	no

Self Contained in Drain Area	Self Contained in Drain Area	Self Contained in Drain Area
Prefilled Tank	Prefilled Tank	Prefilled Tank
Garden Hose	Garden Hose	Garden Hose
Fluorescent/UV	Fluorescent/UV	Fluorescent/UV
Drain	Pump	Storage Collection
-	-	-
0	0	0
0	+	+
-	-	-
0	0	0
+	+	+
-	-	-
1	2	2
3	3	3
3	2	2
-2	-1	-1
no	no	no

Self Contained in Drain Area	Self Contained in Drain Area	Self Contained in Drain Area
Prefilled Tank	Prefilled Tank	Prefilled Tank
Pressure Jet	Pressure Jet	Pressure Jet
Manual Touch	Manual Touch	Manual Touch
Drain	Pump	Storage Collection
-	-	-
+	+	0
0	0	0
-	0	-
0	0	0
-	0	0
0	0	-
1	1	0
3	1	3
3	5	4
-2	0	-3
no	no	no

Self Contained in Drain Area	Self Contained in Drain Area	Self Contained in Drain Area
Prefilled Tank	Prefilled Tank	Prefilled Tank
Pressure Jet	Pressure Jet	Pressure Jet
Foam/Bubble	Foam/Bubble	Foam/Bubble
Drain	Pump	Storage Collection
-	-	-
+	+	+
-	-	-
0	0	-
0	0	0
+	+	+
+	+	-
3	3	2
2	2	4
2	2	1
1	1	-2
no	no	no

Self Contained in Drain Area	Self Contained in Drain Area	Self Contained in Drain Area
Prefilled Tank	Prefilled Tank	Prefilled Tank
Pressure Jet	Pressure Jet	Pressure Jet
Fluorescent/UV	Fluorescent/UV	Fluorescent/UV
Drain	Pump	Storage Collection
-	-	-
+	+	+
+	+	+
0	-	0
0	0	0
+	+	+
0	0	-
3	3	3
1	2	2
3	2	2
2	1	1
no	no	no

In The Cab Line	In The Cab Line	In The Cab Line
Tee Into Existing Water Supply	Tee Into Existing Water Supply	Tee Into Existing Water Supply
Garden Hose	Garden Hose	Garden Hose
Manual Touch	Manual Touch	Foam/Bubble
Pump	Storage Collection	Pump
+	+	+
+	0	+
0	0	0
0	-	0
0	0	0
-	-	+
-	-	-
2	1	3
2	3	1
3	3	3
0	-2	2
no	no	no

In The Cab Line	In The Cab Line	In The Cab Line
Tee Into Existing Water Supply	Tee Into Existing Water Supply	Tee Into Existing Water Supply
Garden Hose	Garden Hose	Garden Hose
Foam/Bubble	Fluorescent/UV	Fluorescent/UV
Storage Collection	Pump	Storage Collection
+	+	+
+	+	+
0	0	0
-	0	-
0	0	0
+	+	+
0	-	+
3	3	4
1	1	1
3	3	2
2	2	3
no	no	no

In The Cab Line	In The Cab Line	In The Cab Line
Tee Into Existing Water Supply	Tee Into Existing Water Supply	Tee Into Existing Water Supply
Pressure Jet	Pressure Jet	Pressure Jet
Manual Touch	Manual Touch	Foam/Bubble
Pump	Storage Collection	Pump
+	+	+
0	0	+
0	0	+
0	-	0
0	0	0
0	0	+
0	0	0
1	1	4
0	1	0
6	5	3
1	0	4
no	no	no

In The Cab Line	In The Cab Line	In The Cab Line
Tee Into Existing Water Supply	Tee Into Existing Water Supply	Tee Into Existing Water Supply
Pressure Jet	Pressure Jet	Pressure Jet
Foam/Bubble	Fluorescent/UV	Fluorescent/UV
Storage Collection	Pump	Storage Collection
+	+	0
+	+	+
0	+	+
-	0	0
0	0	0
+	+	+
0	+	+
3	5	4
1	0	0
3	2	3
2	5	4
no	no	no

In The Cab Line	In The Cab Line	In The Cab Line	In The Cab Line	In The Cab Line
Prefilled Tank	Prefilled Tank	Prefilled Tank	Prefilled Tank	Prefilled Tank
Garden Hose	Garden Hose	Garden Hose	Garden Hose	Garden Hose
Manual Touch	Manual Touch	Foam/Bubble	Foam/Bubble	Fluorescent/UV
Pump	Storage Collection	Pump	Storage Collection	Pump
+	+	+	+	+
0	0	0	0	0
0	0	0	0	+
0	0	0	-	0
0	0	0	0	0
0	0	+	+	+
-	0	0	+	0
1	1	2	3	3
1	0	0	1	0
5	6	5	3	4
0	1	2	2	3
no	no	no	no	no

In The Cab Line	In The Cab Line	In The Cab Line	In The Cab Line	In The Cab Line
Prefilled Tank	Prefilled Tank	Prefilled Tank	Prefilled Tank	Prefilled Tank
Garden Hose	Pressure Jet	Pressure Jet	Pressure Jet	Pressure Jet
Fluorescent/UV	Manual Touch	Manual Touch	Foam/Bubble	Foam/Bubble
Storage Collection	Pump	Storage Collection	Pump	Storage Collection
+	+	+	+	+
0	0	0	0	0
+	0	0	0	0
-	0	-	0	-
0	0	0	0	0
+	0	0	+	+
+	-	0	+	+
4	1	1	3	3
1	1	1	0	1
2	5	5	4	3
3	0	0	3	2
no	no	no	no	no

In The Cab Line	In The Cab Line		Location	Over Drain
Prefilled Tank	Prefilled Tank		Medium Supply	Emitter
Pressure Jet	Pressure Jet		Delivery Supply	Through Air
Fluorescent/UV	Fluorescent/UV		Detection Method	Ultra Sonic Detecter
Pump	Storage Collection	**Sound**	Medium Removal	Hearing Protection
+	+			+
0	0			+
0	+			0
0	-			+
0	0			+
+	+			+
+	+			+
3	4	0	0	6
0	1	0	0	0
4	2	0	0	1
3	3	0	0	6
no	no	no	no	no

Over Drain	Self Contained In Drain Area	Self Contained In Drain Area
Emitter	Emitter	Emitter
Through Air	Through Air	Through Air
Ultra Sonic Detecter	Ultra Sonic Detecter	Ultra Sonic Detecter
Frequency Cancellation	Hearing Protection	Frequency Cancellation
+	+	+
+	+	+
0	0	0
0	+	0
-	+	-
+	+	+
-	+	-
3	6	3
2	0	2
2	1	2
1	6	1
no	no	no

In The Cab Line	In The Cab Line	End of Cab Line	End of Cab Line
Emitter	Emitter	Emitter	Emitter
Through Air	Through Air	Through Air	Through Air
Ultra Sonic Detecter	Ultra Sonic Detecter	Ultra Sonic Detecter	Ultra Sonic Detecter
Hearing Protection	Frequency Cancellation	Hearing Protection	Frequency Cancellation
+	+	+	+
+	+	+	+
0	0	0	0
+	0	+	0
+	-	+	-
+	+	+	+
+	-	+	-
6	3	6	3
0	2	0	2
1	2	1	2
6	1	6	1
no	no	no	no

End of Windrower Line	End of Windrower Line		Location	Over Drain
Emitter	Emitter		Medium Supply	Compressor
Through Air	Through Air		Delivery Supply	Nozzle
Ultra Sonic Detecter	Ultra Sonic Detecter		Detection Method	Trace Gas
Hearing Protection	Frequency Cancellation	Gas	Medium Removal	Dilute
+	+			
+	+			
0	0			
+	0			
+	-			
+	+			
+	-			
				-
				+
				0
				-
				0
				+
				+
6	3	0	0	3
0	2	0	0	2
1	2	0	0	2
6	1	0	0	1
no	no	no	no	no

Over Drain	Over Drain	Over Drain	Over Drain	Over Drain
Compressor	Compressor	Compressor	Compressor	Compressor
Nozzle	Nozzle	Nozzle	Nozzle	Nozzle
Trace Gas	Visual	Visual	Airflow Detector	Airflow Detector
Chemical Reaction	Dilute	Chemical Reaction	Dilute	Chemical Reaction
-	-	-	0	0
+	+	+	+	+
0	0	-	0	-
-	-	-	0	-
-	0	-	0	-
+	0	0	+	0
+	0	0	+	0
3	1	1	3	1
3	2	4	0	3
1	4	2	4	3
0	-1	-3	3	-2
no	no	no	no	no

Over Drain	Over Drain	Over Drain	Over Drain	Over Drain
Prefilled Tank	Prefilled Tank	Prefilled Tank	Prefilled Tank	Prefilled Tank
Nozzle	Nozzle	Nozzle	Nozzle	Nozzle
Trace Gas	Trace Gas	Visual	Visual	Airflow Detector
Dilute	Chemical Reaction	Dilute	Chemical Reaction	Dilute
0	0	0	0	0
+	-	0	0	+
0	-	-	-	0
-	0	0	0	0
-	-	-	-	0
+	+	-	-	+
0	0	-	-	-
2	1	0	0	2
2	3	4	4	1
3	3	3	3	4
0	-2	-4	-4	1
no	no	no	no	no

Over Drain	Self Contained In Drain Area	Self Contained In Drain Area
Prefilled Tank	Compressor	Compressor
Nozzle	Nozzle	Nozzle
Airflow Detector	Trace Gas	Trace Gas
Chemical Reaction	Dilute	Chemical Reaction
0	0	-
+	+	+
0	0	0
0	0	0
-	-	-
+	+	+
-	-	-
2	2	2
2	2	3
3	3	2
0	0	-1
no	no	no

Self Contained In Drain Area	Self Contained In Drain Area	Self Contained In Drain Area
Compressor	Compressor	Compressor
Nozzle	Nozzle	Nozzle
Visual	Visual	Airflow Detector
Dilute	Chemical Reaction	Dilute
-	-	-
+	+	0
-	-	0
0	0	+
0	-	0
-	-	+
-	-	+
1	1	3
4	5	1
2	1	3
-3	-4	2
no	no	no

Self Contained In Drain Area	Self Contained In Drain Area	Self Contained In Drain Area
Compressor	Prefilled Tank	Prefilled Tank
Nozzle	Nozzle	Nozzle
Airflow Detector	Trace Gas	Trace Gas
Chemical Reaction	Dilute	Chemical Reaction
-	-	-
0	0	0
-	-	-
-	-	-
-	0	0
+	+	+
0	0	0
1	1	1
4	3	3
2	3	3
-3	-2	-2
no	no	no

Self Contained In Drain Area	Self Contained In Drain Area	Self Contained In Drain Area
Prefilled Tank	Prefilled Tank	Prefilled Tank
Nozzle	Nozzle	Nozzle
Visual	Visual	Airflow Detector
Dilute	Chemical Reaction	Dilute
-	-	-
-	-	0
+	-	+
-	-	-
0	-	0
-	-	+
0	0	0
1	0	2
4	6	2
2	1	3
-3	-6	0
no	no	no

Self Contained In Drain Area	In The Cab Line	In The Cab Line	In The Cab Line
Prefilled Tank	Compressor	Compressor	Compressor
Nozzle	Nozzle	Nozzle	Nozzle
Airflow Detector	Trace Gas	Trace Gas	Visual
Chemical Reaction	Dilute	Chemical Reaction	Dilute
-	+	+	+
0	+	+	0
-	0	-	0
-	0	0	0
-	0	-	0
+	+	+	-
0	+	-	-
1	4	3	1
4	0	3	2
2	3	1	4
-3	4	0	-1
no	no	no	no

In The Cab Line	In The Cab Line	In The Cab Line	In The Cab Line
Compressor	Compressor	Compressor	Prefilled Tank
Nozzle	Nozzle	Nozzle	Nozzle
Visual	Airflow Detector	Airflow Detector	Trace Gas
Chemical Reaction	Dilute	Chemical Reaction	Dilute
+	+	+	+
0	+	+	+
-	0	-	0
-	0	-	-
-	0	-	-
-	+	+	+
-	+	-	+
1	4	3	4
5	0	4	2
1	3	0	1
-4	4	-1	2
no	no	no	no

In The Cab Line	In The Cab Line	In The Cab Line	In The Cab Line
Prefilled Tank	Prefilled Tank	Prefilled Tank	Prefilled Tank
Nozzle	Nozzle	Nozzle	Nozzle
Trace Gas	Visual	Visual	Airflow Detector
Chemical Reaction	Dilute	Chemical Reaction	Dilute
+	+	+	+
+	0	0	+
-	0	-	0
-	-	-	-
-	-	-	-
+	-	-	+
-	-	-	+
3	1	1	4
4	4	5	2
0	2	1	1
-1	-3	-4	2
no	no	no	no

In The Cab Line	End of Cab Line	End of Cab Line	End of Cab Line
Prefilled Tank	Compressor	Compressor	Compressor
Nozzle	Nozzle	Nozzle	Nozzle
Airflow Detector	Trace Gas	Trace Gas	Visual
Chemical Reaction	Dilute	Chemical Reaction	Dilute
+	+	+	+
+	+	+	0
-	0	-	0
-	0	-	0
-	0	-	0
+	+	+	-
-	+	-	-
3	4	3	1
4	0	4	2
0	3	0	4
-1	4	-1	-1
no	no	no	no

End of Cab Line	End of Cab Line	End of Cab Line	End of Cab Line
Compressor	Compressor	Compressor	Prefilled Tank
Nozzle	Nozzle	Nozzle	Nozzle
Visual	Airflow Detector	Airflow Detector	Trace Gas
Chemical Reaction	Dilute	Chemical Reaction	Dilute
+	+	+	+
0	+	+	+
-	0	-	0
-	0	-	-
-	0	-	-
-	+	+	+
-	+	-	+
1	4	3	4
5	0	4	2
1	3	0	1
-4	4	-1	2
no	no	no	no

End of Cab Line	End of Cab Line	End of Cab Line	End of Cab Line
Prefilled Tank	Prefilled Tank	Prefilled Tank	Prefilled Tank
Nozzle	Nozzle	Nozzle	Nozzle
Trace Gas	Visual	Visual	Airflow Detector
Chemical Reaction	Dilute	Chemical Reaction	Dilute
+	+	+	+
+	0	0	+
-	0	-	0
-	-	-	0
-	-	-	-
+	-	-	+
-	-	-	+
3	1	1	4
4	4	5	1
0	2	1	2
-1	-3	-4	3
no	no	no	no

End of Cab Line	End of Windrower Line	End of Windrower Line	End of Windrower Line
Prefilled Tank	Compressor	Compressor	Compressor
Nozzle	Nozzle	Nozzle	Nozzle
Airflow Detector	Trace Gas	Trace Gas	Visual
Chemical Reaction	Dilute	Chemical Reaction	Dilute
+	+	+	+
+	+	+	0
-	0	-	0
-	0	-	0
-	0	-	0
+	+	+	-
-	+	-	-
3	4	3	1
4	0	4	2
0	3	0	4
-1	4	-1	-1
no	no	no	no

End of Windrower Line	End of Windrower Line	End of Windrower Line	End of Windrower Line
Compressor	Compressor	Compressor	Prefilled Tank
Nozzle	Nozzle	Nozzle	Nozzle
Visual	Airflow Detector	Airflow Detector	Trace Gas
Chemical Reaction	Dilute	Chemical Reaction	Dilute
+	+	+	+
0	+	+	+
-	0	-	0
-	0	-	0
-	0	-	-
-	+	+	+
-	+	-	+
1	4	3	4
5	0	4	1
1	3	0	2
-4	4	-1	3
no	no	no	no

End of Windrower Line	End of Windrower Line	End of Windrower Line	End of Windrower Line
Prefilled Tank	Prefilled Tank	Prefilled Tank	Prefilled Tank
Nozzle	Nozzle	Nozzle	Nozzle
Trace Gas	Visual	Visual	Airflow Detector
Chemical Reaction	Dilute	Chemical Reaction	Dilute
+	+	+	+
+	0	0	+
-	0	-	0
-	0	-	0
-	-	-	-
+	-	-	+
-	-	-	+
3	1	1	4
4	3	5	1
0	3	1	2
-1	-2	-4	3
no	no	no	no

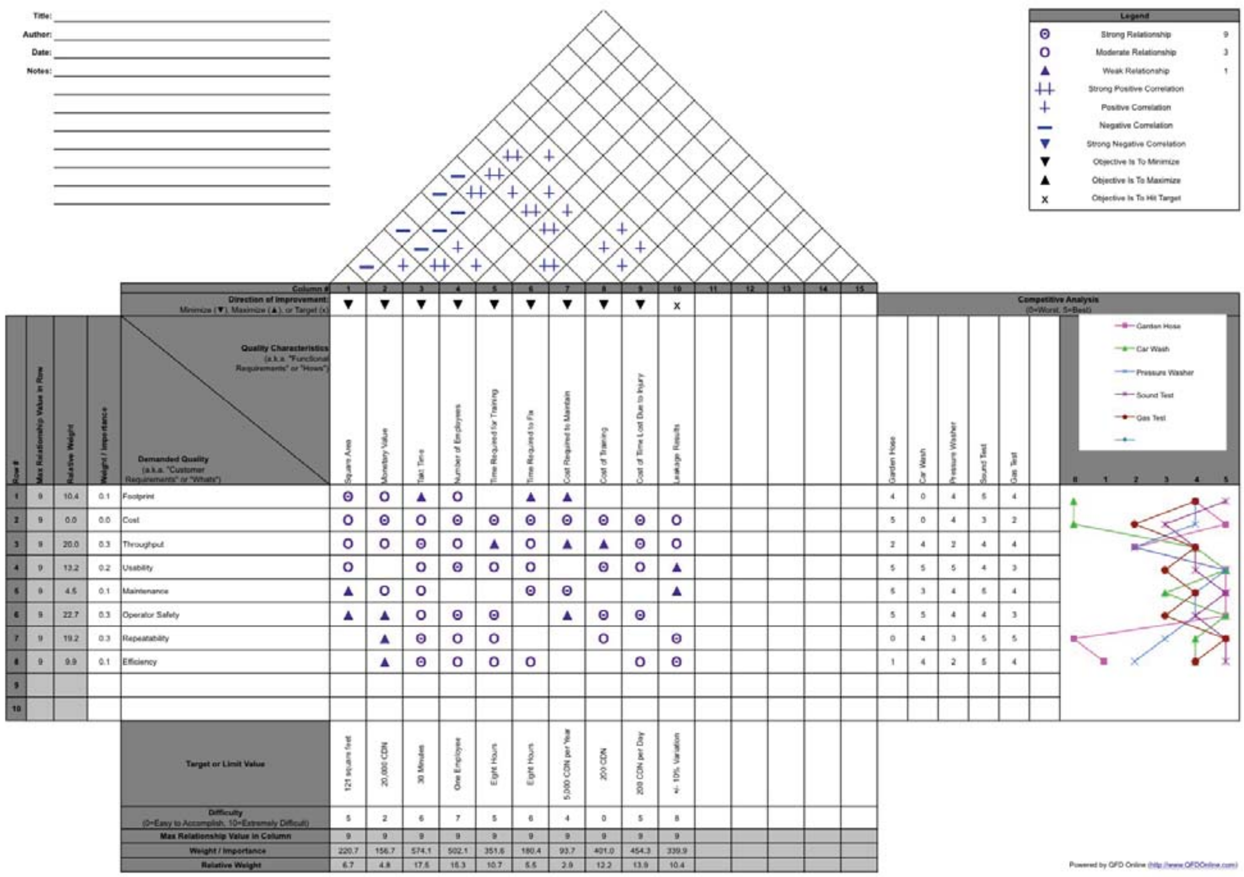
End of Windrower Line
Prefilled Tank
Nozzle
Airflow Detector
Chemical Reaction
+
+
-
-
-
+
-
3
4
0
-1
no

The 202 concepts were ranked, and the top 18 designs were selected to move on to the next phase of concept scoring. After checking the top designs for feasibility and redundancies, the top 18 designs were reduced to seven potential concepts, ready to be scored.

1.2 House of Quality

A House of Quality was created in order to find relative weights for the selection criteria metrics once ideas were merged into full designs. The House of Quality considers the relationships between metrics, and assigned relative weights for each selection criteria as shown in TABLE VII.

TABLE VII. HOUSE OF QUALITY



Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	1 Square Area	2 Monetary Value	3 Takt Time	4 Number of Employees	5 Time Required for Training	6 Time Required to Fix	7 Cost Required to Maintain	8 Cost of Training	9 Cost of Time Lost Due to Injury	10 Leakage Results	11	12	13	14	15	Garden Hose	Car Wash	Pressure Washer	Sound Test	Gas Test
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▼	▼	▼	▼	▼	▼	▼	▼	▼	x										
1	9	10.4	0.1	Footprint	Θ	O	▲	O		▲	▲									4	0	4	5	4
2	9	0.0	0.0	Cost	O	Θ	O	Θ	Θ	Θ	Θ	Θ	Θ	O						5	0	4	3	2
3	9	20.0	0.3	Throughput	O	O	Θ	O	▲	O	▲	▲	Θ	O						2	4	2	4	4
4	9	13.2	0.2	Usability	O		O	Θ	O	O		Θ	O	▲						5	5	5	4	3
5	9	4.5	0.1	Maintenance	▲	O	O			Θ	Θ			▲						5	3	4	5	4
6	9	22.7	0.3	Operator Safety	▲	▲	O	Θ	Θ		▲	Θ	Θ							5	5	4	4	3
7	9	19.2	0.3	Repeatability		▲	Θ	O	O			O		Θ						0	4	3	5	5
8	9	9.9	0.1	Efficiency		▲	Θ	O	O	O			O	Θ						1	4	2	5	4
9																								
10																								
				Target or Limit Value	121 square feet	20,000 CDN	30 Minutes	One Employee	Eight Hours	Eight Hours	5,000 CDN per Year	200 CDN	200 CDN per Day	+/- 10% Variation										
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	5	2	6	7	5	6	4	0	5	8										
				Max Relationship Value in Column	9	9	9	9	9	9	9	9	9	9										
				Weight / Importance	220.7	156.7	574.1	502.1	351.6	180.4	93.7	401.0	454.3	339.9										
				Relative Weight	6.7	4.8	17.6	16.3	10.7	5.6	2.9	12.2	13.9	10.4										

The house of quality shows the various interdependencies between metrics and gave relative weights for designs that are composed of ideas from each functional group (left). The relationships between metrics are shown (middle), and competitor's products are rated for effectiveness (right).

Multiple rounds of concept screening were required to reduce the amount of designs the team dealt with. Once all brainstormed ideas were listed, they were manually screened for feasibility. If the team felt that a certain idea would be unachievable, it was dropped from further consideration. Each idea that passed initial feasibility screening was then ranked against the other ideas in a screening matrix. TABLE VIII shows the screening matrix used for screening delivery method ideas.

TABLE VIII. SCREENING MATRIX, DELIVERY METHOD

	Delivery Method						
	Liquid				Sound	Gas	
Ideas	Garden Hose Nozzle	Pressure Jet/Nozzle	Pump	Physical	Through Air	Nozzle	Pressurized
Cost	0	-	X	X	+	-	-
Maintenance	0	0	X	X	+	0	0
Throughput	0	+	X	X	+	+	0
Usability	0	0	X	X	+	+	-
Operator Safety	0	0	X	X	-	0	-
Reliability	0	+	X	X	+	+	+
Number of Pluses	0	2			5	3	1
Number of Minuses	0	1			1	1	3
Number of Same	6	3			0	2	2
Net	0	1			4	2	-2

A similar screening table was constructed for each functional group in order to identify the best ideas. The highest scoring idea was delivering sound through the air, while the use of a pump and manual application of water were dropped due to being unfeasible.

Ideas that scored highly were kept for the next phase of the design process. Some example ideas that scored highly include locating the testing system in the cab line, using a compressor to supply gas, delivering gas to the cab by using a nozzle, detecting sound by using an ultra sonic detector, and removing water by using a drain. Each idea that was kept from this screening stage was added to other ideas from the other functional groups to create the 202 preliminary concepts. Out of the 202 design ideas that were considered, 132 were liquid, ten were sound, and 60 were gas ideas.

The next round of screening matrices was done on these 202 concepts. Since the ideas had been synthesized into full concepts, each selection criteria was included, as each one would impact the effectiveness of the overall design. TABLE IX contains three screen examples from the 202 concepts.

TABLE IX. SCREENING MATRIX, OVERALL DESIGNS

Medium					Selection Criteria						
Location	**Medium Supply**	**Delivery Supply**	**Detection Method**	**Medium Removal**	**Footprint**	**Throughput**	**Usability**	**Maintenance**	**Operator Safety**	**Repeatability**	**Efficiency**
		Liquid									
Over Drain	Existing Water Supply	Pressure Jet	Fluorescent/ UV	Drain	0	+	+	0	0	+	+
		Sound									
In Cab Line	Emitter	Through Air	Ultrasonic Detector	Hearing Protection	+	+	0	+	+	+	+
		Gas									
In Cab Line	Compressor	Nozzle	Trace Gas	Dilute	+	+	0	0	0	+	+

Each team member took 50 designs, and ranked them according to the second screening matrix as shown in TABLE IX. In order to reduce the number of designs to a manageable amount, only the top ideas from each medium category were chosen to continue to the next phase of being scored. At the end of the second round of screening, there were seven top scoring ideas from liquid, five top scoring ideas from sound, and six top scoring ideas from gas, giving a total of 18 total options.

The 18 final concepts were then analyzed to see if they could be reduced further if the designs were mostly similar. For example, if one design took place “in the cab line” as opposed to “at the end of the cab line, the ideas were merged. By searching for close similarities manually, the final design count was reduced from 18 options to seven options. The final design options are included in TABLE X.

TABLE X. TOP DESIGN CONCEPTS FOLLOWING SECOND ROUND OF SCREENING

Location	Medium Supply	Delivery Method	Detection Method	Medium Removal
Over Drain	Existing/Tee Into	Pressure Jet/Garden Hose	Fluorescent/UV	Drain
Over Drain	Prefilled Tank	Pressure Jet/Garden Hose	Fluorescent/UV	Drain
In Cab Line	Existing/Tee Into	Pressure Jet/Garden Hose	Foam/Bubble	Pump
In Cab Line	Existing/Tee Into	Pressure Jet/Garden Hose	Fluorescent/UV	Pump
In Cab Line	Existing/Tee Into	Pressure Jet/Garden Hose	Fluorescent/UV	Storage
Any	Emitter	Through Air	Ultrasonic Detection	Hearing Protection
Any	Compressor	Nozzle	Airflow Detector	Dilute

In order to score the designs, weights were required for the selection criteria. In order to determine weights, each criterion was analyzed directly against another criterion during the concept screening phase for each functional group. TABLE XI shows the metric weighting matrix for the delivery method functional group.

TABLE XI. METRIC WEIGHTING MATRIX, DELIVERY METHOD

Selection Criteria		Cost	Maintenance	Throughput	Usability	Operator Safety	Repeatability
		A	B	C	D	E	F
Cost	A	X	B	C	D	E	F
Maintenance	B		X	C	D	E	F
Throughput	C			X	C	E	F
Usability	D				X	E	F
Operator Safety	E					X	F
Repeatability	F						X
Metric Amount		0	1	3	2	5	4
Total Amount		15	15	15	15	15	15
Weight		0.00	0.07	0.20	0.13	0.33	0.27

It should be noted that the cost metric received a weight of zero. This weight was due to the fact that the team's initial concept brainstorming predicted that designs would be well within the budget of $20,000. Compared to the difficulty of ensuring a design is within budget compared to throughput for example, cost lost every time. This special consideration was described to the MacDon team who agreed that the cost metric could be removed, as the team is confident the cost limit will be much higher than the cost required.

Similar tables were made for each functional group. The results of the weighting matrices were then averaged, as there were five functional groups. However, in order to understand how the metrics related to each other once the brainstormed ideas were integrated, a higher level tool was required. The House of Quality shown in created in TABLE VII order to find how each metric related to each other, the House of Quality considers the relationships between metrics, and assigned relative weights for each selection criteria.

The house of quality shows the various interdependencies between metrics and gave relative weights for designs that are composed of ideas from each functional group (left). The relationships between metrics are shown (middle), and competitor's products are rated for effectiveness (right).

TABLE XII shows the weight of the selection criteria when considering their interrelationships within a House of Quality.

TABLE XII. RELATIVE METRIC WEIGHTINGS CONSIDERING RELATIONSHIPS VIA HOUSE OF QUALITY

Customer Wants (Selection Criteria)	Max Relationship Value in Row	Calculated Average Weight	Relative Weight Considering Metric Relationships
Footprint	9	0.1	10.4
Cost	9	0.0	0.0
Throughput	9	0.3	20.0
Usability	9	0.2	13.2
Maintenance	9	0.1	4.5
Operator Safety	9	0.3	22.7
Repeatability	9	0.3	19.2
Efficiency	9	0.1	9.9
Total		1.4	100.0

The House of Quality was a critical step in being able to score the designs against each other. Due to the use of five functional groups, the averaged values for each metric did not total to 1 but rather 1.4/1. The House of Quality allowed the metrics to be normalized to a portion of 100%, and were subsequently used to score the designs where all the concepts were integrated together. The weighted metrics were also reviewed during the conceptual design meeting at MacDon on October 27. The MacDon team agreed upon the weightings assigned for all metrics.

1.3 Metric Weighting Matrices

Metrics were also weighted for each functional group. The results of the metric weighting matrices are shown in TABLE XIII to TABLE XVII.

TABLE XIII. METRIC WEIGHTING MATRIX FOR LOCATION

Selection Criteria		Footprint	Cost	Throughput	Usability
		a	b	c	d
Footprint	a	x	a	c	d
Cost	b		x	c	d
Throughput	d			x	c
Usability	e				x
metric amount		1	0	3	2
total amount		6	6	6	6
weight		0.17	0.00	0.50	0.33

TABLE XIV. METRIC WEIGHTING MATRIX FOR MEDIUM SUPPLY

Selection Criteria		Footprint	Cost	Maintenence	Throughput	Usability	Operator Safety
		a	b	c	d	e	f
Footprint	a	x	a	a	d	e	f
Cost	b		x	c	d	e	f
Maintenence	c			x	d	e	f
Throughput	d				x	d	f
Usability	e					x	f
Operator Safety	f						x
metric amount		2	0	1	4	3	5
total amount		15	15	15	15	15	15
weight		0.13	0.00	0.07	0.27	0.20	0.33

TABLE XV. METRIC WEIGHTING MATRIX FOR DELIVERY METHOD

Selection Criteria		Cost	Maintenence	Throughput	Usability	Operator Safety	Repeatability
		a	b	c	d	e	f
Cost	a	x	b	c	d	e	f
Maintenence	b		x	c	d	e	f
Throughput	c			x	c	e	f
Usability	d				x	e	f
Operator Safety	e					x	e
Repeatability	f						x
metric amount		0	1	3	2	5	4
total amount		15	15	15	15	15	15
weight		0.00	0.07	0.20	0.13	0.33	0.27

TABLE XVI. METRIC WEIGHTING MATRIX FOR DETECTION METHOD

Selection Criteria		Cost	Maintenence	Throughput	Usability	Operator Safety	Repeatability
		a	b	c	d	e	f
Cost	a	x	b	c	d	e	f
Maintenence	b		x	c	d	e	f
Throughput	c			x	c	e	f
Usability	d				x	e	f
Operator Safety	e					x	e
Repeatability	f						x
metric amount		0	1	3	2	5	4
total amount		15	15	15	15	15	15
weight		0.00	0.07	0.20	0.13	0.33	0.27

TABLE XVII. METRIC WEIGHTING MATRIX FOR MEDIUM REMOVAL

Selection Criteria		Cost	Maintenence	Throughput	Usability	Operator Safety	Efficiency	Footprint
		a	b	c	d	e	f	g
Cost	a	x	b	c	d	e	f	g
Maintenence	b		x	c	d	e	f	g
Throughput	c			x	c	e	c	c
Usability	d				x	e	f	d
Operator Safety	e					x	e	e
Efficiency	f						x	g
Footprint	g							x
metric amount		0	1	5	3	6	3	3
total amount		21	21	21	21	21	21	21
weight		0.00	0.05	0.24	0.14	0.29	0.14	0.14

The metric scoring matrices for each functional group helped the team understand how the metrics varied in importance from group to group. Additionally, it allowed important metrics to be identified (such as throughput).

1.4 Scoring Matrices

After all ideas were fused, 202 total concepts were created. After the top ideas were checked for redundancies and similar ideas were merged, seven top ideas remained to be scored. The ideas were scored as shown in TABLE XVIII.

TABLE XVIII. SCORED CONCEPTS

		Concepts															
Selection Criteria	**Weight**	**o, Pressure Jet/Garden H**		**, Pressure Jet/Garden Ho**		**g, Pressure Jet/Garden H**		**g, Pressure Jet/Garden H**		**, Pressure Jet/Garden Ho**		**Air, Ultrasonic Detectio**		**ssor, Nozzle, Airflow Det**		**essure Jet/Garden Hose,**	
		Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Footprint	10.4	4	41.6	3	31.2	4	41.6	4	41.6	2	20.8	5	52	5	52		0
Throughput	20	2	40	3	60	4	80	4	80	4	80	5	100	5	100		0
Usability	13.2	3	39.6	3	39.6	2	26.4	3	39.6	4	52.8	4	52.8	2	26.4		0
Maintenance	4.5	4	18	2	9	3	13.5	1	4.5	2	9	5	22.5	4	18		0
Operator Safety	22.7	3	68.1	3	68.1	3	68.1	3	68.1	3	68.1	5	113.5	4	90.8		0
Repeatability	19.2	2	38.4	2	38.4	2	38.4	2	38.4	2	38.4	5	96	3	57.6		0
Efficiency	9.9	2	19.8	1	9.9	1	9.9	3	29.7	3	29.7	5	49.5	2	19.8		0
Total	**99.9**		**265.5**		**256.2**		**277.9**		301.9		298.8		486.3		364.6		

Thus, it was found that the ultrasonic design concept scored the highest, with a value of 486.3, followed by the gas concept with a value of 364.6. Two water designs scored similarly, at 301.9 and 298.8. Due to a large gap between considered scores, a sensitivity analysis is not required.

The team again reviewed the designs from a feasibility standpoint. The water designs and sound design were feasible, and the products required to create the designs exist. However, when the team reconsidered the gas design, concerns were raised regarding the feasibility. Specifically, the design requires two employees working in tandem. The first employee would direct the compressed air to the cab seals. A second employee would be stationed inside of the cab with the airflow meter, attempting to follow the outer employee’s spray path. The repeatability was realized to be low and the results unreliable, as it would be difficult for the employee on the inside to follow the spray path exactly and monitor the airflow simultaneously. While the airflow meter itself is quite accurate, the method imagined for collecting data seemed unreliable. Thus, the gas design was dropped at this stage of the design process.

The three remaining highest scoring concepts will continue to the next phase (CAD modeling) in order to supply MacDon with design ideas using each of the mediums considered (liquid and sound). Additionally, the feedback received from MacDon will be extremely important. The client will provide their insight as to which design they feel the team should pursue for detailed design.

1.5 Concept Recommendations

The three designs were distributed among the team in order to create CAD models to review with Sean and Ed to get their input. The designs were fairly basic following the scoring stage, but detailed enough to be able to get an understanding of the space required, and the overall physical details required to implement the design.

1.5.1 Storage Tank Teed Into Existing Water Line

The first design idea that scored 298.8 was to use a station placed in the cab line, with water provided from the existing pipes, applied by a pressure washer, analyzed for leaks with fluorescent/UV detection equipment, and drained to a storage tank. A possible embodiment of this design is shown in Fig. 1.

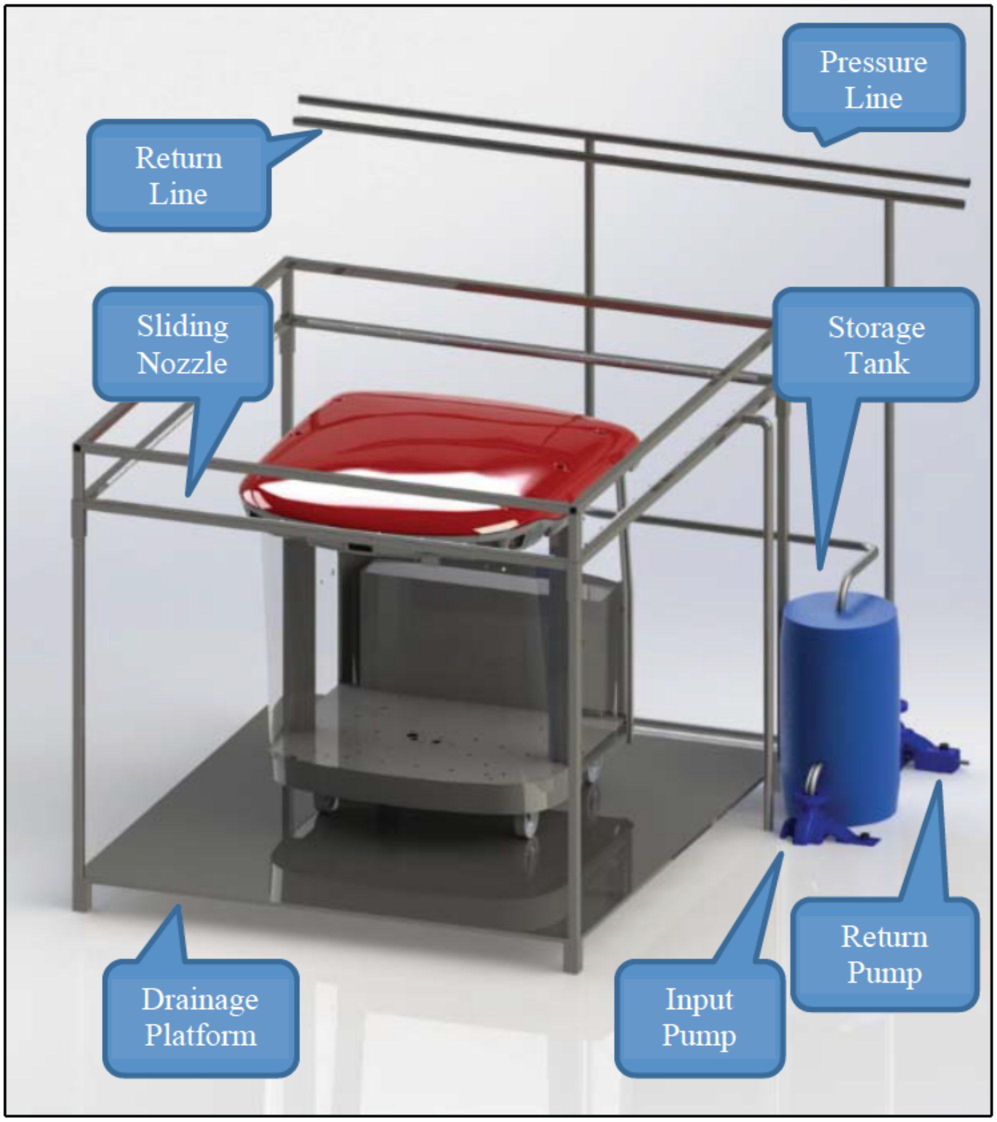


Fig. 1. A basic CAD model of the storage tank design idea, highlighting the use of existing pipes to supply the pressure and return flows, the windrower cab placed on a draining platform, a storage tank to collect water and apply additional pressure/fluorescent tracer to the water before being pump to the return line (shielding would be required in order to contain sprayed water).

Allowing the storage tank to use the existing pipe network provides additional pressure to a handheld pressure washer as well as an area to add the fluorescent tracer. The water would be applied to the cab seals automatically via the sliding nozzle assembly, replicating the method a farmer or dealer would use during cleaning.

Added to the water flow would be a fluorescent tracer, such as Rhodamine WT [1]. A fluorometer that emits a green light (such as the Turner Designs 10-AU Fluorometer) could be used after application in order to find leaks in the cab interior. Any area that turns red shows the fluorescent tracer has leaked through the seal. The fluorometer Turner Designs provides is portable and accurate, allowing the test to be conducted in the cab line and without large quantities of water [1]

The cab is placed on a platform that allows sprayed water to drain to a storage tank located below. A pump is used to remove water from the storage tank and back into the return pipeline. Diluted fluorescent additives can be safely disposed [1].

The shielding required to prevent water from spraying away from the testing area is not pictured. Shielding could easily be custom made on sight at MacDon by using creform tubing and plastic weld shields, used in their lean manufacturing initiatives. Shielding would be lightweight, and easily oriented around the cab.

1.5.2 Pump Drainage System Teed Into Existing Water Line

The other highly scoring water concept was similar to the previous water concept, with the exception that the water is not stored in a tank. Instead, the water that is used is simply pumped away to a drain rather than being kept for additional pressure, as shown in Fig. 2.

Fig. 2. A basic CAD model of the storage tank design idea, highlighting the use of existing pipes to supply the pressure and return flows, the windrower cab placed on a draining platform, and a pump to drain used water (shielding would be required in order to contain sprayed water).

The pump design is similar to the storage tank design, in that it would require a fluorescent tracer applied at some point in the water flow. However, rather than collected water to use for additional pressure, the water would simply be pumped away when used. This design would require less maintenance than the tank design, and therefore scored marginally higher.

The water designs were also reviewed on site with the client. The MacDon team was interested in simpler designs that have a high value for the required construction cost. Of the possible water designs, the MacDon team chose the vertical sliding wash system with a storage tank to be the fall back idea if ultrasonic was unsuccessful. The storage tank idea was chosen over the pump idea as it allows the fluorescent dye to be mixed with the water in a contained area.

1.6 Simplified Technical Analysis for Conceptual Designs

With three top designs found and modelled to a simple representative point, additional analyses could be conducted. The simplified technical analysis deals with the manufacturability of the chosen designs and includes considerations for how such designs would be fabricated.

The manufacturing process has been limited to products that are readily available or purchasable through suppliers commonly used by the Tool & Die Department at MacDon Industries. Examples of readily available products include 2” x 2” square tubing, 3” x 3” square tubing, and high-strength low-alloy (HSLA) steel sheets in gauge/thickness 20, 18, 16, 14, 11, 7, 1/4”, 5/16”, 3/8”, 1/2”, and 3/4". Various imperial hardware is also readily available, including threaded fasteners, flat washers, lock washers, hex nuts, lock nuts, flange nuts, jam nuts, slotted nuts, hex head cap screws, bolts, and dowel pins.

The Tool & Die Department at MacDon will be involved in the manufacturing of the leak test apparatus structure in the future. Therefore, the manufacturing methods available for the production of the design structure will be focused on methods within the means of the Tool & Die Department. Such methods available include laser cutting, forming, sawing, computer numerical controlled (CNC) milling, drilling, reaming, countersinking, tapping, buffing, metal inert gas (MIG) welding, adhesive bonding, fastening, riveting, and press fitting.

The Maintenance Department at MacDon will be installing required water lines as necessary to supply the leak test apparatus with a constant water supply. Furthermore, the Maintenance Department will be tasked with the installation of programmable logic controllers (PLCs), water pipes, pumps, valves, hoses, manifolds, and nozzles. Connections between pumps, valves, hoses, manifolds, and nozzles will use threaded fittings that are appropriately rated for the operating water pressure. All connections between water pipes will be soldered to ensure a strong mechanical leak proof connection.

1.7 Simplified Cost Analysis

With a basic idea of the structures required for each design, rough cost estimates could be conducted. The first selected design concept (water application with storage tank) was analysed to approximate the overall cost to implement the design. TABLE XIX displays an in-depth list of required products to build the design.

TABLE XIX COST ESTIMATE FOR SLIDING WATER NOZZLE FRAME CONCEPT (WITH WATER STORAGE)

While still a rough estimate, the cost analysis shows a final design cost of . This amount is within our allotted budget of $20,000, but the team should be careful to ensure that bulk pricing or other methods be used to ensure that the cost of the design does not increase.

The second chosen design (water application with pump) was similar to the first design, but without the addition of a vertical water storage tank, and one less water pump. The required individual items for the second design and the overall cost of the design are shown in TABLE XX.

TABLE XX. COST ESTIMATE FOR SLIDING WATER NOZZLE FRAME CONCEPT (NO WATER STORAGE)

The cost for the second design is lower than the first by approximately $3000 due to the fact that the water storage tank and additional pump have been removed. However, the team must still be careful with this design moving forwards in order to ensure that no additional costs are incurred that could potentially push the price over the limit.

The third chosen design was the ultrasonic emitter and receiver design. The overall cost of the ultrasonic design was limited to the cost to purchase the ultrasonic testing kit, and the cost of training the operators how to use the device, as seen in TABLE XXI.

TABLE XXI. COST ESTIMATE FOR ULTRASONIC EMITTER AND RECEIVER DESIGN

Compared to the previous two designs, the ultrasonic design is much lower in terms of cost. The simplicity of the design allows it to be implemented without a high cost, and is unlikely to pass the budget at any point.

2. References

[1] Turner Designs. (2015). *"Fluorescent Dye Tracing-Flurometer Applications*" [Online]. Available: http://www.turnerdesigns.com/applications/fluorescent-dye-tracing-application-notes (November 15, 2015).

[2] S. Hakansson (Private Communication), Oct. 15 2015.

[3] Mcmaster-Carr. (2014) "*Stainless Steel Spray Manifold"* [Online]. Available: http://www.mcmaster.com/#2491k62/=zl3woa [October 26, 2015].

[4] Mcmaster-Carr. (2014) "*Flat Spray Nozzle"* [Online]. Available: http://www.mcmaster.com/#3404k36/=zl3y72 [October 26, 2015].

[5] Mcmaster-Carr. (2014) "*Pressure-Washer Hose*" [Online]. Available: http://www.mcmaster.com/#53115k45/=zl466l [October 26, 2015].

[6] Mcmaster-Carr. (2014) "*Parallel Shaft DC Gearmotor*" [Online]. Available: http://www.mcmaster.com/#6470k61/=zl3yqb [October 26, 2015].

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[8] Mcmaster-Carr. (2014) "*Sump Pump for Water*" [Online]. Available: http://www.mcmaster.com/#9989k62/=zl4083 [October 26, 2015].

[9] Mcmaster-Carr. (2014) "*Premium Brass Solenoid Valve*" [Online]. Available: http://www.mcmaster.com/#2660k14/=zl4108 [October 26, 2015].

[10] Mcmaster-Carr. (2014) "*Type 303 Stainless Steel Manifold*" [Online]. Avaliable: http://www.mcmaster.com/#4839k723/=zl41sa [October 26, 2015].

[11] Mcmaster-Carr. (2014) "*High-Efficiency Pump for Water and Coolants*" [Online]. Available: http://www.mcmaster.com/#9923k46/=zl42u9 [October 26, 2015].

[12] Mcmaster-Carr. (2014) "*Steel Vertical Tank with Forklift Entry*" [Online]. Available: http://www.mcmaster.com/#3683k11/=zl449q [October 26, 2015].

Appendix E:
Quotes

Table of Contents

List of Figures

1. Quotes from Ultrasonic Detector Manufacturers

The team sought out various manufacturers of ultrasonic detectors and were provided quotes by the companies. These quotes are shown below from Fig. 1 to Fig. 6.

Bacharach of Canada
20 Amber Street Unit #7
Markham, ON L3R 5P4
Canada
Tel: (905) 470-8985
Fax: (905) 470-8963
support@bachcan.ca

Quote
11257

Date:09-Nov-2015

Page 1 of 1

Bill To:

MDKB Consulting
WINNIPEG, MB CANADA

Attention: Brady Kallert

Ship To:

MDKB Consulting
WINNIPEG, MB CANADA

Ship Contact: Brady Kallert
Ship Fax:
Ship Phone:

Quote	Ship Via	Terms	Purchase Order	Salesperson	Customer ID
11257	N/A	Credit Card	N/A		MDKBCON

Product Code	Product Name	Quantity	UOM	Unit Price	Total
0028-8012	**Tru Pointe® 1100 Ultrasonic Leak Det. Kit w/SoundBlaster®**	1	EACH		
0028-8013	**Tru Pointe® 2100 Ultrasonic Leak Det. Kit w/SoundBlaster®**	1	EACH		
NOTES	Approx: 2- 3 weeks for delivery	0	EACH		

Total CA

Plus Applicable Taxes and Shipping

Prices are good for 30 days from date of issue.

Total does not include applicable taxes and shipping.

Please reference the quote number when ordering.

Fig. 1. Quote for two different ultrasonic detectors with emitters from Bacharach [1].

11/28/2015 Gmail - Ultrasonic leak detection

Gmail by Google

Brady Kallert

Ultrasonic leak detection

AA-AS inquiry (AA-AS/TSS2-NA) <inquiry@service-solutions.com> Mon, Nov 9, 2015 at 8:40 AM
To: Brady Kallert

Hello Brady,

Part 16451 (Sound Generator), suggested list price

Part 16455 (Ultrasonic Leak Detector), suggested list price

We do not sell direct, purchase would have to be made through a distributor. You can locate a distributor on our website with this link: http://www.robinair.com/hvac/distributors

Thanks

Mit freundlichen Grüßen / Best regards

Bill

Bosch Automotive Aftermarket
Automotive Service Solutions
Aftermarket Customer Service (AA-AS)

28635 Mound Rd
Warren, MI 48092
USA
www.bosch.com

Phone
Fax

https://mail.google.com/mail/u/1/?ui=2&ik=1997afe3b6&view=pt&search=inbox&msg=150ecb0d56fbd8b1&siml=150ecb0d56fbd8b1 1/2

Fig. 2. Quote for an emitter and leak detector from Robinair [2].

Fig. 3. Quote from UE Systems [3].

Fig. 4 Quote from SDT page 1 of 3 [4]

Fig. 5. Quote from SDT page 2 of 3 [4].

Fig. 6. Quote from SDT page 3 of 3 [4].

2. References

[1] N. Ganesh (2015, Nov. 9). “RE: Bacharach quote” Personal e-mail.

[2] Bill (2015, Nov. 9). “RE: AA-AS Inquiry” Personal e-mail.

[3] H. Clint (2015, Nov. 11). "RE: UE Systems Quote" Personal e-mail.

[4] D.Sansom (2015, Nov. 5) "RE: SDT Systems Quote" Personal e-mail.