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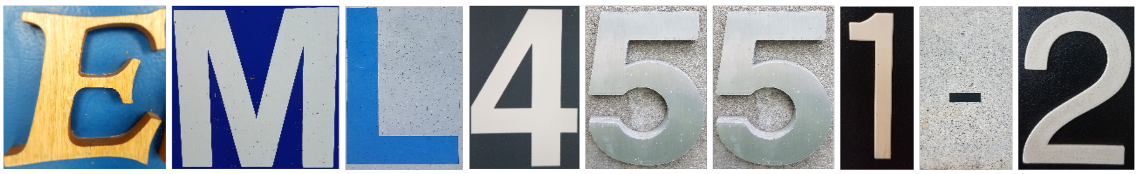

Team 04: Danfoss IGV Monitoring System

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Abstract

The Danfoss IGV Senior Design Team is engineering a monitoring device for the Danfoss testing lab. The compressors Danfoss makes use blades at the entrance to help channel the incoming gas. The blades help control the performance of the compressor. These blades can break due to high pressure zones and vibrations caused by the gas. Danfoss Turbocor does not currently have a method to inspect the blades while the compressor is running. The device we built uses a small camera inside the pipe feeding the gas, aimed at the entrance to provide live video of the blades directly to the test lab. With this, the test lab can see if the blades are working properly. A computer program also uses the live video feed to analyze a set of QR code stickers placed on the blades. This program provides more detailed information about the blades, like if they are broken or moving in unplanned ways. The program inspects the video feed and automatically determines if all of the stickers on the blades are present and estimates the angle of the blades based on the tilt of the stickers. With this computer program our system alerts the Danfoss testing lab technicians if the system detects any problems with the blades. Our team designed the housing for the camera and the lighting system used inside the pipe. We also developed the program to analyze the stickers on the blades. With the device, Danfoss engineers and designers can see the blades during operation for the first time, and they can learn about the conditions that the blades undergo during operation.

Disclaimer

Our sponsor, Danfoss Turbocor, does not require a disclaimer.

Acknowledgement

We would like to thank Danfoss Turbocor and our project liaison, William Bilbow, for sponsoring this project and helping guide us through the project development. We would also like to thank Kevin Lowman for his extensive help in manufacturing our project and for his technical advice. Finally, we would like to thank Dr. McConomy for helping guide us through the senior design process and Dr. Kunihiko for his advice and guidance.

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Notation

CR	Customer Requirement
DIC	Digital Image Correlation
EC	Engineering Characteristic
HOQ	House of Quality
IGV	Inlet Guide Vane

Chapter One: EML 4551C

1.1 Project Scope

Our team has come up with the following project scope using the information from the initial sponsor meeting with Danfoss and the project background they provided (W. Bilbow, personal communication, September 22, 2017).

Description:

Danfoss is currently redesigning and testing new inlet guide vanes (IGVs) to use in their TT series of compressors. The compressors use IGVs to manage inlet refrigerant mass flow and flow direction by changing the angle of the vanes. They are currently testing how the different IGV angles impact the mass flow rate and pressure ratio of the compressor; however, there are limitations to what Danfoss can analyze about the IGVs using their current equipment. Danfoss would like to have a better understanding of how the IGVs react in the flow of the refrigerant, and to have a more accurate reading of the current IGV angle. Therefore, the objective of this project is to design and build a system for real-time visual and position monitoring of the compressor inlet guide vanes

Goals:

The three key goals to complete the objective of this project are as follows:

- Produce a system to reliably measure the angle of the IGV
- Provide detailed monitoring of low cycle and high cycle failures
- Minimize impact on the fluid flow

Primary Market:

The primary market for the testing equipment we are developing is the Danfoss Research and Development Testing Labs.

Assumptions:

- Monitoring and sensing equipment will need to be purchased by the group
- System will be used on the TT series of Danfoss compressors

Stakeholders:

- Danfoss Research and Development Test Lab
- Danfoss Aero-Thermal Engineering Design Team

1.2 Customer Needs

The initial meeting with Danfoss provided a lot of useful information about the individual needs that their test lab has for this monitoring device. Using the information gained from this meeting and the needs outlined in the project description, our team came up with a list of customer statements given in table 1.

Our team then rewrote the customer statements as interpreted need statements. We wanted to remove some of the implied solutions to our project given in the statements so that we have a list of needs which outline what our final system needs to accomplish rather than how it should be accomplished. We also wanted to reword the negative customer statements into positive needs. The table below shows the customer statements and our team's interpreted need.

Table 1
List of Customer Statements and Interpreted Needs

#	CUSTOMER STATEMENTS	INTERPRETED NEED
1	We want a visual of the inlet to monitor guide vane, slip, impedance, flutter and vane loss	Visual monitor allows for qualitative analysis of inlet guide vanes
2	We need an angle reading of all of the Inlet Guide Vanes	The angles of all IGVs are determined
3	The camera needs to be in the center	The view of the vanes is from the center of the inlet
4	The device cannot break and have parts enter the compressor	System malfunction will not damage compressor
5	Compressor inlet flow should not be impacted	Allows for normal flow into the compressor
6	Device components like the camera and sensors need to be serviceable	Components can be replaced or serviced
7	To avoid interference with the rest of the compressor, don't use sonic or magnetic sensors	Allows for normal operation of the compressor's electronic subsystems
8	The vanes need to be illuminated to see them	The vanes are clearly visible

These new interpreted need statements will allow our group to focus on the main customer needs of the project without narrowing the possible solutions to those implied in the customer statements.

1.3 Functional Decomposition

Our team used the project scope and interpreted customer needs to come up with a list of functions that our system needs to accomplish in order meet the goals outlined in the project scope. The list of functions shown below acts as a guideline for our concept generation and selection which takes all the system requirements into account.

- Sense IGV Position
- Provide Power to Position Sensor
- Relay Position Signal to System
- Convert IGV Position Sensor Reading to IGV Percentage
- Send IGV Percentage to Indicator
- Indicate Percentage of IGV to User
- Provide Power to Indicator
- Capture Visual of IGVs
- Provide Power to Visual Sensor
- Relay Visual Signal to System
- Process IGV Visual Signal into a Video Feed
- Send Video Feed to Display
- Provide Power to Monitor
- Display Video of IGV to User
- Get Power from Source

Our team also created a graphical representation using the previously listed functions in order to create a better visualization of the system's main operating requirements. This diagram is included below.

Figure 1. Flow diagram of all items in the functional decomposition.

1.4 Target Summary

In a meeting with the sponsor, our group constructed a list of required targets and their values that we need to accomplish for our project to be successful. The most important targets for our project are the impact on the fluid flow, and the monitoring rates for IGVs changes and failures. The impact on the fluid flow can be represented by the pressure drop across the system and by the induced swirl in the flow. For this project, there can be no induced swirl in the flow of refrigerant, and the overall pressure drop across the system should be less than 0.02 psi.

Our system needs to observe and detect low cycle IGV failures like latching or breaks due to constant forces in the flow, and high cycle failures due to vibrations in the system. To accurately measure these failures, a required measurement frequency is assigned to each. Low cycle failures like latching and breaks due to constant forces only require a sample frequency of 1Hz since the vanes move very slowly when turning and breaks only need to be indicated on a per second basis. Measuring high cycle failures requires a much higher sampling rate of 1kHz due to the high motor revolutions per minute and low natural frequencies of plastics which fall within the range of the motor frequency. A detailed list of targets is given in appendix B.

1.5 Concept Generation

For the concept generation, we conducted background research on possible systems and components that could fulfill the requirements for this system. This research included defining the operating conditions, finding different ways to measure the angle of the IGVs, finding ways to capture a visual of the IGVs, and determining how our system processes all of these signals. Using this information, each member of our group presented and recorded detailed concepts for the system during multiple ideation meetings. Following these meetings, individual subsystems in the concepts were extracted and sorted into the relevant categories. The following table outlines each of the subsystems and the related concepts, and the following sections go into further details all of the concepts.

Table 2
List of Subsystems and Related Concepts

SUBSYSTEM	#	CONCEPT DESCRIPTION
Low Cycle Monitoring Subsystem	1	Camera in pipe elbow to monitor IGVs from center
	2	Fiber optic camera in central body to see from center of pipe
	3	Multiple cameras on pipe side used to construct a composite image
	4	Mirror on central body with external camera to see from center of pipe
High Cycle Monitoring Subsystem	1	High speed camera to see and analyze flutter frequency
	2	Accelerometer on IGV to measure the flutter frequency
	3	Laser vibrometer to measure the flutter frequency
	4	Linear potentiometer with high pass filter to monitor flutter frequency
	5	Digital Image Correlation
Angle Monitoring Subsystem	1	Accelerometer to measure position based on change in gravity
	2	April tags used with a camera to calculate angle based on aspect ratio
	3	Light sensitive paper to easily see and approximate angle of each IGV
	4	Linear potentiometer with low pass filter to monitor distance change
	5	Digital Image Correlation
IGV Lighting Subsystem	1	Individual lights in pipe close to the IGV to light IGVs
	2	Ring light around camera to evenly light IGVs
	3	Clear pipe which allows ambient light in the room to enter pipe

Low Cycle Monitoring Subsystem Overview

The low cycle monitoring system is in charge of monitoring and detecting problems with the IGV that occur over a span of time lasting longer than a second. Its main function is to determine if all the vanes are present in the system, or if some of the vanes have broken during testing. It will also monitor for geometrical interference between vanes when the vanes rotate. This interference is most likely to occur in the center of the inlet where the tips of the IGV could interfere causing a failure of the IGV system.

Low Cycle Monitoring Subsystem Concept 1

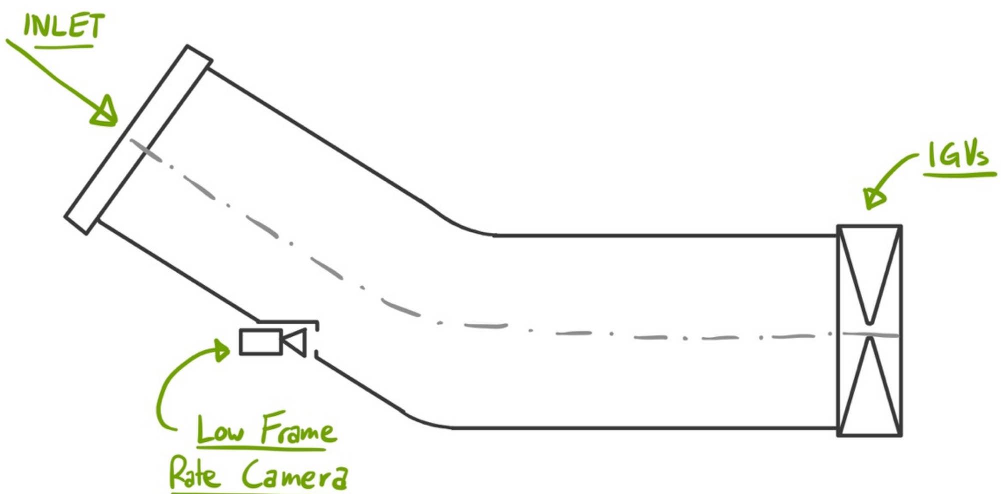


Figure 2. Low cycle monitoring concept utilizing a camera in a pipe elbow.

A low frame rate camera is positioned in the side of a pipe elbow to monitor the IGVs. Placing the camera inside a pipe elbow provides a central view of the IGVs without large disturbances to the inlet refrigerant flow.

Low Cycle Monitoring Subsystem Concept 2

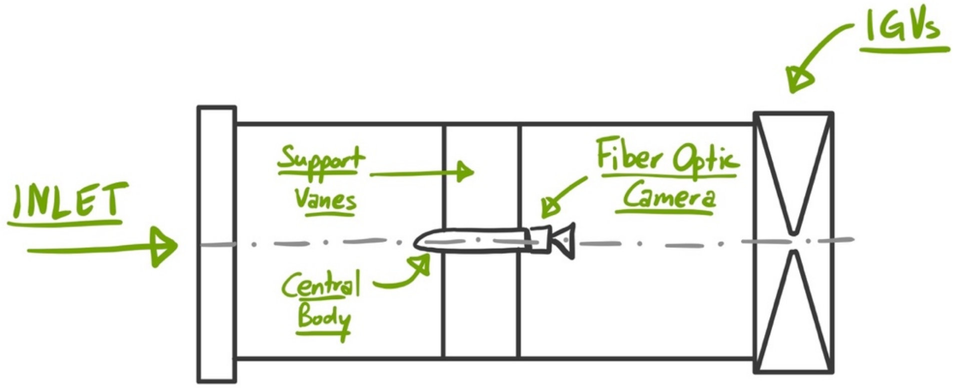


Figure 3. Low cycle monitoring concept utilizing a fiber optic camera in a central body.

Here, a central body acts as a housing for a fiber optic camera. The position of the camera allows the user to see the IGVs from the center of the pipe, and the streamlined design of the central body and support vanes minimizes the impact on the fluid flow.

Low Cycle Monitoring Subsystem Concept 3

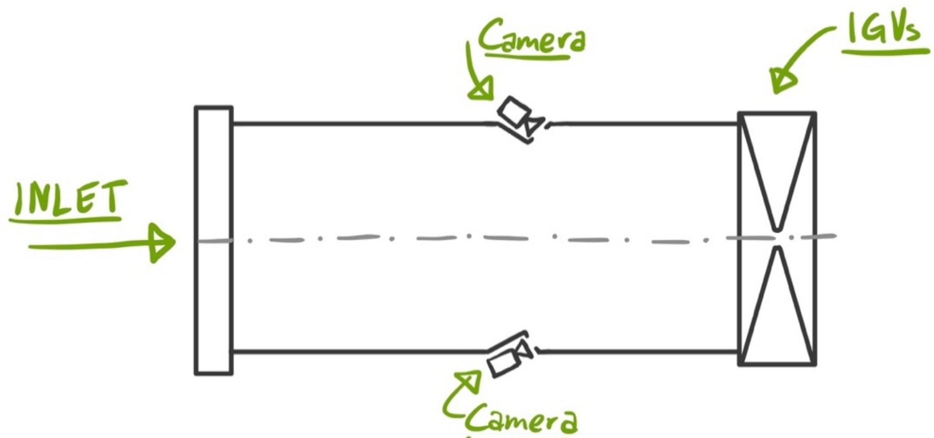


Figure 4. Low cycle monitoring concept utilizing cameras to make a composite image.

Multiple cameras at different locations in the pipe create a composite image of the IGVs whose view appears from the center of the pipe. This concept will also minimize the impact on the flow since no elements are located in the center of the pipe.

Low Cycle Monitoring Subsystem Concept 4

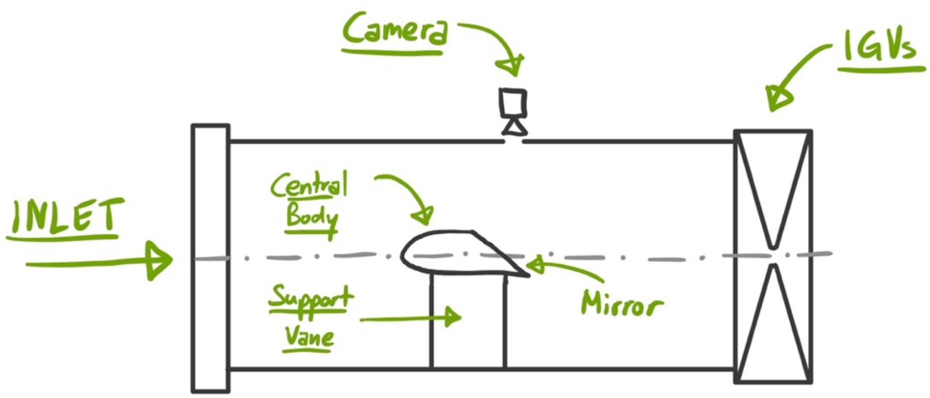


Figure 5. Low cycle monitoring concept utilizing a mirror and external camera.

In the final concept for low cycle monitoring, a central body with a mirror attached at 45 degrees to the inlet provides a clear image to a camera positioned at the side of the pipe. The flow properties are very similar to the previous concept involving the fiber optic camera in the central body, however, the implementation of the camera is less expensive since the size of the camera is less important. Since the flow into the compressor inlet is in the gaseous state, visibility on the mirror shouldn't be a large concern.

High Cycle Monitoring Subsystem Overview

The high cycle monitoring system will be used to analyze high frequency flutter of the vanes in the system. Therefore, the sampling rate of the system needs to sample at double the frequency of flutter. The system should capture the vibrations in the IGV before a failure occurs so that the information can be used in further design iterations.

High Cycle Monitoring Subsystem Concept 1

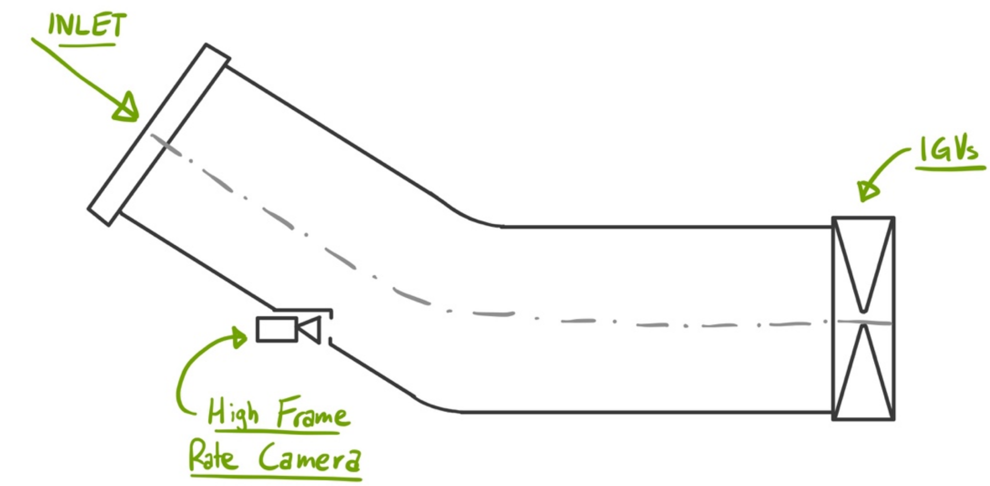


Figure 6. High cycle monitoring concept utilizing a high framerate camera.

A higher frame rate camera is used to measure both low cycle and high cycle events. This configuration allows for the placement of the high frame rate camera in many of the positions outlined in the previous concepts for low cycle monitoring.

High Cycle Monitoring Subsystem Concept 2

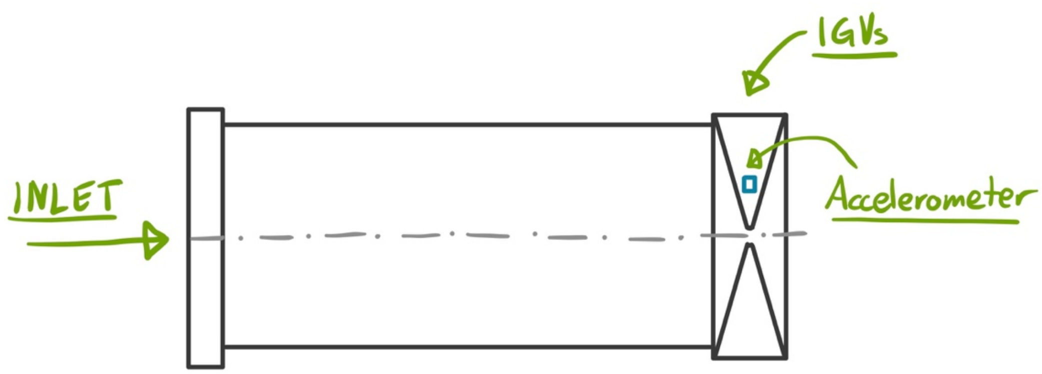


Figure 7. High cycle monitoring concept utilizing an accelerometer.

An accelerometer placed onto or into the IGV provides another method of determining high cycle vibrations. The accelerometer sends voltages to the computer or microcontroller in use which are converted to a frequency of vibration for the IGV.

High Cycle Monitoring Subsystem Concept 3

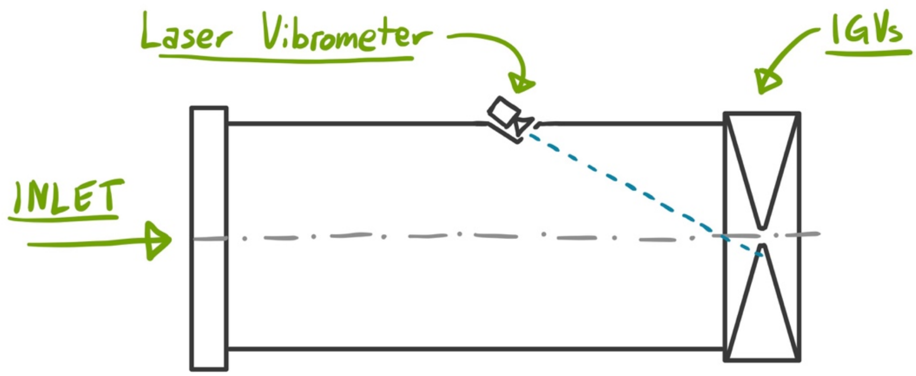


Figure 8. High cycle monitoring concept utilizing a laser vibrometer.

A similar solution uses a laser vibrometer to measure the change in distance of the vane due to vibration. The placement of the vibrometer is near the outside of the pipe to avoid impacting the flow of the refrigerant.

High Cycle Monitoring Subsystem Concept 4

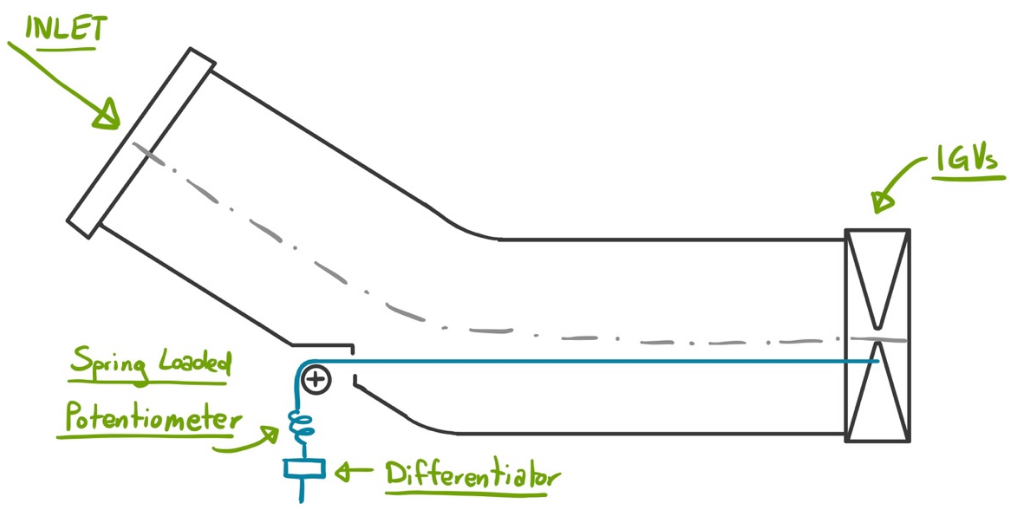


Figure 9. High cycle monitoring concept utilizing a potentiometer with a differentiator.

The cheapest solution is to use a spring loaded linear potentiometer. This potentiometer would connect directly to the vane and only monitor high frequency changes through the differentiator which gives the vibrations of the IGV.

High Cycle Monitoring Subsystem Concept 5

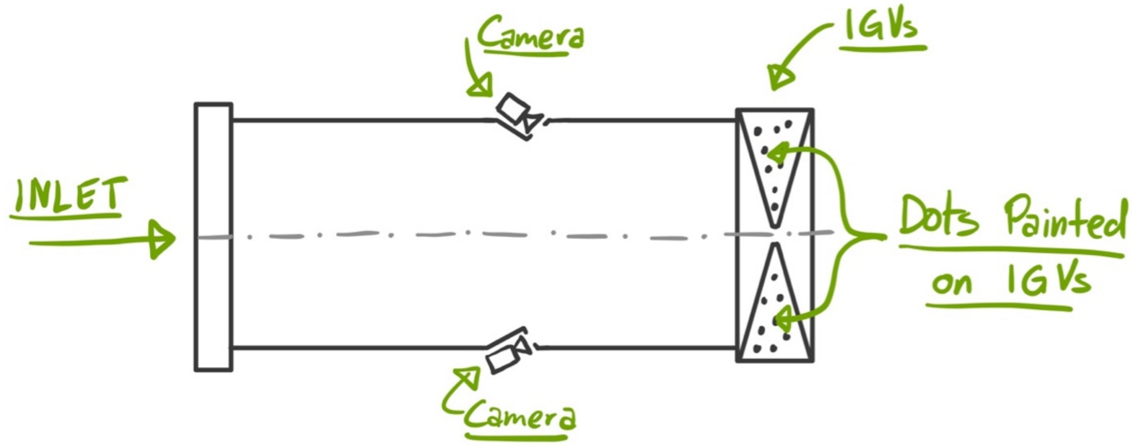


Figure 10. High cycle monitoring concept utilizing digital image correlation.

The final subsystem concept is to use a dot pattern painted onto the IGVs and then use two cameras to analyze the vanes using digital image correlation. The accuracy of this concept is highly dependent on the resolution of the camera and the frame rate would need to be high enough to see any vibrations.

Angle Monitoring Subsystem Overview

The angle monitoring subsystem will be used to determine any major differences in the angles of the IGV, and will be used to see if the stepper motor reading is correct. A large difference in the angle of a few of the IGVs could indicate that some of the blades are interlocked due to geometrical interference, or that one of the IGVs has failed completely.

Angle Monitoring Subsystem Concept 1

Figure 11. Angle monitoring concept utilizing a gyroscope.

For the first concept, a gyroscope is used to determine the angle of the IGV. The implementation of the gyroscope is similar to the accelerometer where it sends voltages to a computer or microcontroller, which will use those voltages to calculate a change in the angle of the IGV.

Angle Monitoring Subsystem Concept 2

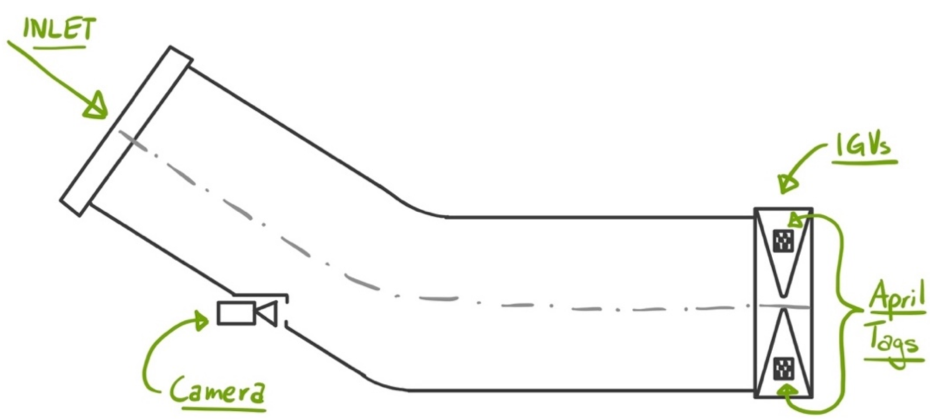


Figure 12. Angle monitoring concept utilizing a camera and April tags.

This system calculates the angles using a camera system and a series of April tags placed on each one of the IGVs. The system uses the camera feed as an input and determines what angle each IGV is at based on the aspect ratio of each of the April tags (which look like QR codes).

Angle Monitoring Subsystem Concept 3

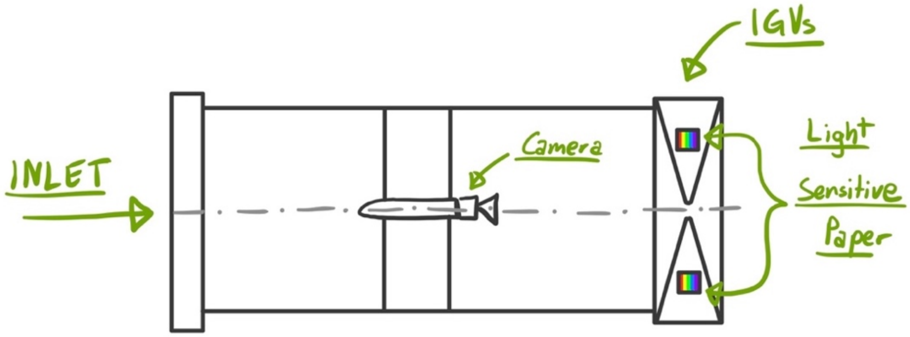


Figure 13. Angle monitoring concept utilizing a camera and light sensitive paper.

Light sensitive paper on each IGV will display a certain color on the spectrum representing one angle based on where the light originates from. This concept doesn't directly calculate each angle; however, angle discrepancies can be identified if one IGV color is significantly different than the others.

Angle Monitoring Subsystem Concept 4

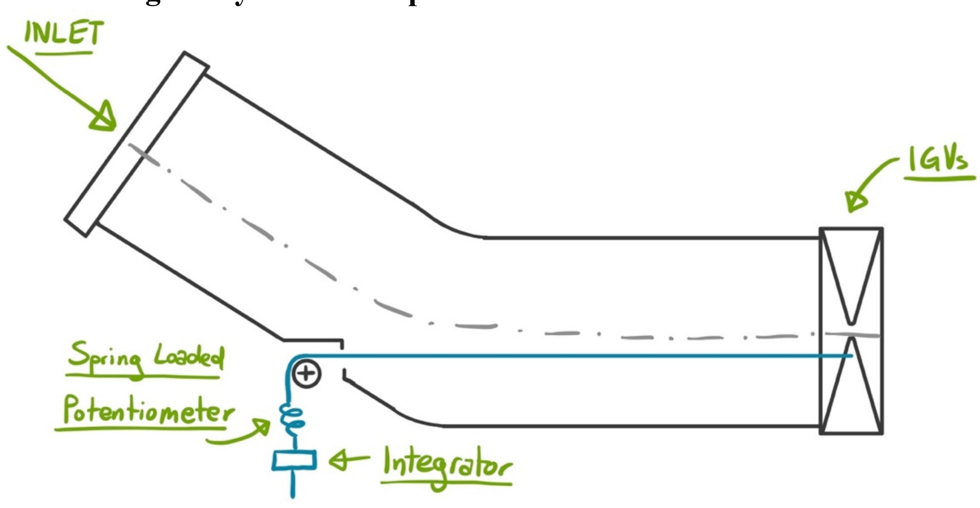


Figure 14. Angle monitoring concept utilizing a potentiometer and an integrator.

Potentiometers can also calculate angles of the IGV by using an integrator instead of a differentiator when reading the voltages. The integrator acts as a output voltage smoother and only relays large changes in distance to the microcontroller, as opposed to the small changed relayed by the differentiator. The system used this voltage change and determines the angle of the IGV.

Angle Monitoring Subsystem Concept 5

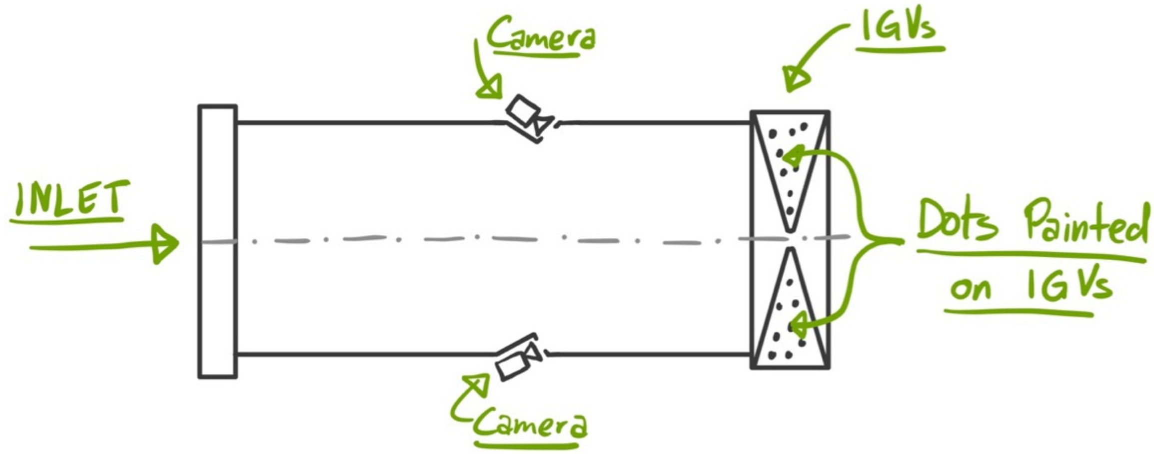


Figure 15. High cycle monitoring concept utilizing digital image correlation.

The final subsystem concept is to use the same DIC system as the high cycle concepts, but to calibrate it to calculate angle instead of vibrations.

IGV Lighting Subsystem Overview

The IGV lighting subsystem must provide enough light in the pipe for the cameras to clearly see the IGVs. Therefore, the system needs to light the IGVs so that the monitoring system provides a clear overview of the status of the blades.

IGV Lighting Subsystem Concept 1

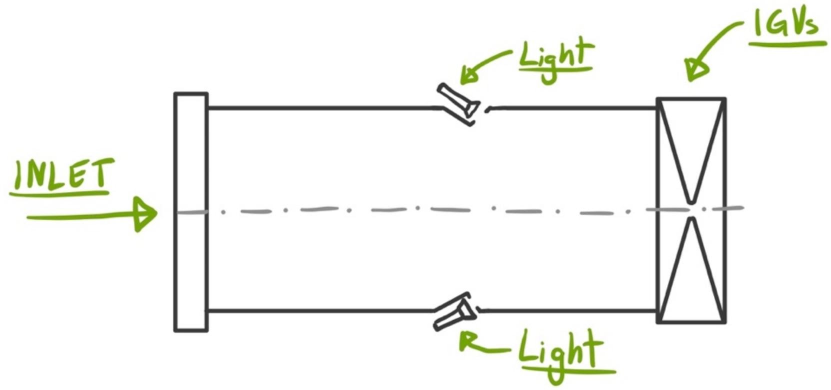


Figure 16. Lighting concept utilizing individual lights in pipe.

Individual lights illuminate the IGVs from multiple angles resulting in a clear and even view of the vanes for the camera monitoring systems. Similar to the cameras in the composite imaging concept, the position of the lights does not impact the flow of refrigerant into the compressor.

IGV Lighting Subsystem Concept 2

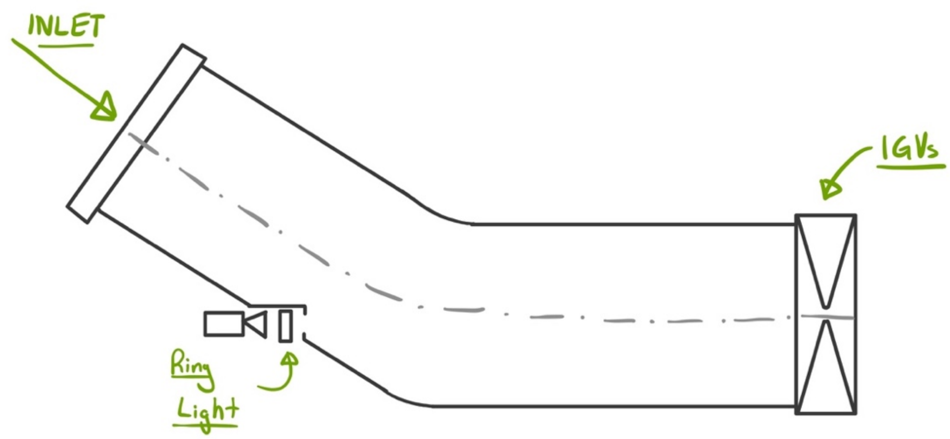


Figure 17. Lighting concept utilizing a ring light around the camera.

A light ring positioned around the lens of the camera provides lighting to the IGVs which is directly from the view of the camera without adding additional lighting components in the center of the pipe, minimizing the flow impact.

IGV Lighting Subsystem Concept 3

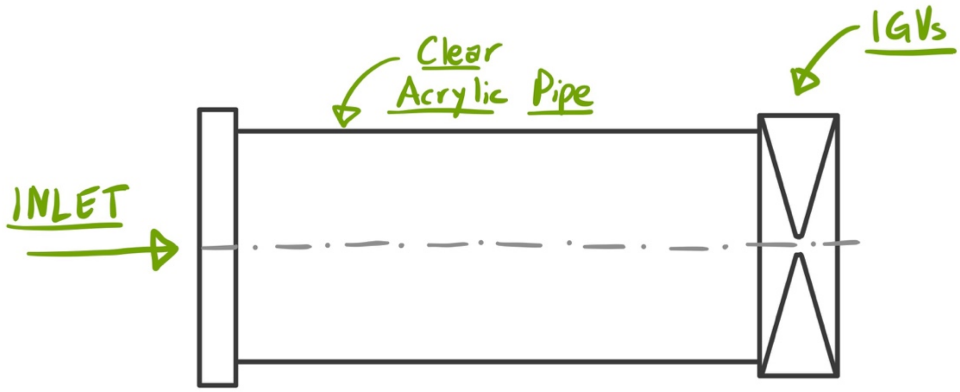


Figure 18. Lighting concept utilizing clear acrylic pipe.

Finally, a clear pipe would negate any additional lighting in the system as ambient light from multiple directions in the test lab evenly illuminates each of the IGVs. This also provides a separate monitoring mode for test lab operators to check on the status of the vanes.

1.6 Concept Selection

Concept Selection Procedure

Our group utilized a house of quality and a decision matrix in order to select the final design for this project. We used the house of quality to determine the engineering characteristics that are required to complete this project and their weight factors determining which engineering characteristics deserve a larger emphasis. Then we made decision matrixes for each of the subsystems using the previously determined engineering characteristics. These decision matrixes will give us a good idea of all of the strengths and weaknesses of the subsystems and will eliminate some of the worst concepts. Finally, we will use the best subsystems from each decision matrix and combine them to get the final concept for the project.

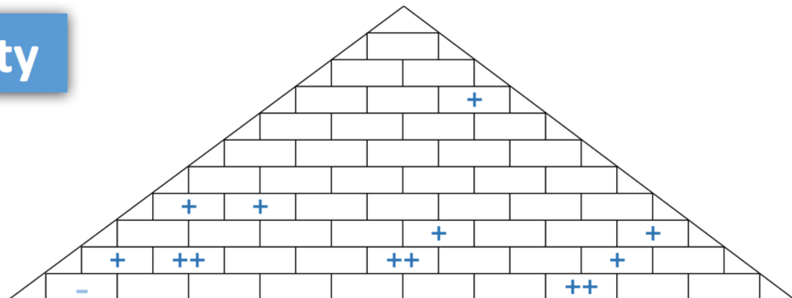
House of Quality

Below is our group's house of quality (Figure 19) outlining the customer requirements, engineering characteristics and their weight factors.

House of Quality

Legend

Symbol	Meaning
++	Very Strong Relationship
+	Strong Relationship
-	Weak Relationship
--	Very Weak Relationship
▲	Increasing is Better
▼	Decreasing is Better
Darker	Higher Importance
Lighter	Lower Importance



Row Number	Relative Weight	Weight / Importance	Engineering Characteristics / Customer Requirements	Image Clarity	Camera Frame Rate	Angle Measurement Accuracy	Angle Measurement Refresh Rate	Vibration Sensing Accuracy	Vibration Sensing Refresh Rate	System Stability	System Length	Ease of Integration	Pressure Drop across System	Pipe Illumination
				1	2	3	4	5	6	7	8	9	10	11
				▲	▲	▲	▲	▲	▲	▲	▼	▲	▼	▲
1	14.7	5.0	Qualitative analysis of IGV's low cycle failure	9	3	1	1			9	3	1	1	9
2	5.9	2.0	Qualitative analysis of IGV's high cycle failure	3	3	1	1	9	9	9	3	1	1	3
3	8.8	3.0	The angle reading is accurate	3	3	9	9			9	3	1	1	3
4	11.8	4.0	The view is of the center			3	1	1		3				
5	14.7	5.0	Malfunction will not damage compressor							9			1	
6	11.8	4.0	Allows for normal flow into the compressor							3	3	1	9	
7	8.8	3.0	Components can be replaced or serviced							1	1	3		
8	14.7	5.0	The vanes are clearly visable	9	3	1	1			9	3			9
9	8.8	3.0	Ease of use by test lab								9	9		
			Technical Importance: Absolute	309	132	150	126	65	53	609	256	147	150	309
			Technical Importance: Relative	13.4	5.7	6.5	5.5	2.8	2.3	26.4	11.1	6.4	6.5	13.4

Figure 19 House of Quality for Concept Selection.

We started our house of quality with the list of customer requirements (CRs) that were previously determined in the customer needs section. With these requirements, we determined the proper engineering characteristics (ECs) that this project needs to meet in order to fulfill the needs of the customer. This includes two ECs for each of the monitoring subsystems (low cycle, angle, high cycle) determining the measurement quality and sampling rate, and also includes various other parameters to measure how well the system integrates into the Danfoss testing environments and how much the system will impact the flow. With these ECs determined, we filled out the center of the house of quality with factors determining the relation between the ECs and CRs based on how strong that relation is. With this information, we could determine the weight factors. The top EC for this project is system stability. This is very important because it represents the overall integrity of the monitoring tool which is required to keep the compressor loop from failing but is also required to keep all of the cameras and sensors in our monitoring system stable. Without a stable system, camera views could be blurry and sensor reading may not be accurate. The second most important ECs are Pipe Illumination and Image Clarity. These represent the main goal of the project which is to have a clear view of the compressor inlet to monitor low cycle failures. Achieving this alone would make our project successful. The lowest ranked ECs are those for vibration sensing. This is because the vibration sensing component of our design is not a firm requirement but rather an addition to the system that Danfoss characterized as extra credit. Therefore, our group will not make large design changes or select concepts that impact the integrity of the other monitoring subsystems to accommodate this function.

Decision Matrix: Low Cycle Monitoring Subsystem

With the engineering characteristics determined, the decision matrices can be made. The first decision matrix is for the low cycle monitoring system (Table 3) and compares the concepts that our group generated in the previous section.

Table 3
Decision Matrix for Low Cycle Monitoring Subsystems

		Camera in Elbow		Camera & Central Body Mirror		Camera in Central Body		Composite Imaging	
Option	Weight Factor	Score	Rating	Score	Rating	Score	Rating	Score	Rating
Image Clarity	13.4	8	107.1	6	80.4	7	93.8	8	107.1
Camera Frame Rate	5.7	8	45.9	8	45.9	7	40.2	8	45.9
Angle Measurement Accuracy	6.5	0	0.0	0	0.0	0	0.0	0	0.0
Angle Measurement Refresh Rate	5.5	0	0.0	0	0.0	0	0.0	0	0.0
Vibration Sensing Accuracy	2.8	0	0.0	0	0.0	0	0.0	0	0.0
Vibration Sensing Refresh Rate	2.3	0	0.0	0	0.0	0	0.0	0	0.0
System Stability	26.4	8	211.2	5	132.0	6	158.4	8	211.2
System Length	11.1	2	22.2	8	88.8	8	88.8	6	66.6
Ease of Integration	6.4	3	19.1	8	51.0	7	44.6	5	31.9
Pressure Drop across System	6.5	8	52.0	7	45.5	7	45.5	9	58.5
Pipe Illumination	13.4	4	53.6	3	40.2	7	93.8	3	40.2
			511.2		483.8		565.1		561.5

The main focus of this comparison is around the image clarity and framerate offered by each subsystem. Since individual cameras have not been selected yet, the rating for this matrix represents how limited we are in selecting from a large range of cameras and how the shape and design of the subsystem will impact overall performance.

For image clarity, composite imaging and camera in an elbow score highest because they allow for a wide range of cameras that can be used since the placement of the cameras will be external of the pipe. For the camera in a central body, the score is slightly worse because the range of cameras is limited to small form factor and fiber optic cameras. Therefore, the image clarity would be less than the other options for a camera costing the same. The camera pointing at a central body with a mirror scores the worst because this subsystem requires keeping the camera and the mirror clean. If these cannot be regularly cleaned and maintained, then image clarity will be severely impacted.

We used a similar approach for the camera frame rate analysis. All of the subsystems where the cameras can be placed outside the pipe score the same, but the camera in the central body scores slightly worse because the range of cameras available for use in our price range cannot achieve the same performance as those that could be used externally. All subsystems received scores of zero for the angle and vibration sensing systems because none of them can achieve these ECs. For the rest of the subsystem analyses we will give ratings to systems that can perform multiple functions to reward those that can serve more of our needs.

The scores in system stability have a more significant range in this matrix. Both subsystems with central bodies score lower due to the vibrations that could occur with the support vanes (similar phenomenon to what the IGVs experience) while the pipe elbow and composite imaging score higher because they do not have large components inside the system. The rest of the EC scores are filled out based on how long the system is, how easy it would be to implement it into the current testing refrigerant loop, and how much the flow inside the pipe would be impacted.

Given these scores, the pipe in an elbow concept is eliminated because its length and shape make it hard to implement into the current test loop. We also eliminated the camera looking at a central body because of the risk that the image would not be clear enough and that a mirror held in place by just one or two support vanes would not be stable enough to have usable data from the camera feed. Composite imaging and camera in a central body stay and will be further discussed later in the section.

Decision Matrix: Angle Monitoring Subsystem

The next decision matrix (Table 4) compares all of the concepts generated for the angle monitoring subsystem.

Table 4
Decision Matrix for Angle Monitoring Subsystems

		Potentiometer with Integrator		Iridescent Measurement		Camera with April Tags		Gyroscope/ Gyrometer		Digital Image Correlation	
Option	Weight Factor	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating
Image Clarity	13.4	0	0.0	7	93.8	6	80.4	0	0.0	6	80.4
Camera Frame Rate	5.7	0	0.0	7	40.2	7	40.2	0	0.0	7	40.2
Angle Measurement Accuracy	6.5	4	26.0	3	19.5	9	58.5	6	39.0	9	58.5
Angle Measurement Refresh Rate	5.5	8	43.9	7	38.4	7	38.4	8	43.9	7	38.4
Vibration Sensing Accuracy	2.8	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Vibration Sensing Refresh Rate	2.3	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
System Stability	26.4	1	26.4	7	184.8	8	211.2	1	26.4	8	211.2
System Length	11.1	7	77.7	6	66.6	6	66.6	7	77.7	6	66.6
Ease of Integration	6.4	1	6.4	5	31.9	4	25.5	1	6.4	4	25.5
Pressure Drop across System	6.5	3	19.5	4	26.0	7	45.5	2	13.0	7	45.5
Pipe Illumination	13.4	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
			199.9		501.1		566.3		206.4		566.3

For the angle monitoring subsystems, some concepts received scores for the image clarity and camera frame rate sections. Even though none of these subsystems are specifically designed for these functions, we reward these concepts with scored in these sections to indicate that they could serve multiple functions. However, no subsystem received a score for the vibration sensing since none are capable of providing a usable measurement.

For angle measurement accuracy, the camera with April tags and composite imaging score the highest since they use a camera view which would not have as much noise introduced into the measurement signal. This is not the same for the potentiometer since there could be flow tugging on the string which could make the measurement useless. For the iridescent measurements, the color spectrum range would not be clear enough to have a great accuracy in the measurement.

For the angle measurement refresh rate, the potentiometer and the gyroscope score the highest since the sampling rate is done of an analog voltage so the rate can be determined by the microprocessor used. The others score slightly lower due to the dependence on the refresh rate of the camera. However, all of the subsystems have high scores because they easily meet the required sampling rate for angle measurements.

For system stability, the potentiometer and gyroscope subsystems score very low because they have strings or wires attaching to the vanes which could break off and impact performance. In the case of the gyroscope, computer components would need to be placed on the vanes themselves. This is similar for system integration. The need to attach things to the IGVs will make these concepts very hard to integrate into the testing environment and workflow while the other systems would be much easier to use.

For the pressure drop across the system, the potentiometer subsystem scores lower because it requires 7 waterproof potentiometers inside the pipe whose placement along the outer pipe edge will cause the flow inside the system to be impacted. For the iridescent paper and gyroscope concepts, a very thick sticker or computer chip will be placed on the IGV which will impact their overall performance and lead to a pressure drop. The April tags and DIC concepts score highest because the required image can be painted on the IGVs and will result in minimal flow impact.

Based on this matrix, the potentiometer concept is eliminated based on how hard it would be to integrate into the testing setup and how unstable it will make the system. The gyroscope is eliminated because it requires a computer component on every IGV and because of the instability it introduces. Finally, the iridescent concept is eliminated because it requires a thick sticker on each IGV and because of the low accuracy in the measurement of the angle. Camera with April tags and DIC will stay and be further discussed later in the section.

Decision Matrix: IGV Lighting Subsystem

The third decision matrix (Table 5) compares all of the concepts generated for the IGV lighting subsystem.

Table 5
Decision Matrix for IGV Lighting Subsystems

		Lighting Around Pipe		Camera Ring Light		Clear Acrylic Pipe	
Option	Weight Factor	Score	Rating	Score	Rating	Score	Rating
Image Clarity	13.4	0	0.0	0	0.0	0	0.0
Camera Frame Rate	5.7	0	0.0	0	0.0	0	0.0
Angle Measurement Accuracy	6.5	0	0.0	0	0.0	0	0.0
Angle Measurement Refresh Rate	5.5	0	0.0	0	0.0	0	0.0
Vibration Sensing Accuracy	2.8	0	0.0	0	0.0	0	0.0
Vibration Sensing Refresh Rate	2.3	0	0.0	0	0.0	0	0.0
System Stability	26.4	7	184.8	7	184.8	6	158.4
System Length	11.1	7	77.7	7	77.7	5	55.5
Ease of Integration	6.4	7	44.6	7	44.6	9	57.4
Pressure Drop across System	6.5	7	45.5	6	39.0	10	65.1
Pipe Illumination	13.4	7	93.8	7	93.8	4	53.6
			446.4		439.9		389.9

All IGV lighting subsystems received scores of 0 for the first 6 engineering characteristics because they cannot serve those functions. All of the concepts for this subsystem have acceptable system stabilities but the clear acrylic pipe scores slightly lower because it uses a different material which may introduce problems if the material properties of the pipe network don't all match. For system length, the clear acrylic pipe scores lower again. This is because it requires a longer pipe section to allow for more of the ambient light to enter the pipe while the other concept could just be implemented into a thin ring attached between the compressor inlet and the inlet pipe.

For ease of integration and pressure drop, the acrylic pipe scores the highest because it is just a straight section of pipe that doesn't require any computer hardware or electronics to function, while the other concepts need power to work and will have components placed inside or along the edge of the pipe.

The acrylic section of pipe scores the lowest for pipe illumination because of how dependent it is on the lighting in the room. In addition, it is possible that the lights in the room have a frequency that could impact our sensing equipment and could result in a stroboscopic effect. We can control and remove this risk with our own dedicated lights.

Given this decision matrix, the clear acrylic pipe concept is eliminated because of the high dependence on the ambient light in the room and how a different material may introduce instability into the system. The ring light around the pipe and the lighting around the pipe concepts will stay and will be further discussed later in the section.

Decision Matrix: High Cycle Monitoring Subsystem

The final decision matrix (Table 6) compares the high cycle monitoring subsystems.

Table 6
Decision Matrix for High Cycle Monitoring Subsystems

		Potentiometer w/ Differentiator		Accelerometer on IGV		High Frame Rate Camera		Laser Vibrometer		Digital Image Correlation	
Option	Weight Factor	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating
Image Clarity	13.4	0	0.0	0	0.0	6	80.4	0	0.0	6	80.4
Camera Frame Rate	5.7	0	0.0	0	0.0	7	40.2	0	0.0	7	40.2
Angle Measurement Accuracy	6.5	2	13.0	2	13.0	0	0.0	3	19.5	9	58.5
Angle Measurement Refresh Rate	5.5	3	16.5	4	21.9	0	0.0	9	49.4	7	38.4
Vibration Sensing Accuracy	2.8	2	5.6	4	11.2	3	8.4	8	22.4	6	16.8
Vibration Sensing Refresh Rate	2.3	8	18.4	8	18.4	5	11.5	8	18.4	5	11.5
System Stability	26.4	1	26.4	2	52.8	8	211.2	8	211.2	8	211.2
System Length	11.1	7	77.7	7	77.7	6	66.6	6	66.6	6	66.6
Ease of Integration	6.4	1	6.4	1	6.4	7	44.6	5	31.9	4	25.5
Pressure Drop across System	6.5	3	19.5	2	13.0	7	45.5	8	52.0	7	45.5
Pipe Illumination	13.4	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
			183.4		214.4		508.4		471.4		594.6

Again, some of the subsystems received scores for the first four engineering characteristics to reward those concepts for serving multiple functions.

When looking at the vibration sensing accuracy, the laser vibrometer scores the highest due to the laser it uses. The accuracies of the high frame rate camera and digital image correlation are highly dependent on the camera used. The cameras would need to be very high resolution in order to detect very small changes in motion of the vane. For the potentiometer, the accuracy will be impacted because the strings attached to the IGV will move based on the flow in the pipe. The accelerometer also has a low accuracy score because the computer chip placed on the vane will likely impact the vibrations enough so that the measurement doesn't represent the true vibration that the vane is undergoing.

For the vibration sensing refresh rate, the potentiometer, accelerometer and laser vibrometer all score the highest because they output a voltage which can be read to get the data.

The high framerate camera and DIC concept's refresh rates are dependent on the refresh rate of the camera which will be lower than that of the voltages.

For system stability, the accelerometer and potentiometer score low for the same reasons as previously discussed where components need to be attached to each vane. For system length, all concepts that require a camera view have a lower score since the cameras need to be far away enough to get a full view of the IGVs while the potentiometer and accelerometers can be placed right next to the IGVs.

The potentiometer and accelerometer received lower scores for ease of integration and pressure drop for the same reasons as previously discussed where components need to be placed on the IGVs. The DIC received a lower integration score because it requires dots to be painted on the IGVs and the laser vibrometer received a low integration score because it needs to be calibrated onto the vane tip.

Because of how hard it is to integrate into the system, both the potentiometer and accelerometer concepts are eliminated. While the high frame rate camera has a pretty high score, it is also eliminated because of its low performance in the vibration measurement. The DIC and laser vibrometer concepts stay and will be further discussed.

Final Concept Selection

From the previous matrices, only a few concepts remain, outlined in table 7 below.

Table 7
Remaining Concepts from Each Subsystem

Low Cycle Monitoring	Angle Monitoring Subsystem	IGV Lighting Subsystem	High Cycle Monitoring
Camera in Central Body	Camera With April Tags	Camera With Ring Light	Laser Vibrometer
Composite Imaging	Digital Image Correlation	Lighting Arround Pipe	Digital Image Correlation

These remaining concepts need to be combined in a way that best meets the needs of the customer and provides an easy to use comprehensive monitoring system. For the low cycle monitoring subsystem, the camera in the central body is the better solution. This is because Danfoss specified that they want a view directly from the center of the inlet. While this could be achieved with composite imaging, the processing would be much more intensive and the hardware would be harder to calibrate. In addition, composite imaging requires the use of multiple cameras which would increase the cost of our system by a factor of two. While the central body might impact the flow more than the composite imaging, Danfoss has a lot of experience with designing central bodies since some of their higher end compressors use them in the IGV assembly. This is expertise that we could leverage in our design.

For similar reasons, the camera with April tags is the more desirable subsystem for angle measurement. Since Danfoss only requires an angle accuracy range of ±10%, the larger cost of the DIC system with multiple cameras would provide no real benefit over the much cheaper solution using the camera in the central body. Both of these concepts require thin stickers or paint on the IGVs so there is no real difference in the flow impact or ease of integration between the two subsystems.

Given that our range of possible cameras is already somewhat restricted to match the size specifications of our central body, requiring a ring light to be a part of the camera assembly would further limit our options. For this reason, specifying a separate lighting system with lights placed around the pipe gives us more options to provide the best lighting of the IGVs. Therefore, it is the concept that we select for this subsystem. If we do find a suitable camera with a ring light, then we can still remove this separate component but for the purposes of this project, it is better to plan for a separate subsystem then to have to make one last minute.

Since Danfoss has told us that the high cycle measurement subsystem is more of an extra credit component than a requirement, our group decided that it would be better to have a system that is more modular in measuring vibrations as opposed to a system that is deeply integrated into the rest of the project. That way it can be easily added or removed depending on if the presence of IGV vibrations is detected. For this reason, the laser vibrometer is chosen for the high cycle monitoring subsystem. Not only does this subsystem better fit the needs of our sponsor, but it is also cheaper than a DIC system which requires two cameras, and has much better performance than the DIC solution.

The final concept selection that we will move forward with is given below in table 8.

Table 8
Final Concepts Selected

Low Cycle	Angle Monitoring	IGV Lighting	High Cycle
Camera in Central Body	Camera With April Tags	Lighting Arround Pipe	Laser Vibrometer

Chapter Two: EML 4552C

2.1 Restated Project Scope

Our team has come up with the following project scope using the information from the initial sponsor meeting with Danfoss and the project background they provided (W. Bilbow, personal communication, September 22, 2017).

Description:

Danfoss is currently redesigning and testing new inlet guide vanes (IGVs) to use in their TT series of compressors. The compressors use IGVs to manage inlet refrigerant mass flow and flow direction by changing the angle of the vanes. They are currently testing how the different IGV angles impact the mass flow rate and pressure ratio of the compressor; however, there are limitations to what Danfoss can analyze about the IGVs using their current equipment. Danfoss would like to have a better understanding of how the IGVs react in the flow of the refrigerant, and to have a more accurate reading of the current IGV angle. Therefore, the objective of this project is to design and build a system for real-time visual and position monitoring of the compressor inlet guide vanes.

Goals:

The three key goals to complete the objective of this project are as follows:

- Produce a system to reliably measure the angle of the IGV
- Provide detailed monitoring of low cycle failures
- Minimize impact on the fluid flow

Primary Market:

The primary market for the testing equipment we are developing is the Danfoss Research and Development Testing Labs.

Assumptions:

- Monitoring and sensing equipment will need to be purchased by the group
- System will be used on the TT series of Danfoss compressors
- Manufacturing will take place through Danfoss facilities

Stakeholders:

- Danfoss Research and Development Test Lab

2.2 Spring Plan

Now that the design has been selected, our team has created a plan for the next semester to design, prototype and build the final product for Danfoss. The timeline for our plan is included in our Gantt Chart in figure 20. The critical path of our project is shown by the boxes in dark blue.

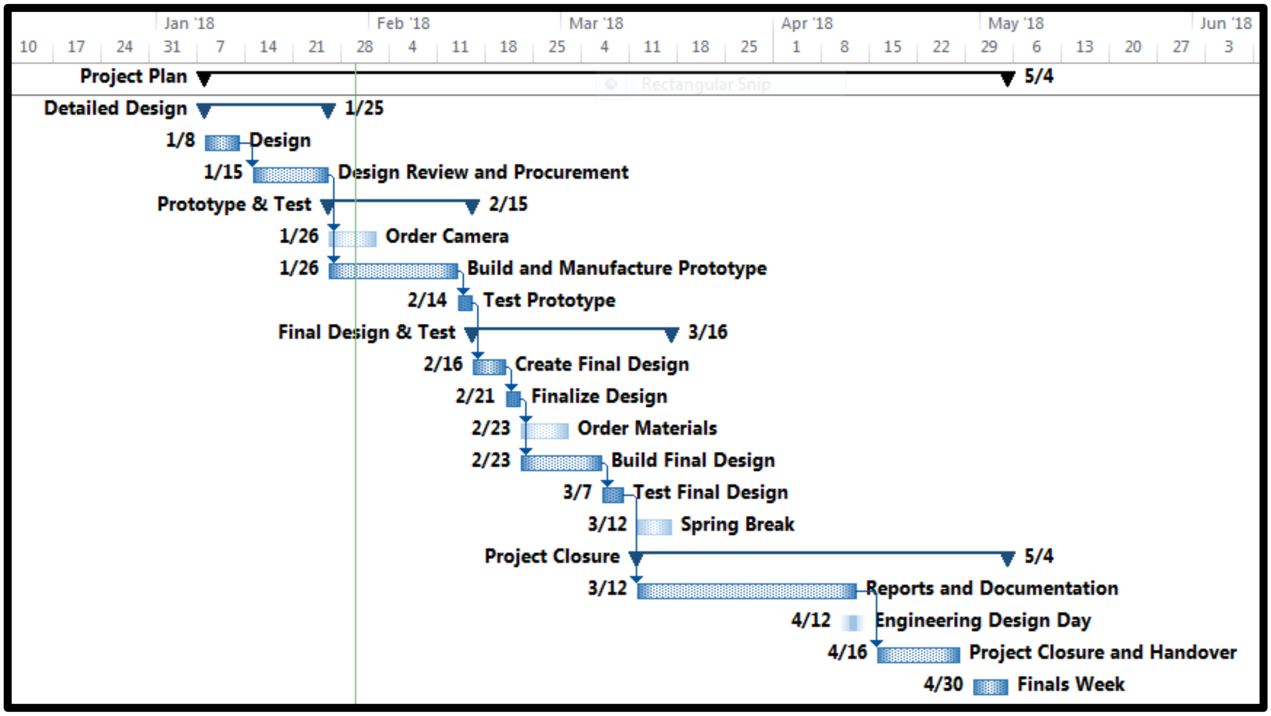


Figure 20 Spring Project Plan Gantt Chart.

This timeline includes the dates for spring break, engineering design day, and finals week. These gauge how the project is progressing in relation to major dates in the semester. The final product must be completed by engineering design day so we can present it to the sponsors and instructors. In order to meet this deadline, we plan on completing the design process in late January so that we can order parts and build the prototype by the middle of February. After building and testing the prototype, our team will do a redesign to address any issues discovered in the original prototypes. We plan on having this completed by the start of spring break.

The time between spring break and senior design day will be spent on final tweaks to the product and documentation. This also act as our buffer time if any of our other tasks take longer than expected. After engineering design day, we will complete the project and hand it over to our sponsor.

Our main bottleneck in this project will be testing our prototype due to the Danfoss test lab which is currently under construction. As a result, testing time is limited. Additional bottlenecks include the time to manufacture parts at Danfoss and other processes that we will need to go through in assembling our prototype (like brazing the brass components). Since the camera has already been purchased and has arrived, procurement is no longer a bottleneck.

Details about the project budget and individual task assignments can be seen in the One Page Project Manager (OPPM). This is included in appendix C.

2.3 Results and Discussion

Testing Methods

With the design of the device finalized and constructed, we ran a series of tests to make sure that everything operates as expected and that the device will not fail. These tests fell into two categories. The first set of tests validated that our system can withstand the conditions in the test lab while the compressor is running. We identified the areas of concern for this category of tests using a risk assessment procedure. The second category of tests validated that our system works as expected and can properly provide the needed monitoring data to the Danfoss Turbocor test lab. Table 9 shows the first set of tests and shows what the passing conditions were for each.

Table 9
Tests run to validate that the system withstands compressor conditions

Test	Passing Conditions
AprilTag Refrigerant Compatibility	Material used to paint the AprilTags on the IGV does not corrode or dissolve in the presence of refrigerant
Sightglass Epoxy Refrigerant Compatibility	Epoxy used to insert the sight glass into the airfoil housing does not corrode or dissolve in the presence of refrigerant
Final Assembly Pressure Test	Epoxy seals withstand the pressures inside the refrigerant loop
Final Assembly Seal Test	Epoxy seals prevent refrigerant leaks into ambient environment

We tested for refrigerant compatibility by exposing a piece of brass coated in our selected paint to the refrigerant for a total of one week. After exposure, we removed the piece of brass to inspect the paint and see if any corrosion had occurred or if the paint dissolved in the environment. We conducted the same test to check the compatibility of the epoxy with the refrigerant where a brass piece containing the epoxy was exposed to refrigerant for one week and inspected to see if there was any corrosion. For the remaining 2 tests, we constructed a separate testing device. This testing device is shown in figure 21.

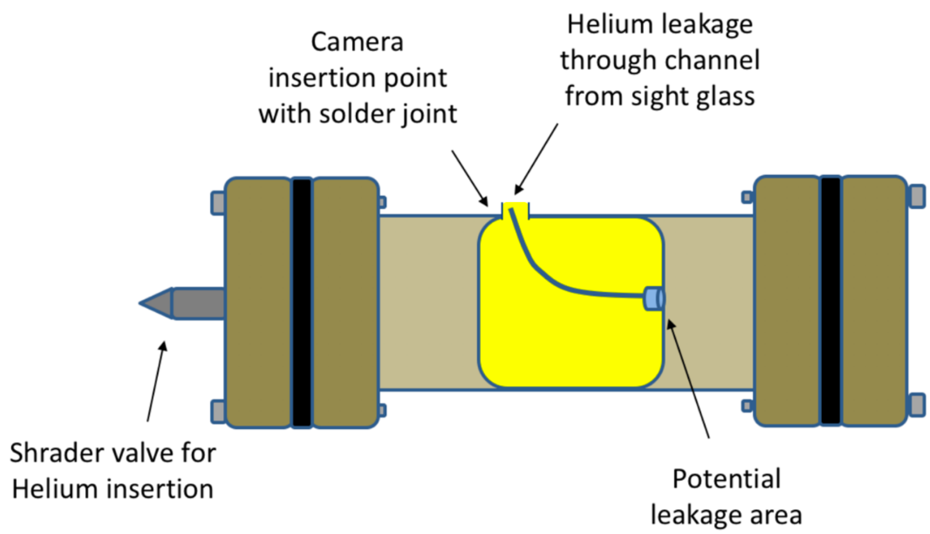


Figure 21 Testing device for leakage and pressure tests.

Since our testing device has flange connections on either end, we used two flange caps to create a sealed environment separate from the compressor refrigerant loop. We modified one of these caps with a Schrader Valve and inserted helium into the assembly for the leak test and water for the pressure test. We inserted helium into the assembly to check if all of the epoxy seals functioned properly and to ensure that no refrigerant would leak. We used the water to test how much pressure the assembly could withstand. We used water instead of gas because the water is incompressible, so if the assembly were to burst, it would not cause an explosion. The results for all of these tests for environment compatibility are in terms of pass/fail. Table 10 below shows the second set of tests that our team ran to make sure that the system works as expected after we verify the environment compatibility.

Table 10
Tests run to validate that the system works as expected

Component Tested	Passing Conditions
Camera Visual System	Camera is centered in pipe and each vane is shown in the video
Angle Measuring System	AprilTags are identified and each angle is calculated to 10°
Lighting System	Lighting is strong enough so that each of the vanes is easily identified by the camera

We tested all of these systems together since they all rely on each other to properly function. The first step in establishing if the system satisfies the passing conditions was to see if the lighting system properly lights the inside of the pipe enough so that each of the vanes is visible. We then tested the camera placement to see if each of the vanes are visible in the camera view. Then we tested the camera and computer software required for reading the AprilTags together to check that the image is sharp enough to pick up the AprilTags. Finally, we tested the accuracy of the tags by comparing the output reading of the computer program with the actual angle of the vanes. We repeated this series of tests for a range of IGV angles while the compressor was running, to validate that the functionality of the device does not change with the angle of the IGVs. Testing the vane visibility and the AprilTag identification occurred on a pass/fail scale while the angle measurement results were in terms of the angle error.

Results

We got the results from the refrigerant exposure testing first since we needed this information first before constructing our final assembly. As previously mentioned, we exposed a piece of brass with the spray paint for the AprilTags and two different epoxies. After examining the brass piece, our team - in conjunction with experts at Danfoss - concluded that the spray paint and one epoxy passed the refrigerant exposure test. The other epoxy did not pass the test because it showed signs of discoloration. Therefore our team decided to only use the epoxy that passed the refrigeration test for the final assembly.

Our team then conduced the pressure and leak tests once we constructed our final assembly. We started with the water burst test by filling the assembly with water in a burst chamber and then rapidly raising the pressure. Since we could not precisely control the pressure inside the assembly, the pressure rose rapidly to 375psi, well above the intended pressure test of 300psi. However, the assembly survived and 12 minutes passed before we decided to pressurized the assembly. From this test, our team determined that the assembly is strong enough to withstand the test conditions in the refrigerant loop. Figure 22 shows some pictures of the burst test setup with the pressure gages showing that our assembly holds 375 psi.

Figure 22 Pressure Burst Test Setup.

Our team then conducted a helium leak test by filling the assembly with helium and checking the leak rate out of the assembly. From this test, we determined that the helium leak rate out of the assembly was 4.67e-7 atm cc/s. This means that our assembly leaks about one cubic centimeter of helium at atmospheric pressure every 26 days. This rate is very much in the range of acceptable leak rates and likely means that no refrigerant will leak into the environment because the refrigerant molecules are much larger than the helium molecules. Based on the results of these tests, our device can withstand the conditions present in the refirgerant loop. Table 11 gives a summary of these test results.

Table 11
Test results to withstand compressor conditions

Test	Result
AprilTag Refrigerant Compatibility	Pass
Sightglass Epoxy Refrigerant Compatibility	Pass
Sightglass Epoxy Pressure Text	Pass
Sightglass Epoxy Seal Test	Pass
Vane Brazing Seal Test	Pass

While these test results verify that our device will work in the short term, we cannot draw any conclusions to indicate that there is a certain lifespan of the device. Our group could only conduct these tests for a short amount of time, so we do not know the long term effects of the environment on the materials used in our final assembly. Table 12 below gives the results of the tests conducted to test the function of the device.

Table 12
Test results to withstand compressor conditions

IGV Position (°)	Vanes can all be seen	AprilTags are picked up by computer	Angle Error (°)
0	Pass	Fail	N/A
10	Pass	Fail	N/A
20	Pass	Fail	N/A
30	Pass	Fail	N/A
40	Pass	Pass	± 2
50	Pass	Pass	± 2
60	Pass	Pass	± 2
70	Pass	Pass	± 2
80	Pass	Pass	± 2
90	Pass	Pass	± 2

Our device was able to properly see the vanes and AprilTags for all angles greater than 30°. At 0° to 10° the AprilTags were not visible because the orientation of the vanes was parallel to the inlet flow and the the camera view, but the vanes were visible and we were able to verify their integrity. The AprilTags were visible in the view of the camera at IGV positions of 10° to

30°, but given the angle of the vane, the computer was not able to pick up the tags and provide a reading. Our device worked properly over the rest of the range of IGV positions and was able to provide angle readings for each of the IGVs. These angle reading were all within the allowable error range and had an error of roughly 2°**.** Figure 23 shows a picture of the inlet taken from behind the assembly and a picture of the camera view from the videoscope. Unfortunately, the AprilTaged vanes were not installed for these pictures.

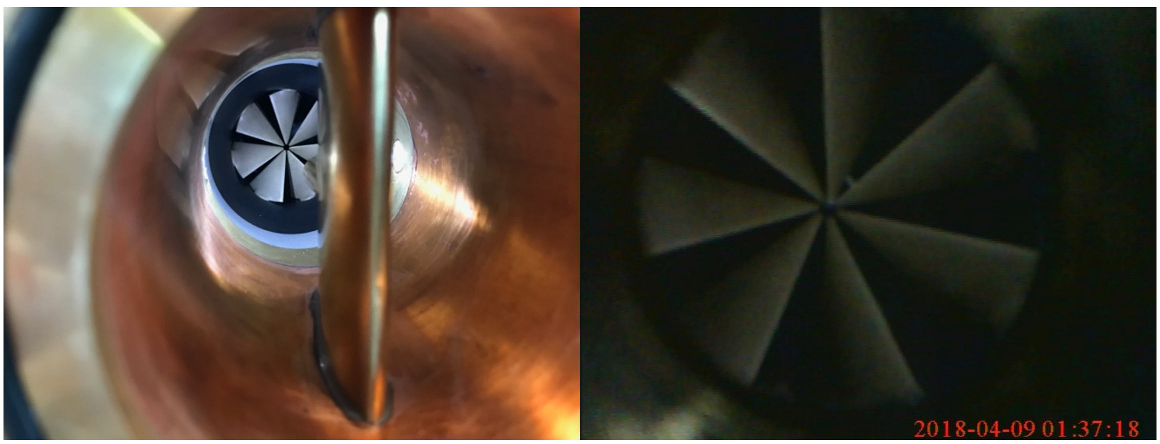


Figure 23 Final assembly and sample image from videoscope.

2.4 Conclusion

Our senior design group was able to design and construct a monitoring device for Danfoss Turbocor that gives the test lab a live feed of the compressor inlet. With this monitoring device, the test lab is able to see the vanes in the camera view for all operating conditions and IGV positions to monitor if any of the vanes have broken off. Additionally, the device allows the test lab to check and verify the angle of the IGVs for all positions of the IGV greater than 30° with an accuracy of up to 2°. With this device, the Danfoss Turbocor testing lab can run tests on their compressor prototypes for weeks at a time with the ability to monitor the IGVs so that there is no risk of corrupting weeks worth of test data due to an unidentified broken vane.

In addition to the advantages that this device provides to the Danfoss Turbocor test lab, our device shows that it is possible to develop a monitoring device that could be used in applications other than the test rig. For example, someone could use this device in the field for compressor installations in areas where regular checks of the IGV are not possible so that maintenance is only called out when there is a confirmation of an IGV breaking.

2.4 Future Work

There are a few things that our group wants to do to make the design of this product even better. First, we would like to conduct more refrigerant compatibility testing on the materials that we used. These tests would focus on long term effects on the materials so that we have a better estimation of the product lifespan and so we can research and select better materials. We would also like to test more high-end cameras. While we think that we picked the best possible camera for our price range, there are more expensive cameras available with larger resolutions and higher frame rates that could make the video sharper and make the AprilTags easier to read. We would like to put some focus on changing the design of the sightglass so that it is modular. This way, inserting the sighglass would not require epoxy and would be much easier to assemble. Additionally, we would like to implement a high cycle monitoring system. This system should measure the vibrations of the vanes to help the test lab identify any failures due to high cycle fatigue. Finally, we would like to further develop the AprilTag software to implement an alarm system so that we can immediately alert the test lab when one of the vanes breaks.

References

Cengel, Yunus A, et al. "Chapter 15: External Flow" Fundamentals of Thermal-Fluid Sciences, McGraw-Hill, 2012. Accessed April 2 2018.

"NACA 0015 - NACA 0015 Airfoil." *NACA 0015 (naca0015-Il)*, airfoiltools.com/airfoil/details?airfoil=naca0015-il.

Appendices

Appendix A: Code of Conduct

Mission Statement

Team 4 is dedicated to ensuring a positive work environment that supports professionalism, integrity, respect, and trust. Every member of this team will contribute a full effort to the creation and maintenance of such an environment to bring out the best in all of us as well as this project.

Roles

Each team member is assigned one of the following roles based on their previous experiences and skill set and is responsible for completing the following actions. All team members must contribute to the project in the following ways:

- Must work on their certain tasks for the project
- Must work toward the project goals and its success
- Deliver any commitments on time
- Work as an effective team member with team spirit

Arnold M. Schaefer - Team Leader

Manages team as a whole; develops a plan and timeline for the project; delegates tasks among group members according to their skill sets; finalizes all documents and provides input on other positions where needed. The team leader is responsible for promoting synergy and increased teamwork. If a problem arises, the team leader will act in the best interest of the project.

The team leader keeps the communication flowing, both between team members and the sponsor. The team leader takes the lead in organizing, planning, and setting up all of the meetings. The team leader will also be responsible for editing the evidence manual and keeping it up to date. The team leader is responsible for the overall project plans and progress.

Brandon A. Klenck - Lead Mechanical Engineer

Takes charge of the mechanical design aspects of the project. Lead ME is responsible for knowing the details for the design, and presenting the options for each aspect to the team for the decision process. Keeps all design documentation for record and is responsible for gathering all reports and maintains product quality and safety. In addition, the lead ME is responsible for keeping a record of all correspondence in group meetings.

Peter R. House – Lead Efficiency Engineer

Takes charge of the efficiency of the project design. Will work in conjunction with the Lead ME to identify problem areas and to work on smaller improvements and iterations leading to a more streamlined final product.

Will also work to identify problematic areas in the rest of the team to try and implement solutions to increase the team's overall workflow. Will finally be responsible for aggregating documentation and working on final presentations.

Travis J. Carter – Operations Officer

Manages the orders and budget and maintains a record of all credits and debits to the project account. Any product of expenditure requests must be presented to the advisor, whom is then responsible for reviewing and the analysis of equivalent/alternative solutions. They then relay the information to the team and if the request is granted, order the selection. A record of all these analyses and budget adjustment must be kept.

Additionally, the Operations Officer will build and maintain the team website to ensure that all relevant information is posted and up to date and maintain the group's one page project manager.

Team Role Matrix

Team Member:	Team Leader	Lead ME	Lead Efficiency Engineer	Operations Officer
Travis Carter				X
Brandon Klenck		X		
Peter House			X	
Arnold Schaefer	X			

Communication

All remote team communication will occur in two main places, GroupMe and email. GroupMe will be used for casual conversations and planning while email will be used for more official purposes such as document preparation, review and submission. Therefore, all team members must have access to a working email account, access to GroupMe and regularly check all accounts to keep up with group progress. All files transferred via email to Danfoss or the instructors should have the rest of the team members carbon copied, while files emailed between team members should only have the rest of the team members carbon copied if their input is needed.

The team will also conduct weekly meetings on Tuesdays and Thursday from 12:30PM to 2:00PM to discuss all progress and further actions. Team members must all be present for this meeting. 24 hour notices should be given if a member cannot make the meeting in time. Repeated absences will not be tolerated. All members of the team must also attend all meetings with the sponsor. 24 hour notices should be given if a member cannot make the meeting in time. Repeated absences will not be tolerated.

All team members must be present for presentation practice sessions in the week leading up to the due date. Practice times will be decided a week in advance at the weekly team meeting.

Team Dynamics

All team members will work with a team dynamic allowing the others to make comments and suggestions without fear of embarrassment or ridicule. If any team member finds their given task too difficult or they face a roadblock, they should inform the rest of the team members and ask for help so that the tasks can be completed with the quality and timeliness expected of our team. If any team member feels that they are not being respected or taken seriously, they should address the issue with the team so that a resolution can be found. Everything is done for the benefit of all members and no individual member should suffer an unequal burden.

Ethics

Team members are required to be familiar with the NSPE Engineering Code of Ethics as they are responsible for their obligations to the public, the client, the employer, and the profession. There will be stringent following of the NSPE Engineering Code of Ethics.

Dress Code

Team meetings will all be held in casual attire. Meetings with the sponsor will be held in business casual attire (i.e. pants & button down shirts). Team presentations will be held in formal attire (i.e. suits). Color coordination will be decided on a case by case basis at team meetings.

Weekly and Biweekly Tasks

Team members will participate in all meetings with the sponsor, adviser, and instructor. During said times ideas, project progress, budget, conflicts, timelines and due dates will be discussed. In addition, tasks will be delegated to team members during these meetings. Repeat absences or incomplete tasks will not be tolerated.

Decision Making

It is conducted by consensus and the majority of the team members. Should ethical or moral reasons be cited for dissenting reason, then the ethics or morals shall be evaluated as a group and the majority will decide on the plan of action. At least 3 team members must participate in the vote. In the case that the vote ends up in a tie, the advisor to the team will be given a vote. Individuals with conflicts of interests should not participate in decision-making processes but do not need to announce said conflict. It is up to everyone to act ethically and for the interest of the group and the goal of the project. Achieving the goal of the project will be the top priority for each group member. Below are the steps to be followed for each decision-making process:

- Problem Definition – Define the problem and understand it. Discuss among the group.
- Tentative Solutions – Brainstorm possible solution. Discuss among most plausible group.

- Data/History Gathering and Analyses – Gather data required for implementing tentative solution. Re-evaluate tentative solution for plausibility and effectiveness.
- Design – Design the tentative solution product and construct it. Re-evaluate for plausibility and effectiveness.
- Test and Simulation/Observation – Test design for tentative solution and gather data. Re-evaluate the testing phase and determine its level of success. Decide if design can be improved and if time/budget allows for it.

Conflict Resolution

In the event of discord amongst team members the following steps shall be employed:

- Communication of points of interest from both parties which may include demonstration of active listening by both parties though paraphrasing or other tools.
- Administration of a vote, if needed, favoring majority rule.
- Team leader intervention.
- Instructor will facilitate the resolution of conflicts.

Work Schedule Prioritization

The team will attempt to organize tasks and meetings in a way that time spent working during the weekend is minimized. In addition, federal, university and religious holidays will be observed and no work will be required of any team member during that time.

Individual Work Schedules

In addition to the weekly team meetings and sponsor meetings, each team member is required to commit to at least 15 working hours per week, and more if needed. This working time can be completed by working on individually assigned tasks or working with others in the team.

Amendment Procedure

In the case that a change is required to be made to this document, the following amendment process will be followed. Any team member can present an amendment in a written email or text message to the group. Following the proposal, each team member must vote on the issue before a decision is made. One vote will be given to each team member with the option to vote for the amendment, vote against the amendment, or to voluntarily abstain from the vote. To pass, the proposal must receive at least 3 votes for the amendment. If the vote is 3 to 1 for the amendment, the change will be made effective one week after the decision is made. A unanimous vote for the proposal will leads to immediate effective implementation. A new code of conduct will then be written and re-signed by all members.

Statement of Understanding

By signing this document, the following members of team 4 agree to all of the above and agree to abide by the code of conduct set forth by the group.

Peter R. House:

Sign: ____________________ Date: 10/5/17

Travis J. Carter:

Sign: ____________________ Date: 10/5/17

Brandon A. Klenck:

Sign: ____________________ Date: 10/05/17

Arnold M. Schaefer:

Sign: ____________________ Date: 10/5/17

Amendments

10/5/17

- Changed team meetings from Thursdays after senior design lectures to Tuesdays and Thursdays from 12:30PM to 2:00PM
- Added team leader responsibility of maintaining the evidence manual
- Added operations officer responsibility of maintaining the one page project manager

Appendix B: Functional Decomposition Charts

Figure 24. Flow diagram of all items in the functional decomposition.

Appendix C: Target Catalogue

Below is a table outlining all of the individual targets that are required for the project.

Table 13
List of Required Targets and Their Values

TARGET	VALUE
Minimum Camera View Resolution	720 x 720 pixels
Minimum Sample Rate for Measuring Vane Low Cycle Failure	1 Hz
Minimum Sample Rate for Measuring Vane High Cycle Failure	1 kHz
Minimum Refresh Rate for Measuring Vane Latching Failure	1 Hz
Minimum Angle Sensor Accuracy (in terms of percent open)	± 10%
Minimum Sample Rate for Measuring Angle	1 Hz
Required Source of Power	US Outlet AC at 110V
Allowable Flow Impact	No Detectible Swirl
Maximum Allowable Pressure Drop Across Device	0.02 psi
Internal Pipe Illumination	1000 lux
Minimum Video Display Resolution	720 x 720 pixels
Minimum Video Display Refresh Rate	60 Hz
Required Inner Pipe Diameter	80 mm
Maximum Monitoring System Length	0.5 m
Minimum Angle Display Refresh Rate	1 Hz
Maximum Refrigerant Pressure	110 psi (absolute)
Minimum Refrigerant Pressure	10 psi (absolute)
Maximum Refrigerant Temperature	80° F
Minimum Refrigerant Temperature	-10° F
Maximum Refrigerant Mass Flow	2.5 kg/s
Minimum Refrigerant Mass Flow	0 kg/s

Appendix D: Engineering Drawings

Inlet Guide Vane Monitoring System Engineering Drawings

Danfoss Turbocor

Mechanical Engineering Department at the **Florida State University**

February 28, 2018

Senior Design Team Members:

Arnold Schaefer - Team Leader

Travis Carter

Brandon Klenck

Peter House

Company Sponsor / Machinist:

William Bilbow / Kevin Lohman

University Professor

Dr. Shayne McConomy

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CONSTRUCTION DETAILS AND NOTES **1**

BILL OF MATERIALS **2**

ENGINEERING DRAWINGS **3-10**

ASSEMBLY – EXPLODED VIEW WITH PARTS LAYOUT 3

ASSEMBLY – COMPLETED VIEW 4

RIGHT AIRFOIL 5

LEFT AIRFOIL 6

ENTRY PIECE 7

ALIGNMENT PIN 8

SUCTION PIPE 9

VIDEOSCOPE HEAD 10

CONSTRUCTION DETAILS AND NOTES

THE INLET GUIDE VANE MONITORING SYSTEM CONSTRUCTION IS BROKEN UP INTO EIGHT MAIN STEPS LAID OUT AS FOLLOWS.

DEFINITIONS:

- THE FRONT OF THE AIRFOIL IS THE SIDE WITH THE CAMERA VIEW.
- THE TOP OF THE AIRFOIL IS THE SIDE WITH THE CAMERA ENTRY.
- THE RIGHT AND LEFT OF THE AIRFOIL ARE DEFINED WHILE LOOKING DOWN THE SUCTION PIPE TOWARDS THE COMPRESSOR IN THE DIRECTION OF THE CAMERA VIEW.
- THE OUTSIDE OF EACH AIRFOIL IS THE SIDE FACING THE SUCTION PIPE WITH THE NACA PROFILE.
- THE INSIDE OF EACH AIRFOIL IS THE SIDE FACING THE MIRRORED AIRFOIL WITH THE FLAT SURFACE AND CAMERA CHANNEL.
- THE CAMERA HOUSING IS THE AREA DIRECTLY BEHIND THE SIGHT GLASS WHERE THE CAMERA HEAD VIEWS THE IGVS.

STEPS 1 THROUGH 3 TO BE COMPLETED IN THE DANFOSS TURBOCOR MACHINE SHOP

STEP 1: CONSTRUCTION OF THE PIPE CHANNEL AND ALIGNMENT HOLES ON THE INSIDE OF EACH AIRFOIL

1. MACHINE AT DANFOSS TURBOCOR MACHINE SHOP
2. START WITH TWO COPPER BLOCKS.
3. ON THE INSIDE OF THE AIRFOIL, MACHINE THE CHANNEL FOR THE PIPE WITH A BALL END MILL AS SHOWN IN THE ENGINEERING DRAWINGS.
4. DRILL THE ALIGNMENT PIN HOLES WITH A DRILL POINT MILL.

STEP 2: CONSTRUCTION OF NACA PROFILE ON OUTSIDE OF EACH AIRFOIL

1. MACHINE THE NACA AND CYLINDER PROFILE USING A CNC MILL WITH THE DIMENSIONS AND TOLERANCES IN THE ENGINEERING DRAWINGS.
2. MACHINE THE TOP AND BOTTOM EDGES TO A RADIUS SLIGHTLY SMALLER THAN THE INSIDE RADIUS OF THE SUCTION PIPE FOR EASE OF SOLDERING.

STEP 3: MACHINING OF ENTRY PIECE

1. MACHINE THE ENTRY PIECE TO THE DIMENSIONS AND TOLERANCES IN THE ENGINEERING DRAWINGS.
2. DIMENSIONS OF THIS PIECE TO BE SLIGHTLY SMALLER THAN THE AIRFOIL HOLE TO PROVIDE ROOM FOR THE SOLDER JOINT.

STEP 4: FIT TEST

1. TEST FIT LEFT AND RIGHT AIRFOIL ALIGNMENT WITH SLIP FIT PINS. PAY CLOSE ATTENTION TO EDGE ALIGNMENT OF ENTRY HOLE. EDGES TO BE WITHIN A 0.05MM TOLERANCE.
2. TEST FIT IN SUCTION PIPE AS ONE PIECE. AIRFOIL SHOULD BE A TIGHT FIT IN THE SUCTION PIPE AND STICK IN PLACE.

STEPS 5 AND 6 TO BE OUTSOURCED TO PRECISION BRAZING

STEP 5: ATTACHMENT OF LEFT AND RIGHT AIRFOILS

1. ALIGN THE TWO AIRFOILS TOGETHER WITH THE SLIP FIT ALIGNMENT PINS IN PLACE.
2. SOLDER THE FLAT INSIDE SURFACES OF THE AIRFOIL TOGETHER.

STEP 6: ATTACHMENT OF AIRFOIL TO INSIDE SURFACE OF SUCTION PIPE

1. LINE UP CENTERLINE OF AIRFOIL WITH CENTERLINE OF THE SUCTION PIPE.
2. INSERT ENTRY PIECE INTO AIRFOIL THROUGH THE TOP OF THE SUCTION PIPE.
3. SOLDER ALONG ALL JOINING SURFACES OF THE AIRFOIL, ENTRY PIECE AND SUCTION PIPE.

STEPS 7 THROUGH 12 TO BE COMPLETED IN THE DANFOSS TURBOCOR MACHINE SHOP

STEP 7: FABRICATION OF SIGHT GLASS AND CAMERA HEAD CASING ON FRONT OF AIRFOIL

1. DRILL, BORE AND REAM THE HOLE FOR THE CAMERA.
2. DRILL, BORE AND REAM THE HOLE FOR THE SIGHT GLASS.

STEP 8: FINISH AND POLISH THE BRASS AIRFOIL

1. DEBUR ANY ROUGH EDGES.
2. RINSE BRASS WITH SOAP AND WATER.
3. POLISH WITH BRASS CLEANER.
4. BUFF BRASS TO SHINY FINISH.

STEP 9: CUT HOLE IN SUCTION PIPE WITH CNC MILL TO DIMENSIONS AND TOLERANCES IN ENGINEERING DRAWINGS

STEP 10: ATTACHMENT AND SEAL OF SIGHT GLASS

1. TEST THE SEALANT FOR REFRIGERANT COMPATIBILITY PRIOR TO USE.
2. ROUGH THE EDGES OF THE SIGHT GLASS AND THE INSIDE OF THE SIGHT GLASS HOUSING IN THE AIRFOIL FOR SEALANT TO SEEP INTO.
3. APPLY THIN LAYER OF SEALANT TO OUTSIDE CURVED SURFACE OF SIGHT GLASS ONLY.
4. INSERT SIGHT GLASS INTO HOUSING WHILE TWISTING TO GIVE SEALANT CONTACT ACROSS ENTIRE CURVED SURFACE OF HOUSING AND SIGHT GLASS.
5. CLAMP THE SIGHT GLASS INTO ITS HOUSING OR HOLD TIGHTLY IN PLACE TO PREVENT SEALANT FROM FLOWING INTO CAMERA HOUSING. THIS IS MEANT TO CREATE A GLASS TO BRASS SEAL ON THE BACK SURFACE OF THE SIGHT GLASS.
6. APPLY EXTRA SEALANT AROUND CIRCUMFERENCE OF SIGHT GLASS LETTING THE SEALANT FILL AROUND THE GLASS. WIPE OFF FRONT OF GLASS.
7. USE MINIMAL AMOUNT OF SEALANT SO OVERFLOW DOES NOT ENTER THE CAMERA HOUSING.

STEP 12: LIGHTING SUBSYSTEM TO FOLLOW

STEP 13: PERFORM PRESSURE TEST

1. ATTACH FLANGE CONNECTION TO FRONT END OF MONITORING SYSTEM AND CONNECT TO TEST STAND.
2. BRING PRESSURE IN PIPE UP TO 300 PSI FOR 10 MINUTES AND PERFORM LEAK TEST TO ENSURE NO LEAKAGE INTO THE ATMOSPHERE BEFORE INTRODUCTION OF REFRIGERANT.

FINAL STEP 13 COMPLETED BY SENIOR DESIGN TEAM IN CONJUNCTION WITH DANFOSS TURBOCOR TESTING LAB

STEP 13: HOOK UP CAMERA SYSTEM TO TESTING AND MONITORING EQUIPMENT

SHEET 1 OF 13

BILL OF MATERIALS

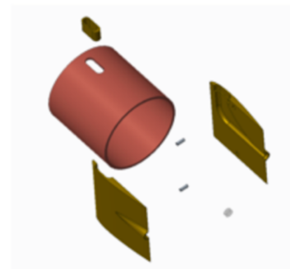
Assembly Name: IGV Monitoring System

Review Date: Wednesday, February 28, 2018

Assembly Revision: 3

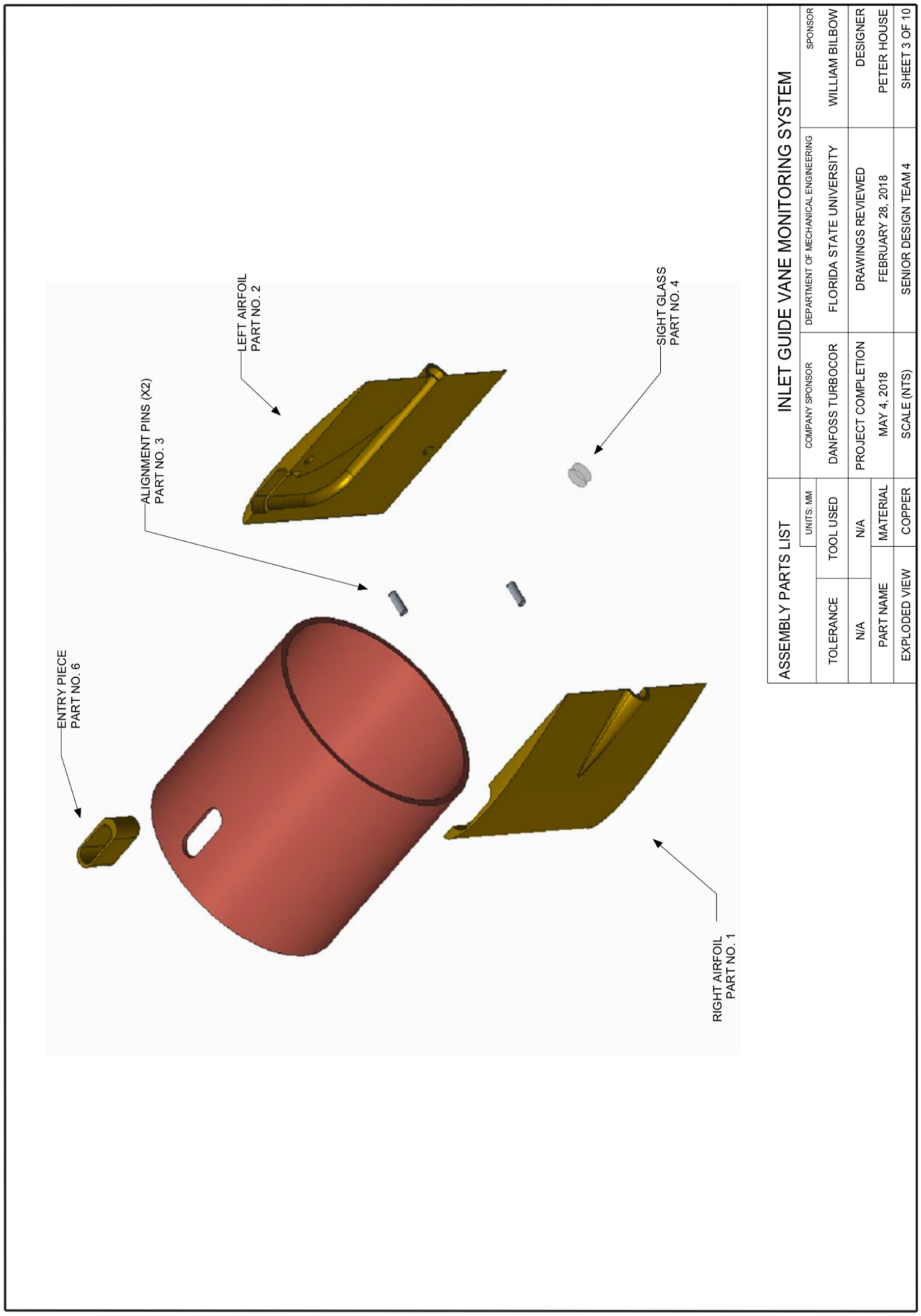
Part Count: 9

Total Material Cost: $1,370.92



Part #	Part Name	Description	Qty	Supplier	Material	Cost per Item	Estimated Total Cost
1	Right Airfoil	The left side of the airfoil casing to house the camera	1	Danfoss Turbocor	Brass	$53.00	$53.00
2	Left Aifoil	The right side of the airfoil casing to house the camera. Mirrored version of the right airfoil	1	Danfoss Turbocor	Brass	$53.00	$53.00
3	Alignment Pin	3x8mm pins to align the two airfoil halves	2	Danfoss Turbocor	Steel	$0.00	$0.00
4	Sight Glass	7.5x3mm glass cut with a diamond drill bit and smoothed to fit copper housing in airfoil	1	Senior Design Team	Glass	$0.00	$0.00
5	Suction Pipe	Suction pipe with flange connection to attach to the inlet of the TT-series oil free compressor	1	Danfoss Turbocor	Brass	$0.00	$0.00
6	Entry Piece	Insertion piece for surface area increase at camera point of entry	1	Danfoss Turbocor	Brass	$20.00	$20.00
7	Videoscope	Extech HDV540 High Definition Videoscope	1	Extech	Misc.	$1,200.00	$1,200.00
8	Sealant	High-Strenth Silicone Sealants Model RTV157 from McMaster-Carr	1	Danfoss Turbocor	Sealant	$44.92	$44.92
		Total:	9	Estimated Total Material Cost:			$1,370.92

SHEET 2 OF 13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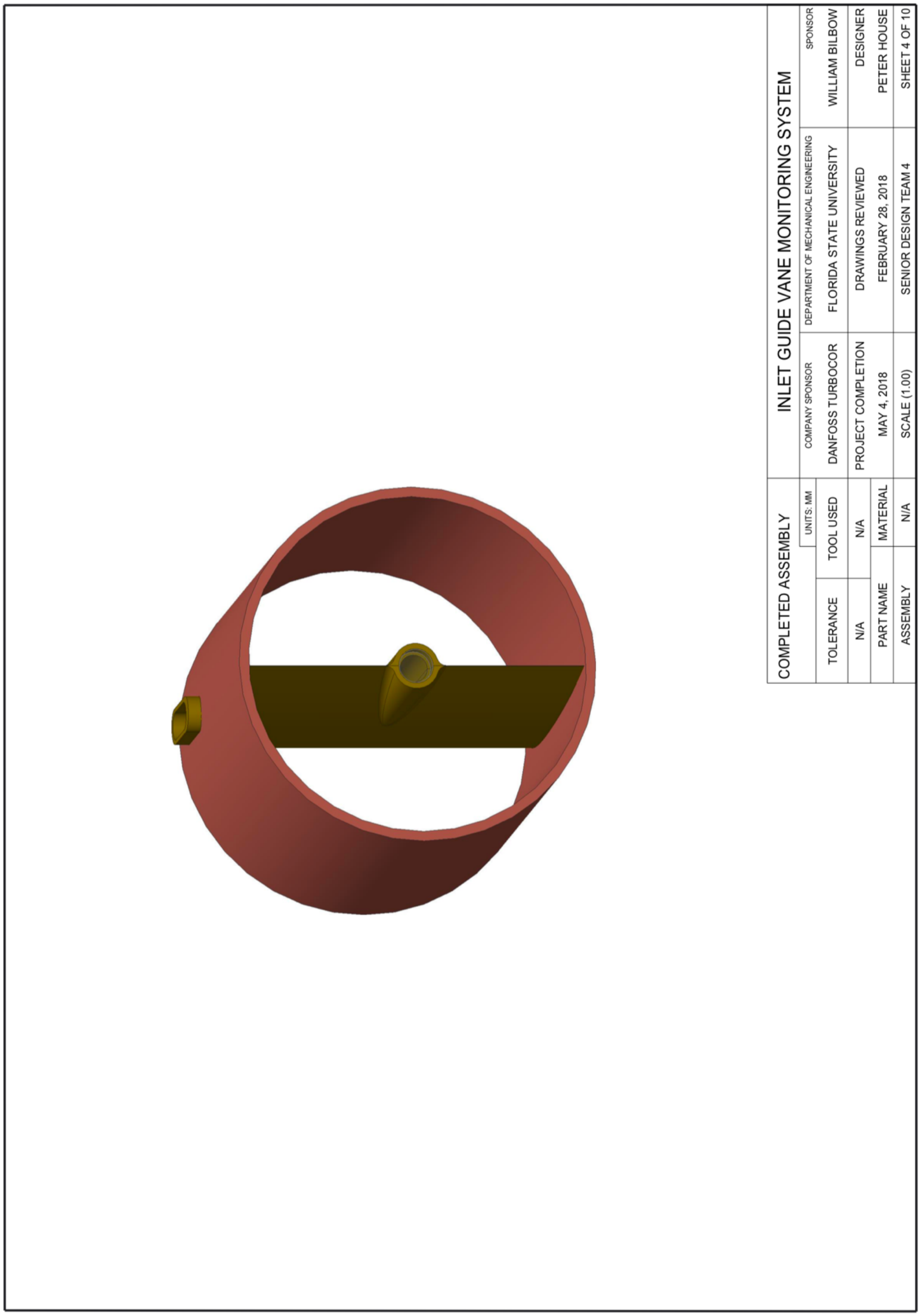
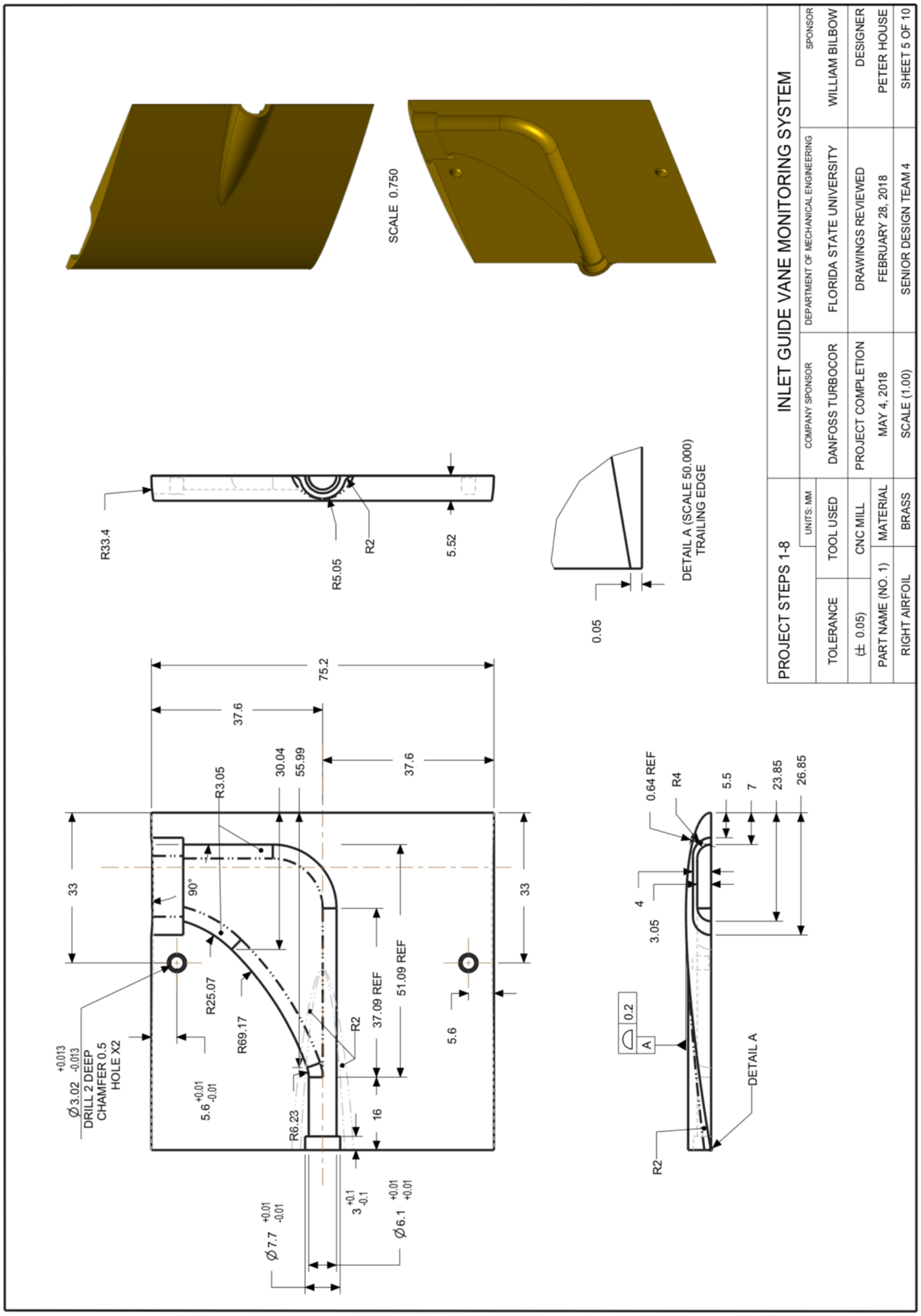
PART NO. 6
ALIGNMENT PINS (X2)
PART NO. 3
LEFT AIRFOIL
PART NO. 2
SIGHT GLASS
PART NO. 4
RIGHT AIRFOIL
PART NO. 1
ASSEMBLY PARTS LIST
UNITS: MM
TOLERANCE
TOOL USED
N/A
N/A
PART NAME
MATERIAL
EXPLODED VIEW
COPPER
INLET GUIDE VANE MONITORING SYSTEM
COMPANY SPONSOR
DANFOSS TURBOCOR
PROJECT COMPLETION
MAY 4, 2018
SCALE (NTS)
DEPARTMENT OF MECHANICAL ENGINEERING
FLORIDA STATE UNIVERSITY
DRAWINGS REVIEWED
FEBRUARY 28, 2018
SENIOR DESIGN TEAM 4
SPONSOR
WILLIAM BILBOW
DESIGNER
PETER HOUSE
SHEET 3 OF 10


INLET GUIDE VANE MONITORING SYSTEM
COMPLETED ASSEMBLY
UNITS: MM
TOLERANCE
N/A
TOOL USED
N/A
PART NAME
ASSEMBLY
MATERIAL
N/A
COMPANY SPONSOR
DANFOSS TURBOCOR
PROJECT COMPLETION
MAY 4, 2018
SCALE (1.00)
DEPARTMENT OF MECHANICAL ENGINEERING
FLORIDA STATE UNIVERSITY
DRAWINGS REVIEWED
FEBRUARY 28, 2018
SENIOR DESIGN TEAM 4
SPONSOR
WILLIAM BILBOW
DESIGNER
PETER HOUSE
SHEET 4 OF 10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TOLERANCE
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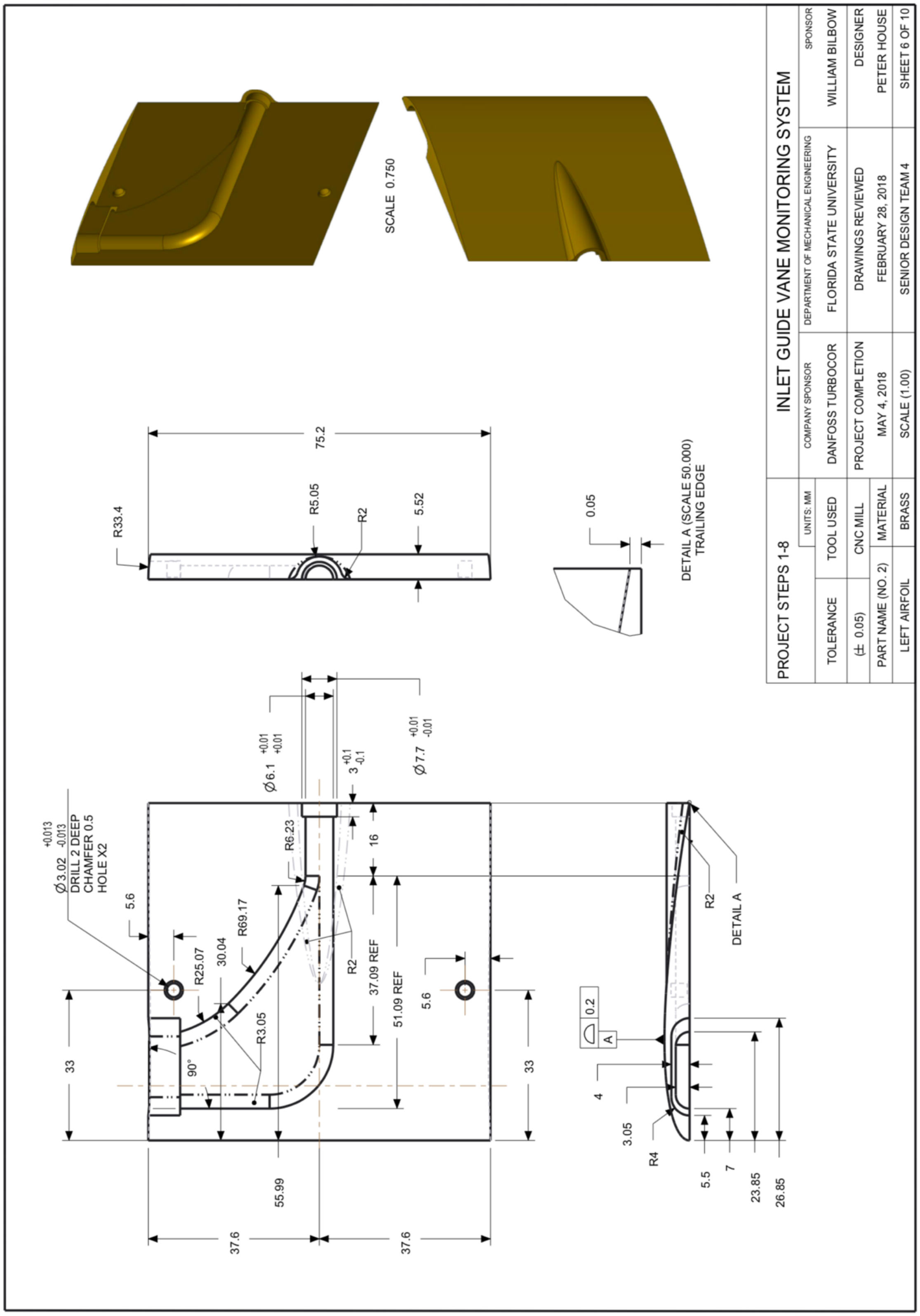
PART NAME (NO. 1)
RIGHT AIRFOIL
TOOL USED
CNC MILL
MATERIAL
BRASS
COMPANY SPONSOR
DANFOSS TURBOCOR
PROJECT COMPLETION
MAY 4, 2018
SCALE (1.00)
DEPARTMENT OF MECHANICAL ENGINEERING
FLORIDA STATE UNIVERSITY
DRAWINGS REVIEWED
FEBRUARY 28, 2018
SENIOR DESIGN TEAM 4
SPONSOR
WILLIAM BILBOW
DESIGNER
PETER HOUSE
SHEET 5 OF 10
SCALE 0.750
DETAIL A (SCALE 50.000)
TRAILING EDGE
DETAIL A
DRILL 2 DEEP
CHAMFER 0.5
HOLE X2



PROJECT STEPS 1-8
INLET GUIDE VANE MONITORING SYSTEM
TOLERANCE
(± 0.05)
UNITS: MM
TOOL USED
CNC MILL
COMPANY SPONSOR
DANFOSS TURBOCOR
DEPARTMENT OF MECHANICAL ENGINEERING
FLORIDA STATE UNIVERSITY
SPONSOR
WILLIAM BILBOW
PART NAME (NO. 2)
LEFT AIRFOIL
MATERIAL
BRASS
PROJECT COMPLETION
MAY 4, 2018
DRAWINGS REVIEWED
FEBRUARY 28, 2018
DESIGNER
PETER HOUSE
SCALE (1.00)
SENIOR DESIGN TEAM 4
SHEET 6 OF 10
SCALE 0.750
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TRAILING EDGE
DETAIL A
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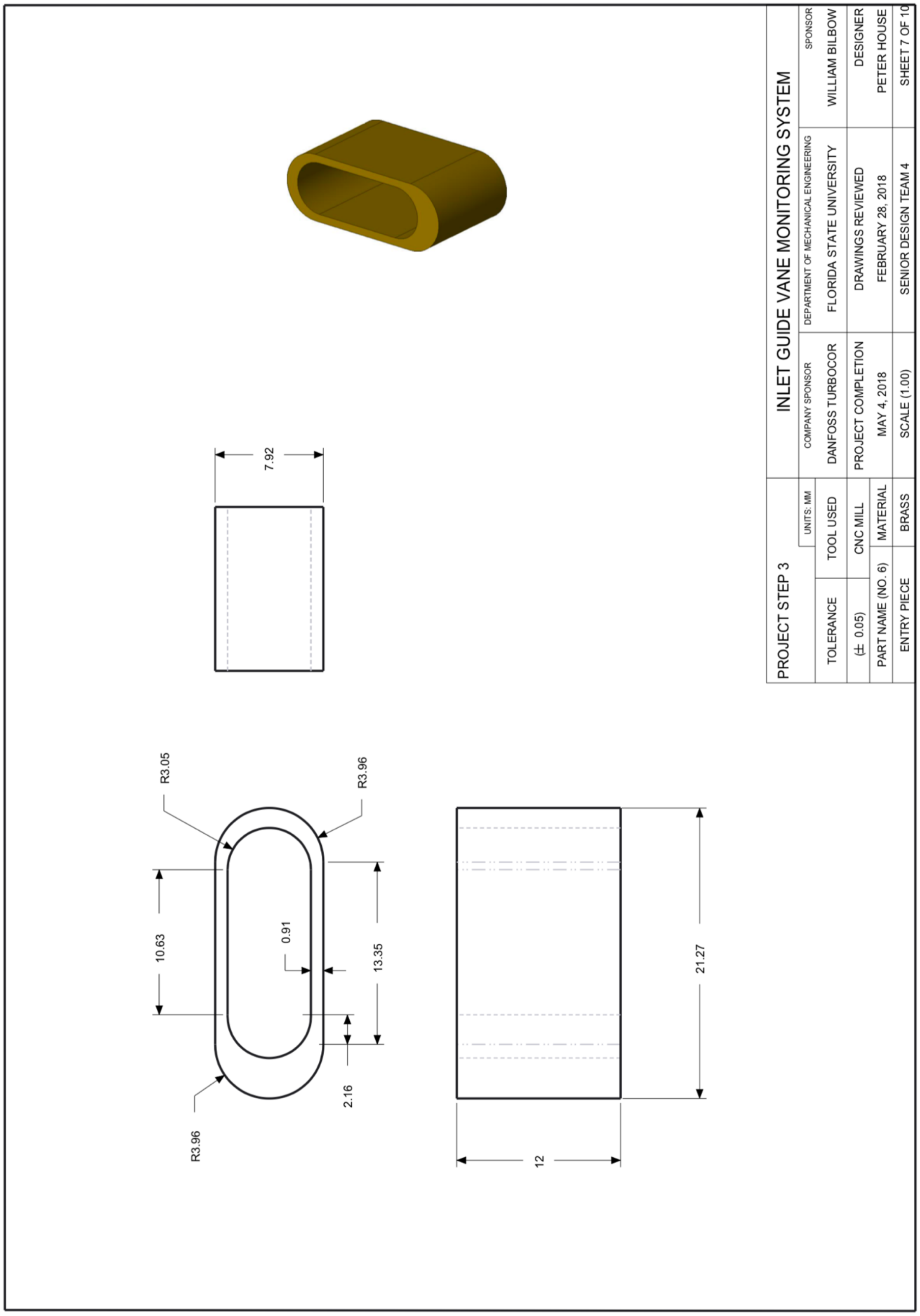
CHAMFER 0.5
HOLE X2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DEPARTMENT OF MECHANICAL ENGINEERING
SPONSOR
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TOOL USED
DANFOSS TURBOCOR
FLORIDA STATE UNIVERSITY
WILLIAM BILBOW
(± 0.05)
CNC MILL
PROJECT COMPLETION
DRAWINGS REVIEWED
DESIGNER
PART NAME (NO. 6)
MATERIAL
MAY 4, 2018
FEBRUARY 28, 2018
PETER HOUSE
ENTRY PIECE
BRASS
SCALE (1.00)
SENIOR DESIGN TEAM 4
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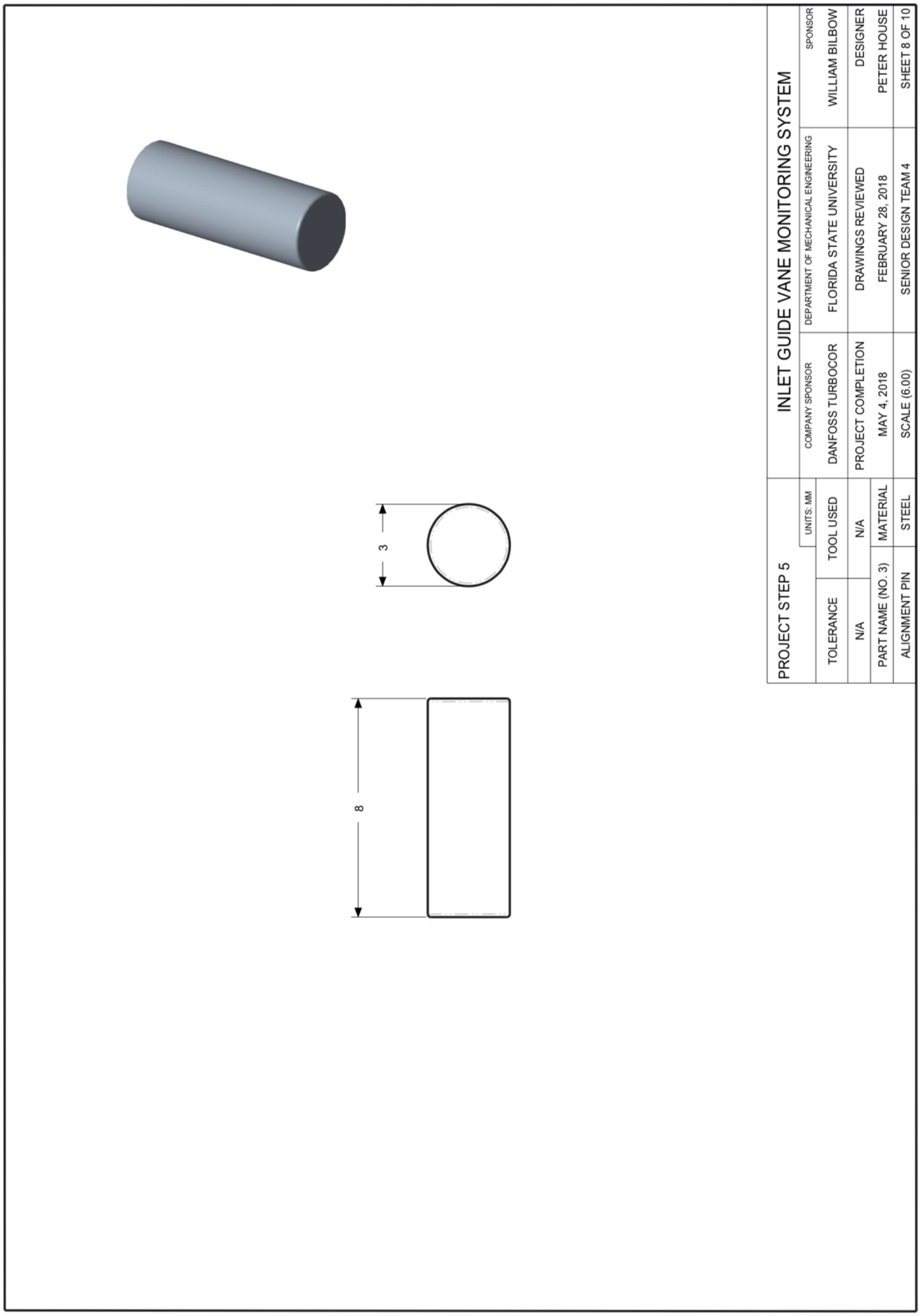
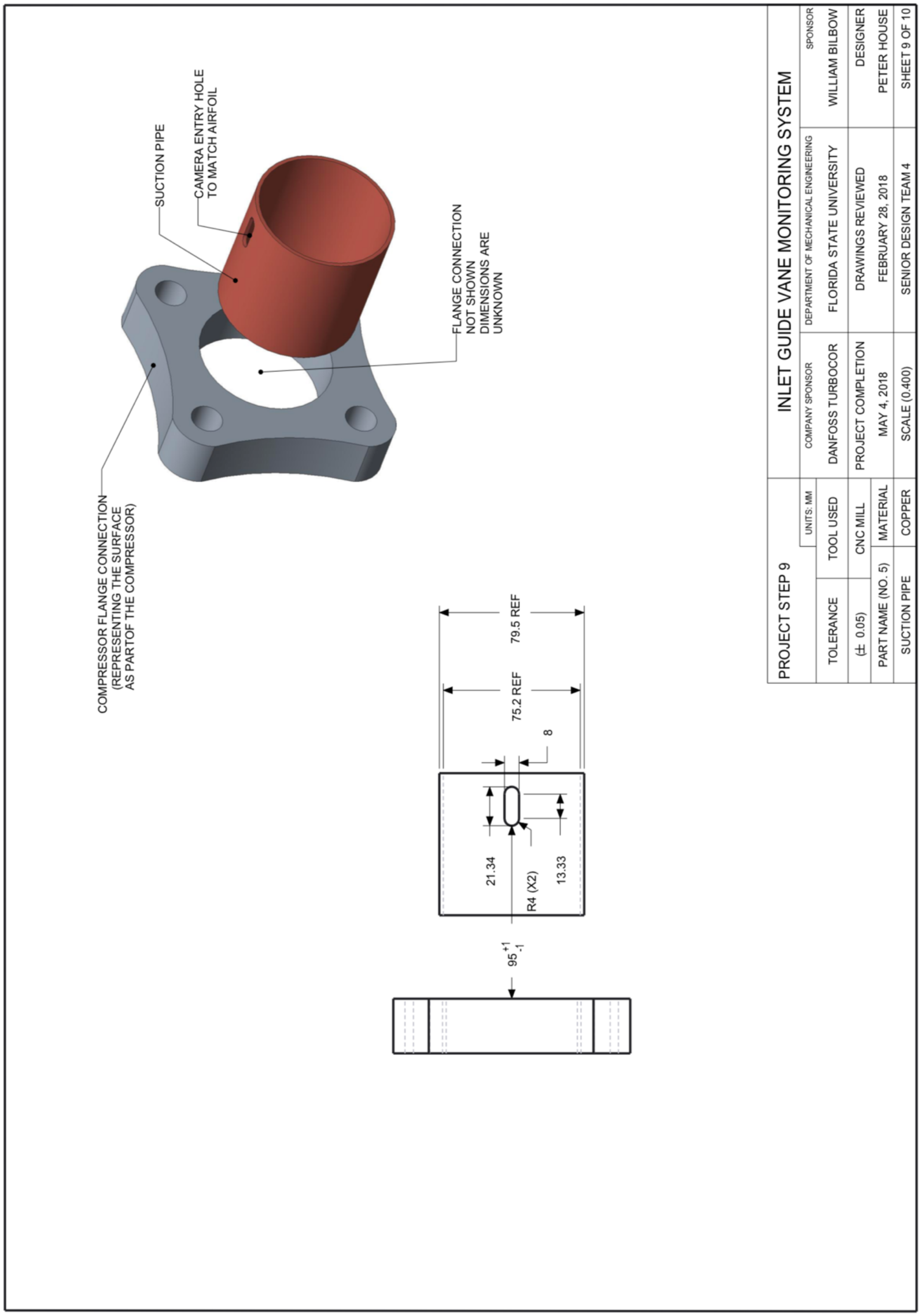
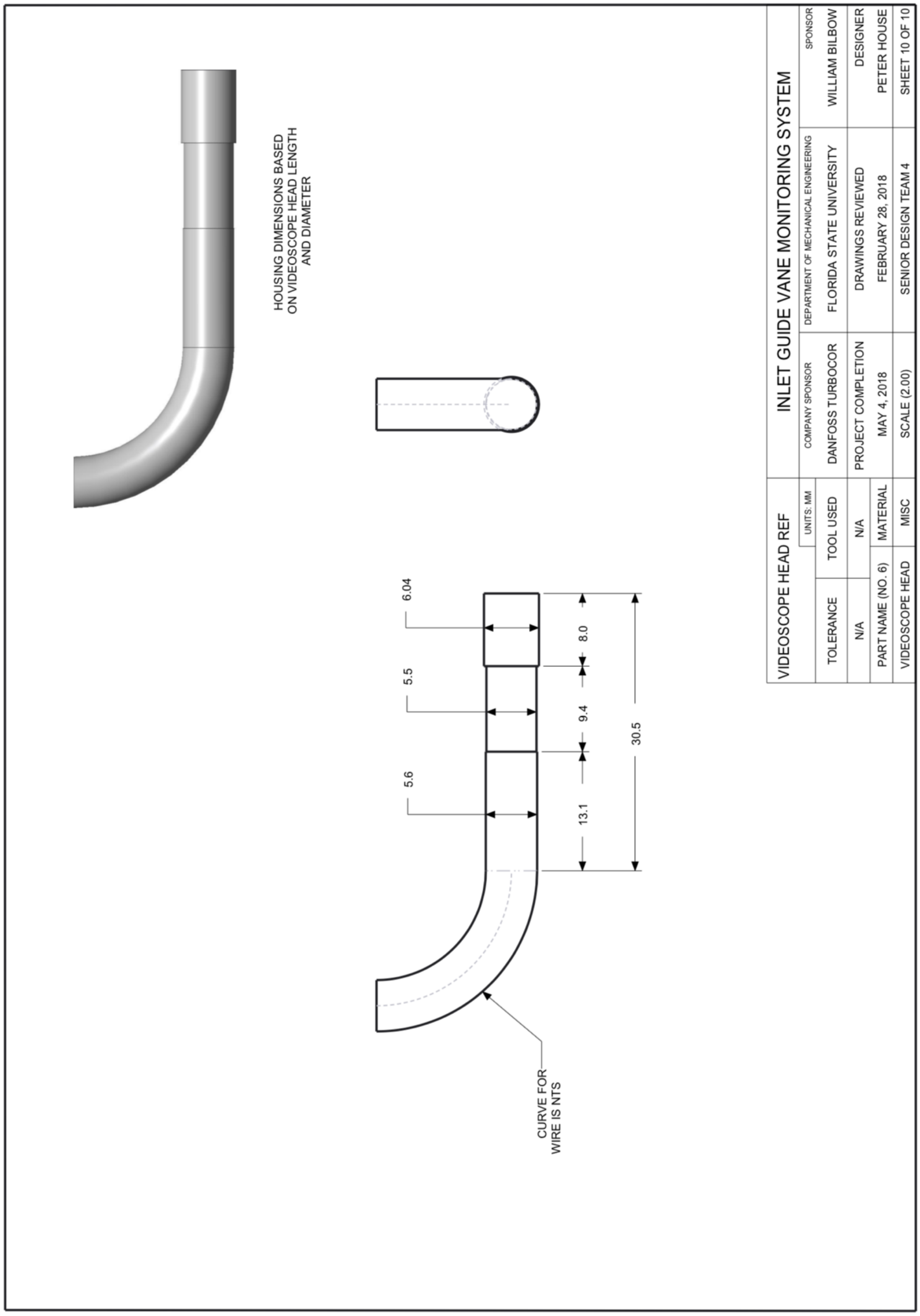


INLET GUIDE VANE MONITORING SYSTEM
PROJECT STEP 5
UNITS: MM
TOLERANCE
N/A
TOOL USED
N/A
COMPANY SPONSOR
DANFOSS TURBOCOR
DEPARTMENT OF MECHANICAL ENGINEERING
FLORIDA STATE UNIVERSITY
SPONSOR
WILLIAM BILBOW
PART NAME (NO. 3)
ALIGNMENT PIN
MATERIAL
STEEL
PROJECT COMPLETION
MAY 4, 2018
DRAWINGS REVIEWED
FEBRUARY 28, 2018
DESIGNER
PETER HOUSE
SCALE (6.00)
SENIOR DESIGN TEAM 4
SHEET 8 OF 10
3
8

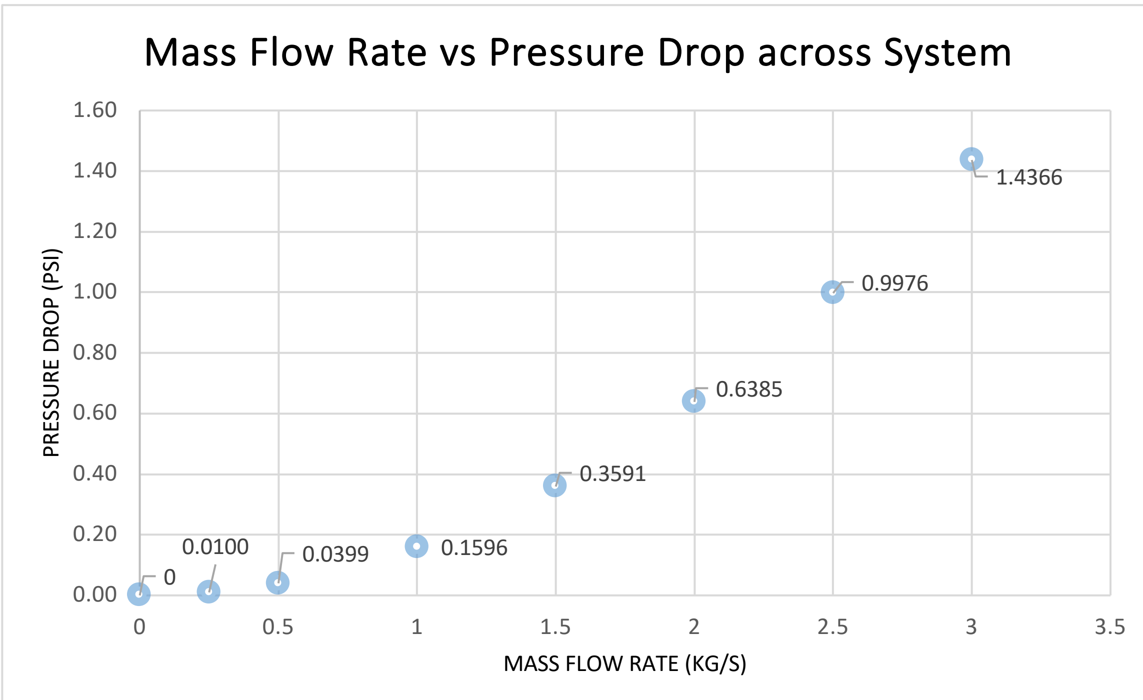

SUCTION PIPE
CAMERA ENTRY HOLE TO MATCH AIRFOIL
FLANGE CONNECTION NOT SHOWN DIMENSIONS ARE UNKNOWN
COMPRESSOR FLANGE CONNECTION (REPRESENTING THE SURFACE AS PARTOF THE COMPRESSOR)
79.5 REF
75.2 REF
8
21.34
R4 (X2)
13.33
95 +1 -1
PROJECT STEP 9
INLET GUIDE VANE MONITORING SYSTEM
UNITS: MM
COMPANY SPONSOR
DEPARTMENT OF MECHANICAL ENGINEERING
SPONSOR
TOLERANCE
TOOL USED
DANFOSS TURBOCOR
FLORIDA STATE UNIVERSITY
WILLIAM BILBOW
(± 0.05)
CNC MILL
PROJECT COMPLETION
DRAWINGS REVIEWED
DESIGNER
PART NAME (NO. 5)
MATERIAL
MAY 4, 2018
FEBRUARY 28, 2018
PETER HOUSE
SUCTION PIPE
COPPER
SCALE (0.400)
SENIOR DESIGN TEAM 4
SHEET 9 OF 10


HOUSING DIMENSIONS BASED
ON VIDEOSCOPE HEAD LENGTH
AND DIAMETER
6.04
5.5
5.6
8.0
9.4
13.1
30.5
CURVE FOR
WIRE IS NTS
VIDEOSCOPE HEAD REF
UNITS: MM
TOLERANCE
N/A
TOOL USED
N/A
PART NAME (NO. 6)
VIDEOSCOPE HEAD
MATERIAL
MISC
INLET GUIDE VANE MONITORING SYSTEM
COMPANY SPONSOR
DANFOSS TURBOCOR
DEPARTMENT OF MECHANICAL ENGINEERING
FLORIDA STATE UNIVERSITY
SPONSOR
WILLIAM BILBOW
PROJECT COMPLETION
MAY 4, 2018
DRAWINGS REVIEWED
FEBRUARY 28, 2018
DESIGNER
PETER HOUSE
SCALE (2.00)
SENIOR DESIGN TEAM 4
SHEET 10 OF 10

Appendix E: Calculations

Below is a table outlining all of the individual targets that are required for the project.

Calculations of the pressure drop across the system a varying with flow rate in the suction pipe using Bernoulli's equation based on an orifice calculation.



Variable Properties	Symbol	Units	Table with Pressure Drops Varying with Different Mass Flow Rates							
Mass Flow Rate	$\dot{m}$	kg/s	0	0.25	0.5	1.0	1.5	2.0	2.5	3.0
Volume Flow Rate	$\dot{V}$	m^3/s	0	0.0179	0.0357	0.0714	0.1071	0.1429	0.1786	0.2143
Velocity without Device	V_1	m/s	0	3.94	7.87	15.75	23.62	31.49	39.36	47.24
Velocity with Device	V_2	m/s	0	5.03	10.06	20.13	30.19	40.26	50.32	60.38
Pressure Drop across System	ΔP	Pa	0	69	275	1101	2476	4402	6878	9905
Pressure Drop across System	**ΔP**	**PSI**	**0**	**0.0100**	**0.0399**	**0.1596**	**0.3591**	**0.6385**	**0.9976**	**1.4366**

Constant Properties	Symbol	Units	Constants
Density of R134a	ρ	kg/m^3	14
Inside Diameter of Pipe	ID	m	0.076
Diameter of Camera with Case	D_c	m	0.01372
Area of Camera	A_c	m^2	1.48E-04
Length of Vane	L_v	m	0.070
Width of Vane	W_v	m	0.00400
Area of 1 Vane	A_{v1}	m^2	2.80E-04
Area of 3 Vanes	A_{v3}	m^2	8.40E-04
Area of Wire	A_w	m^2	0.00E+00
Area of Device	A_d	m^2	9.88E-04
Area of Flow without Device	A_1	m^2	0.00454
Area of Flow with Device	A_2	m^2	0.00355
Percentage of Area Used	P_A	%	78.2%

Pressure calculation of needed epoxy shear strength.

	Data	Units	Data	Units
Model	1838L	N/A	RTV157	N/A
Type	Epoxy	N/A	Sealant	N/A
Tensile Strength	4167	PSI	975	PSI
Shear Strength (55% of Tensile)	2500	PSI	585	PSI
Pressure inside pipe required to cause shear	-3995	PSI	-927	PSI
Shear force from epoxy/sealant	274	lbf	64	lbf
Force on the glass due to atmospheric pressure	0.68	lbf	0.68	lbf
Force on the glass due to pressure in suction pipe (Worst Case)	0	lbf	0	lbf

Calculation for needed sight glass thickness for plexiglass and glass.

Sight Glass Material: Plexiglass	Symbol	Metric	Imperial	Units
Radius of Unsupported Area	R	3	0.12	mm and in.
Area of Unsupported Area	A	28.3	0.0438	mm2 and s
Safety Factor	F	7	7	N/A
Modulus of Rupture	M	72.4	10500	Mpa and PSI
Ambient Pressure across Material	P	2.21	320	Mpa and PSI
Thickness Needed	**T**	**1.39**	**0.0547**	**mm and in.**

Safety Factor	110	110	320	320 PSI
1	0.308	0.012	0.526	0.021
2	0.436	0.017	0.743	0.029
4	0.616	0.024	1.051	0.041
5	0.689	0.027	1.175	0.046
6	0.755	0.030	1.287	0.051
7	0.815	0.032	1.390	0.055

Sight Glass Material: Glass	Symbol	Metric	Imperial	Units
Radius of Unsupported Area	R	3	0.12	mm and in.
Area of Unsupported Area	A	28.3	0.0438	mm2 and s
Safety Factor	F	7	7	N/A
Modulus of Rupture	M	27.5	3989	Mpa and PSI
Ambient Pressure across Material	P	2.21	320	Mpa and PSI
Thickness Needed	**T**	**2.26**	**0.0888**	**mm and in.**

Safety Factor | Pressure in Pipe	110	110	320	320 PSI
1	0.308	0.012	0.526	0.021
2	0.707	0.028	1.206	0.047
4	1.000	0.039	1.705	0.067
5	1.118	0.044	1.907	0.075
6	1.225	0.048	2.089	0.082
7	1.323	0.052	2.256	0.089

Appendix F: Risk Assessment

Project information:		
Danfoss Turbocor Compressor Inlet Sting Apparatus		Date of submission
Dynamic real-time monitoring and recording of compressor inlet guide vane operations		March 2, 2018
Team Member	**Phone Number**	**e-mail**
Arnold Schaefer	(561) 578-7771	ams14w@my.fsu.edu
Brandon Klenck	(321) 544-0026	bak14@my.fsu.edu
Travis Carter	(407) 414-9447	tjc13f@my.fsu.edu
Peter House	(850) 566-3098	prh13@my.fsu.edu
Faculty mentor	**Phone Number**	**e-mail**
William Bilbow	N/A	william.bilbow@danfoss.com
Shayne McConomy	N/A	smcconomy@eng.famu.fsu.edu
Kunihiko Taira	N/A	ktaira@fsu.edu
Obiechina Abakporo	N/A	abakporo@caps.fsu.edu

I. Project description:

Our project provides Danfoss Turbocor with a method of real time monitoring and recording of the Inlet Guide Vanes (IGVs) at the front of the compressor to help determine the failure modes for the IGVs. It achieves this through a camera placed in front of the inlet in an aerodynamic housing spanning the diameter of the pipe. This housing acts as a sealed chamber that the camera sits in which protects it from the refrigerant flowing through the inlet pipe. The lighting for the vanes is provided by integrated lights in the video scope which shine through the sight glass at the front of the housing. To determine the angle of the IGVs, April Tag codes placed on the IGVs will be read in by the camera. These codes will either be placed on the vanes using stickers or painted directly onto the vanes using refrigerant resistant paint. With these codes on the vanes, computer software with access to the camera feed will be able to approximate the angle of the IGVs.

II. Describe the steps for your project:

When installing the system into the testing loop, the first step is to attach the tags to the IGVs at the front of the compressor. Then the front flange is connected to the front of the compressor, and the rear of the system is connected to the rest of the refrigerant loop with a brazing process. Once the system is integrated into the testing loop, the camera can be inserted into the top of the camera housing until it is resting in front of the sight glass. Then the camera is connected to the computer at the Danfoss testing facilities where the video feed is processed to output the angle of the vanes. Once testing is complete, the camera will be disconnected from the computer and removed from the housing. The pipe section can then be removed from the testing loop by disconnecting the flange connection and breaking the brazed connection at the rear. Finally, the tags can be removed now that the inlet of the compressor is exposed.

III. Given that many accidents result from an unexpected reaction or event, go back through the steps of the project and imagine what could go wrong to make what seems to be a safe and well-regulated process turn into one that could result in an accident. (See examples)

There are limited risks while installing and removing the device in the test lab that could cause significant damage, more of the risks occur while the compressor is running and the camera is recording a video feed while inside the housing where none of the previous steps are taking place and where no action is required. However, some of the risks associated with the installation include: the flange or braze seal at the front and rear of the compressor not being sealed correctly, the camera being damaged while being inserted to the housing, and incorrectly attaching the tags to the inlet guide vanes.

IV. Perform online research to identify any accidents that have occurred using your materials, equipment or process. State how you could avoid having this hazardous situation arise in your project.

There are quite a few accidents that could occur while the system is running that we have identified from some online research and extensive discussions with Danfoss. The largest risk associated with our project is that the sight glass of the camera housing fails. This can happen in a few different ways. The first is where the sight glass breaks and shatters due to the pressure differences on either side of the sight glass. A shattered sight glass could expose the compressor to small glass particles entering the inlet flow and damaging the IGVs or the impellers. The other failure mode of the sight glass occurs if the epoxy holding the sight glass in place fails causing the entire sight glass to enter the front of the compressor. This would cause more damage than the shattered sight glass since a larger particle is entering the compressor. In both of these scenarios, the camera could be damaged due refrigerant exposure in the pipe. This risk could be mitigated by modifying the design so that there is a mechanical constraint to keep the sight glass from popping out as a single piece. Additionally, the thickness of the glass could be increased to have a larger safety factor with respect to the pressures. Another risk associated with our project is if our tags on the IGVs fail.

With both stickers or paint the risk of damaging the compressor is minimal since none of the materials used will be strong enough to damage the impellers. Instead, there is the risk of contaminating the refrigerant in the loop and the associated time required to reapply the tags to the IGVs. This risk could be mitigated by etching the required patters directly into the vanes which would add some time to the installation and could impact the fluid dynamics of the vanes in operation.

V. For each identified hazard or "what if" situation noted above, describe one or more measures that will be taken to mitigate the hazard. (See examples of engineering controls, administrative controls, special work practices and PPE).

For the risks associated with the sight glass, we will conduct testing with sample sight glasses in an effort to provide Danfoss with estimates in the lifespan of the glass and the epoxy. Additionally, we will include inspection steps in our installation procedure to make sure that there are no cracks in the sight glass or gaps in the epoxy before being installed to the refrigerant loop. We will also suggest that the compressor loop should be turned on and allowed to run for a few minutes before inserting the camera so that any problems identified with the housing can be fixed before the camera is inserted and potentially damaged. Waiting to insert the camera will also allow the testing facility to validate the flange connection and braze connection at the front and back of the device. For the IGV tags, we will make sure to use materials that do not contaminate the refrigerant and test our final tag materials in refrigerant to provide Danfoss with an estimate for the frequency at which the tags need to be replaced.

VI. Rewrite the project steps to include all safety measures taken for each step or combination of steps. Be specific (don't just state "be careful").

When installing the system into the testing loop, the first step is to visually inspect the sight glass to determine that there are no cracks in the glass and no gaps in the epoxy between the glass and the brass. Then attach the tags to the IGVs at the front of the compressor. After inspecting the glass and attaching the tags, the front flange is connected to the front of the compressor, and the rear of the system is connected to the rest of the refrigerant loop with a brazing process. Once the system is integrated into the testing loop, the compressor should be turned on and allowed run for a few minutes to make sure that the sight glass stays in place and that the connections to the rest of the loop at the front and rear have been sealed properly. The camera can then be inserted into the top of the camera housing until it is resting in front of the sight glass. Then the camera is connected to the computer at the Danfoss testing facilities where the video feed is processed to output the angle of the vanes. If the system is installed for extended periods of time, the tags or sight glass may need to be replaced to mitigate any risk of failure. Once testing is complete, the camera will be disconnected from the computer and removed from the housing. The pipe section can then be removed from the testing loop by disconnecting the flange connection and breaking the brazed connection at the rear. Finally, the tags can be removed now that the inlet of the compressor is exposed.

VII. Thinking about the accidents that have occurred or that you have identified as a risk, describe emergency response procedures to use.

The emergency response procedure is the same for failure of the April tags and for failure of the sight glass. If one of these failures occur, the compressor should be shut down immediately and the camera needs to be removed from the housing. Once the compressor has come to rest, the refrigerant loop needs to be drained. Once everything is off and the loop is drained, the device can be disconnected from the loop and the April tags or the sight glass can be inspected and fixed. If the camera fails and the sight glass and the April tags have not failed, then the compressor does not need to be shutdown. Instead, the camera can just be removed from the housing and inspected to see if it can be fixed or if it needs to be replaced.

VIII. List emergency response contact information:

- Call 911 for injuries, fires or other emergency situations
- Call your department representative to report a facility concern

Name	Phone Number	Faculty or other COE emergency contact	Phone Number
Arnold Schaefer	(561) 578-7771	William Bilbow	N/A
Brandon Klenck	(321) 544-0026	Shayne McConomy	N/A
Travis Carter	(407) 414-9447	Kunihiko Taira	N/A
Peter House	(850) 566-3098	Obiechina Abakporo	N/A

IX. Safety review signatures

- Faculty Review update (required for project changes and as specified by faculty mentor)
- Updated safety reviews should occur for the following reasons:
  1. Faculty requires second review by this date:
  2. Faculty requires discussion and possibly a new safety review BEFORE proceeding with step(s)

3. An accident or unexpected event has occurred (these must be reported to the faculty, who will decide if a new safety review should be performed.
4. Changes have been made to the project.

Team Member	Date	Faculty mentor	Date
Arnold Schaefer	March 1, 2018		
Brandon Klenck	March 1, 2018		
Travis Carter	March 1, 2018		
Peter House	March 1, 2018		

Report all accidents and near misses to faculty mentor.