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Team #514: Electrical Capacitance Tomography for Cryogenic Fluids

Fall 2021



# Abstract

The abstract is a concise statement of the significant contents of your project. The abstract should be one paragraph of between 150 and 500 words. The abstract is not indents.

*Keywords*: list 3 to 5 keywords that describe your project.

# Disclaimer

Your sponsor may require a disclaimer on the report. Especially if it is a government sponsored project or confidential project. If a disclaimer is not required delete this section.

# Acknowledgement

These remarks thanks those that helped you complete your senior design project. Especially those who have sponsored the project, provided mentorship advice, and materials. 4

1. Paragraph 1 thank sponsor!
2. Paragraph 2 thank advisors.
3. Paragraph 3 thank those that provided you materials and resources.
4. Paragraph 4 thank anyone else who helped you.

**Team 514 Code of Conduct Contract**

**Mission Statement: “**To further humanity's journey into the universe.”

**Dress Code:** Casual for internal meetings, business casual for meetings with sponsor/professional interactions, and business professional for presentations

**Attendance & Tardiness Policy:** If a member misses any meeting and does not notify the group beforehand, they will be contacted by the group members and asked to explain their reasoning. Failure to respond will result in disciplinary action taken (as seen below).

If a member frequently misses meetings, regardless of notification to the group or not, they will be contacted asking for their reasoning and how they will adjust to attend meetings in the future. If no adjustments are made disciplinary actions will be taken. Missed meetings will be tracked in a separate document for documentation.

Frequent tardiness to meetings will also be addressed and acted upon at the discretion of the team members.

**Meeting Etiquette:** When in a professional meeting, come with predetermined questions if applicable, speak formally, refer to individuals by their title if pronoun preference is unknown and conduct yourself respectably.

**How to notify group:** Meetings that aren’t the predetermined check-ins should be scheduled at least **1 day in advance** to allow for scheduling and prevent delays. If at the last minute a member cannot attend, they must notify the group both through email and group chat (should email everyone or email one other member and CC others).

**Communication:** Every member will be treated with respect and will not be judged or discriminated based on their religious, cultural, or social beliefs. This applies to sexual orientation as well. During formal meetings it is always best to read the room before using language that may be deemed inappropriate or not. Disciplinary action guidelines apply as well.

**Methods of Communication:** Email will be used to communicate with sponsor/professionals. For internal team discussion a group chat in Microsoft Teams will be used.

**Disciplinary Action:**

1st Offense) Team members will be warned against further offenses and the offense will be documented.

2nd Offense) Team member’s offense will be reported to TA’s and again documented. A meeting between all team members and a TA will be requested to discuss the issue.

3rd Offense) Team member will be reported to Dr. McConomy. A meeting will be requested to discuss the situation and what action will be taken regarding the team member’s grade**.**

**Outside Obligations:**

Gaby: Wed. 5pm-7pm; Fr. 11am-1pm; Sun. 4pm – Until

Jean Ambrose: Sunday mornings; Sun. 4pm – Until

King Paul: Wed 5-10pm; Friday 8am-1pm; Sunday 3pm-5pm

Aaron Wolfson: Sunday 1pm-8pm

**Lack of Communication:** If a member is not participating/responding they will be contacted by a member and every member of the team will be CC’d. If the member does not respond within 24 hours, they will be contacted again informing them that if they do not respond within the next 12 hours that a TA will be contacted at that time.

At what point do we contact Dr. McConomy: After TA’s have been contacted and the issue has not been resolved.

**What should Dr. McConomy do:** Meet with the individual/individuals involved, take into consideration the input of them and the records of the issue. If Dr. McConomy deems it appropriate lower the individual’s participation grade or give them a predetermined period to remedy the issue. If the issue continues or increases in severity Dr. McConomy will determine further action at his discretion.

**How to Amend:** Three out of four members must agree on the amendment to either remove or add. Must be in a meeting, a soft copy signed document must be drafted, signed, and emailed to every member.

**Transparency Clause:** At the end of the day, we’re students working towards a common goal. So, communicate with each other before it's too late, failing to plan is like planning to fail.

**Statement of Understanding**: “*I hereby agree to follow the contents above and state that I have read and understand the contents of the document.”*

Jean Ambrose (Systems Engineer) Date:

X\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

Gabrielle Mayans (Fluids Engineer) Date:

X\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

King Paul (Software Engineer) Date:

X\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

Aaron Wolfson (Materials Engineer) Date:

X\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

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# Notation

|  |  |
| --- | --- |
| A17 | Steering Column Angle |
| A27 | Pan Angle |
| A40 | Back Angle |
| A42 | Hip Angle |
| AAA | American Automobile Association |
| AARP | American Association of Retired Persons |
| AHP | Accelerator Heel Point |
| ANOVA | Analysis of Variance |
| AOTA | American Occupational Therapy Association |
| ASA | American Society on Aging |
| BA | Back Angle |
| BOF | Ball of Foot |
| BOFRP | Ball of Foot Reference Point |
| CAD | Computer Aided Design |
| CDC | Centers for Disease Control and Prevention |
| CU-ICAR | Clemson University - International Center for Automotive Research |
| DDI | Driver Death per Involvement Ratio |
| DIT | Driver Involvement per Vehicle Mile Traveled |
| Difference | Difference between the calculated and measured BOFRP to H-point |
| DRR | Death Rate Ratio |
| DRS | Driving Rehabilitation Specialist |
| EMM | Estimated Marginal Means |
| FARS | Fatality Analysis Reporting System |
| FMVSS | Federal Motor Vehicle Safety Standard |
| GES | General Estimates System |
| GHS | Greenville Health System |
| H13 | Steering Wheel Thigh Clearance |
| H17 | Wheel Center to Heel Pont |
| H30 | H-point to accelerator heel point |
| HPD | H-point Design Tool |
| HPM | H-point Machine |
| HPM-II | H-point Machine II |
| HT | H-point Travel |
| HX | H-point to Accelerator Heel Point |
| HZ | H-point to Accelerator Heel Point |
| IIHS | Insurance Institute for Highway Safety |
| L6 | BFRP to Steering Wheel Center |
|  |  |
|  |  |
|  |  |

# Chapter One: EML 4551C

## Project Scope

## Project Description:

A sensor that can detect and output the amount of cryogenic fluid in a container in zero gravity.

Key Goals:

1) Capable of gauging the mass of any cryogenic fluid in zero gravity

2) Can output the measured mass to a computer or display

3) Design can be extrapolated to a larger scale

## Market:

Primary Market: The National Aeronautics and Space Administration and other space travel research organizations that send vehicles to space need a way to measure cryogenic propellants in zero gravity environments.

Secondary Markets: Private space travel companies sending up space shuttles for commercial travel, Virgin Galactic for example. These markets need to measure fuel as well, and cryogenic propellants are common in space travel in both government funded and private space travel organizations. Another market is companies that create products or vehicles that require mass gauging outside of zero gravity that are interested in a new design for a mass gauging sensor. Another market is eccentric car owners that are interested in upgrading their vehicle with new and interesting systems. The final secondary market is the United States Air Force and Space Force as the sensor could be used to upgrade their existing mass gauging systems.

## Assumptions:

Assumptions include that the fluid being measured is a cryogenic fluid. The device and fluid will not be experiencing extreme changes in environment including temperature and pressure. It is assumed that these conditions will be kept within a certain range. A container is assumed to be made independently from the sensor and is of a material that can be easily modified. It is also assumed that the sensor will be attached or integrated into the container. It is assumed that the container the sensor will be attached to will be secured within the vehicle.

## Stakeholders:

Stakeholders in the development of this product are the National Aeronautics and Space Administration (NASA). Other stakeholders include Dr. Kourosh Shoele, Dr. Shayne McConomy, and the Research and Development and legal teams at both NASA and companies that are interested in commercial space travel such as Virgin Galactic and SpaceX.

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## 1.2 Customer Needs

To determine the true need that the design will address, we need to collect as much information as possible. To collect useful information from the customer, our design team had a meeting with the sponsor and asked a series of questions. The questions asked, responses, and interpretation of these respective responses from the customer interview is presented below in Table 1.

|  |  |  |
| --- | --- | --- |
| Question: | Response: | Interpretation: |
| Is electrical capacitance mass gauging all you want us to work on, or is it just a guide and we are addressing the need to measure mass of the propellant in general? | Electrical capacitance does not need to be used the device just has to measure the mass of the fluid without gravity affecting the system. | Device measures mass of cryogenic fluid; technique is not constrained. |
| Is there a specific type of cryogenic propellent we will be measuring, or should the device be able to measure the mass of any cryogenic propellant? | For the purpose of the prototype, you will be measuring liquid Nitrogen, but it should be able to measure Hydrogen, Oxygen, and Methane as well. | Device operates with Nitrogen, Hydrogen, Oxygen, and Methane. |
| Will the device be contained in a controlled environment? | Yes, it will be within a shuttle. | Device operates within a predetermined environment, not extreme conditions. |
| Will the device draw power from a specific type of power connection? | No, you can use any connection that you select. | Device draws power from a power source. |
| Is there a limit to the power supply that the device will have access to? | No, but it will probably be operating within the 12V-24V range. | Device does not have a set power supply but can operate within a range of 12V-24V. |
| Should the device display outputs constantly or should certain conditions be met for the outputs to be displayed? | The fuel mass and tomography should be constantly displayed especially if fluid is being put into or drawn from the tank. | Device interface displays output values constantly. |

Table 1: Sponsor interview and responses

|  |  |  |
| --- | --- | --- |
| Question: | Response: | Interpretation: |
| Is there a predetermined size for the device? | The device should be able to be scaled up and applied to larger systems, but the prototype should just prove the concept. | Device is large enough to have a gradient to measure. |
| Are we designing the measuring device independent of the cryogenic propellant storage itself? | Yes, you will not be designing the container. | Device is a measuring tool for a container. |
| Should we also be including a function within the system that displays the mass of the fuel? | Yes. | Device takes, and display measurements. |
| What are the desired output values a user will see on the interface? | It should show the mass of the fluid in the tank and the tomography. | Device interface displays fluid mass and tomography. |

Table 1 Continued: Sponsor interview and responses

In gathering information from the sponsor regarding their wants and needs for the mass and tomography device for cryogenic fluids, we asked questions to get an idea of their vision for the product as well as questions to determine needs for subfunctions of the device. To interview the sponsor about their needs we used a traditional interview method via video call with predetermined questions. When formulating questions, we prioritized that the questions were appropriate based on the information we had on the project, but vague so that the sponsor would not be more likely to give biased responses. While interviewing the sponsor we recorded the responses provided and accounted for both the content and tone of responses.

## 1.3 Functional Decomposition

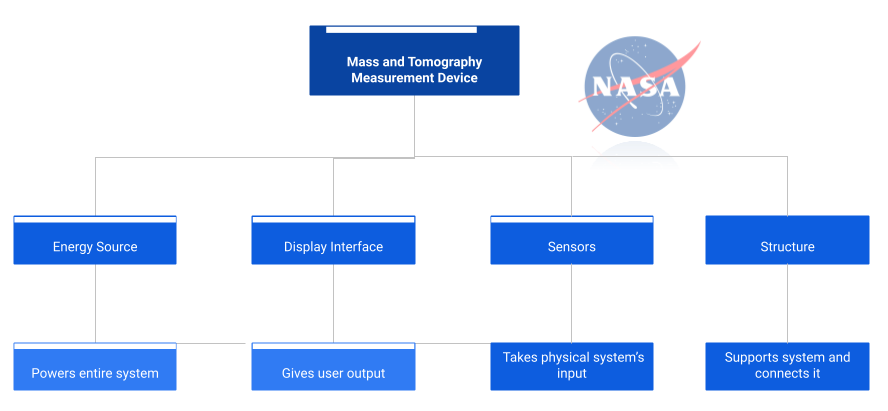
**Explanation of Results:**

Functional decomposition is a design tool that is used to assign functions that a design should address and separate functions into smaller subfunctions. The breaking up of the devices' subfunctions facilitates the identification of targets and metrics and makes alterations to future designs easier. The main goal of a functional decomposition is to create a framework of functions and their intended action while being vague to allow for creativity in the concept generation process while also proposing useful concepts.

The data collected to support our functional decomposition was collected from the sponsor through conducting a structured interview. Using the data generated, the necessary functions and subfunctions of the product were determined. These functions will support us throughout the design process.

Using the collected data from the interview, a flow chart was then created as seen below in Figure 1. The chart progressed from top to bottom respectively, starting with the subsystems of the device to the function of each respective subsystem. These systems were subsequently broken down into their main functions. One function may relate to another system; Table 1 displays these relationships.

Figure 1: Functional Decomposition Flow Chart



The functions of the product are the structure, the sensors, the energy source, and display interface. The structure supports the sensors, the energy source and the display interface. The energy source provides the power source so that the sensors and the display interface can operate. The sensors take in the physical readings and the display interface outputs the readings to the reader in a digestible format.

**Connection to Systems:**

The functional decomposition cross reference table, shown in Table 1, is a visual comparison of the system’s function and how they relate to the sub systems of our project. This visualization allows us to determine the function that will take priority during the design process. The National Aeronautics and Space Administration, (NASA), symbol represents which of the sub systems the given function impacts; from the table is seen that the function may affect multiple sub systems. For example, the function *Withstand High Temperatures* relates to three out of the four sub systems: *Structure, Sensors,* and *Energy Source.* From the F.D. cross reference table, the sub system with the most function relation impact was identified to be the *Structure.* This entails that the *Structure* will be the sub system with the highest priority. The anticipated outcome of this project is to sense the amount of cryogenic fluid, in a liquid state, within the fuel tank. While the goal for this project is to measure the cryogenic fluid, the physical structure will be taken as a main priority for the entirety of the design process.

Table 1: Functional Decomposition Cross Reference Table

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Function** | **Structure** | **Sensors** | **Energy Source** | **Display Interface** |
| **Encapsulates Entire System** | Symbols of NASA | NASA |  |  |  |
| **Withstand Extreme Temperatures** | Symbols of NASA | NASA | Symbols of NASA | NASA | Symbols of NASA | NASA |  |
| **Maintain**  **Durability** | Symbols of NASA | NASA | Symbols of NASA | NASA | Symbols of NASA | NASA | Symbols of NASA | NASA |
| **Displays Information** |  |  |  | Symbols of NASA | NASA |
| **Operate without Power** | Symbols of NASA | NASA |  |  |  |
| **Monitors Fuel Levels** |  | Symbols of NASA | NASA |  |  |

Functional decomposition will be used to break down the steps needed to utilize the zero-gravity mass gauging device. The functional decomposition cross reference table (Table 1) shows the goals and intended achievements of the device.

**Smart Integration:**

Each function varies in the number of cross-system relationships they have, with some encapsulating most or all systems while others focus on one system only. These relationships will be described going down the list of functions in Table 1:

1) **Encapsulates Entire System**: This function’s only relation is to the *structure* of the design. While it will interact with all other sub systems physically, the way this function is designed will have no impact on the physical performance of the other sub systems. Each will operate independently of this function as it is a parameter describing how each sub system will be related to the overall. However, the design of the structure will affect the physical design of the other sub-systems as well as how they are placed, so it remains the highest priority sub system.

2) **Withstand Extreme Temperatures**: Contrasting with the previous function, this function almost all the sub-system's design, except for *display interface*. Each sub system it affects will be submerged in a cryogenic propellant, and they must all be resistant to the induced extreme temperatures or suffer critical failure. Being inside the rocket in potentially non-pressurized regions could result in extreme heat.

3) **Durability**: Durability is important for all the sub systems. Each of one will be securely fastened on a rocket that experiences 4x the normal effects of gravity during launch. Each one must be durable enough to withstand such pressure as well as any accidental impacts that could occur during the flight.

4) **Displays Information**: This function relates only to the *display interface* sub system. This is the direct purpose of the *display interface,* and the physics of this function will be tailored only for that sub system.

5) **Operate Without Power**: This function will only impact the design of the *structure* as all other sub systems will require power to operate. All other sub-systems will need to draw power from the *energy source*.

6) **Monitors Fuel Levels**: This function is similar to the *Displays Information* function as it only impacts the design of one sub system, the *sensors*. This sub-system will be designed only around its ability to monitor fuel levels and no other sub system will need to be designed with the monitoring of fuel levels.

**Action and Outcome:**

This project’s purpose is to accurately measure and display the mass of a cryogenic propellant that is in zero gravity. To do this, a structure will be built that houses all the other sub-systems. The structure will be in cryogenic propellant as well as the *sensors* used to measure it. The sensors will then measure the mass of the cryogenic propellant and will quantify that physical measurement into a mass that will be read out to the user on a display interface outside of the cryogenic propellant.

**Function Resolution:**

At its core, this project has four core sub-systems that each cover a range of functions necessary for the project to have its desired outcome based on the actions taken. Each function works to support the main goal of the project, which is to measure the amount of mass in a cryogenic propellant and display that mass to the user via a display interface. The smallest element of this design would be the *sensors* sub-system, as it will be measuring and quantizing the data measured.

## 1.4 Target Summary

**Withstand Extreme Temperatures:**

The cryogenic propellant within the fuel tank will need to be held at temperatures between minus 252 degrees Celsius and minus 183 degrees Celsius. [6] Therefore, the device will need to be made of materials that can withstand these temperatures without failing. For temperatures minus 252 degrees Celsius and higher, high-alloy austenitic stainless steels are the only materials that can withstand such temperatures without failure. High-alloy austenitic stainless steel 304 and 310 will be able to withstand these low temperatures. In this case, if welding is required than the use of low carbon variants is advised. Aluminum alloys that can be used within this temperature range, are all within the 2000 and 5000 series range, as well as the 6061-T6 alloy. Copper alloys can be generally used in contact with such low temperatures, particularly 70-30 brass, copper-beryllium, iron-silicon, and aluminum bronzes. [8]

**Durability:**

As stated above in the withstand extreme temperatures section, the device will be exposed to a range of temperatures from minus 252 degrees Celsius and minus 183 degrees Celsius. [6]. The device will have to withstand extreme high temperatures as a result of spikes when the shuttle is either exiting or entering the atmosphere and low temperatures as a result of the shuttle's exposure to the vacuum of space. While the selection of materials that can withstand this range of extreme temperatures is addressed above, this does not account for the number of times that the materials will be exposed. Durability of the material is the material’s ability to withstand the extreme temperature exposure for multiple cycles without developing flaws within the material or affecting the accuracy of the device or efficiency. A test to determine how a material will be affected by extreme temperature cycles is the Thermal Cycle Test. There are multiple test standards that thermal cycle test can undergo, but the test that would be best for our device is the MIL-STD-883 method 1010 [2] as the cycles are more rapid with a time that more closely resembles the time of when a shuttle will exit the extreme high temperature environment of exiting the atmosphere to the extreme cold of space. Another durability test that would be useful for our device to undergo is thermal shock testing. While thermal cycle testing goes from extreme temperatures in a cyclic manner even the fasted change from extreme heat to extreme cold is not in a short enough span of time for our device when we account for factor of safety. Thermal shock testing also uses both liquid and gas extreme temperature fluids [3]. The structure subsystem would be tested using a thermal shock test of gas, and the sensors that interact directly with cryogenic fluid would be tested using thermals shock testing with liquid. As the sensor subsystem will be exposed to both liquid and gases at extreme low temperatures so the liquid thermal shock will account for a factor of safety since liquids will conduct heat at a higher rate. The MIL-STD-750 Method 1056 will be used to test the durability of the sensor subsystem as it is a liquid-to-liquid test [4] and the structure subsystem will undergo an air-to-air thermal shock test.

**Display Information:**

Displaying information is the end goal of the project since there is no point in measuring the mass and tomography of the cryogenic fluid if these results will not be displayed to the user. This display will be integrated with the rest of the rocket’s displays and must be easily identified and read especially when in the presences of numerous displays similar to it. There is no quantitative metric to measure the display’s ability to convey the measured data, however using Nielsen’s Heuristics it is possible to measure feedback from users and see how they correlate to the Interface Design [5].

There are 10 major heuristics:

1. Visibility of system status
2. Match between system and real world
3. User control and freedom
4. Consistency and standards
5. Error prevention
6. Recognition rather than recall
7. Flexibility and efficiency of use
8. Aesthetic and minimalist design
9. Help users recognize, diagnose, and recover from errors
10. Help and documentation

These will all be taken into consideration when designing how the information will be displayed. Modern rockets utilize almost entirely digital displays, and the fluid tomography and mass gauging will also be displayed digitally. To measure the effectiveness of which the heuristics are utilized, different users will use multiple iterations of the interface to and give feedback on which proved most useful.

**Monitor Fuel Levels:**

To monitor the fuel levels of the cryogenic propellant a Fiber Optic Sensor System (FOSS) will be utilized. FOSS operates via inducing a temperature change in the fluid and observing the cooling process of the fluid, with liquids cooling quicker than gasses. Measuring this along with the displacement of the fluid allows a tomography of the fluid to be generated as well as the mass of the fluid [7]. After speaking with the project sponsor, it was determined that the measurements should be within 5% of the expected value at the most. This is a target coming directly from the client and is critical to achieve.

|  |  |  |  |
| --- | --- | --- | --- |
| System | Function | Target | Metric |
| Structure | Encapsulates Entire System | All sub-systems except display interface | N/A |
| Structure, Sensor, & Energy Source | Withstand Extreme Temperatures | 126-1011 | Temperature Range (°R) |
| All Systems | Maintain Durability | MIL-STD-750 Method 1056 | Thermal Cycle Test |
| Display Interface | Display Information | N/A | Nielsen’s Heuristics |
| Structure | Operate Without Power | 0 | Volts (V) |
| Sensors | Monitor Fuel Levels | 5 | Accuracy (%) |

## 1.5 Concept Generation

1.5.1 Concept Generation Tools

Concept generation is important so that designers of a device are not swayed to immediately commit to an idea based on their personal bias and have multiple options if certain designs are not executable and to have other designs to reference. Our team used three main concept generation tools: morphological chart, biomimicry, and crap shoot. The most utilized concept generation tool was the SCAMPER method, substitute, combine, adapt, modify, put to another use, eliminate and reverse. This approach uses previous concepts and applies one of those techniques to come up with new ideas. After using these tools, a resulting 100 concept ideas were recorded and can be found in Appendix D.

1.5.1.1 Biomimicry

The concept generation tool of biomimicry was used especially when creating all concepts relating to RMF. It relies on soundwaves traveling throughout the cryogenic propellent and bounce of the walls of the container and return to the sensor, where it will obtain and quantize the change in the sound waves to accurately map out the space that the propellant is occupying. This is like how bats use sonar to navigate dense foliage and be aware of objects they otherwise are unable to observe visually, not unlike the inability to observe the space that the fluid in the container is occupying.

1.5.2 Medium Fidelity Concepts

Medium fidelity concepts are concepts that were generated during the concept generation that address needs for the device design, but the team has decided it is not a design that does not deserve a large amount of attention and effort. These concepts will be used later during concept selection and are designs that may be pursued if high fidelity concepts are not suitable. Table X below shows the five medium fidelity concepts that were selected from our generated concept list.

|  |  |
| --- | --- |
| Concept Number | Medium Fidelity Concept |
| # 2 | 3D printed fiberoptic cable combined with stainless steel, multiple small helical sweeps suspended from top of tank all the same size and operating parallel to each other. Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image |
| #8 | RMF transmitter on bottom and top of tank Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image |
| #59 | Piston like system that compresses the space available for the fluid based on pressure readings so that the 3D image is determined by space available. Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image |
| #62 | Small 3D printed fiberoptic cable/stainless steel helical sweep that is small enough to enter top of tank after construction that has extended probes of the helical sweep to get readings besides from center of tank. Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image |
| #83 | RMF transmitter on bottom and top of tank Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image |

During our concept generation, these were the ideas we decided would have been a good fit for our design. Each was evaluated and assessed based on the complexity. Concepts 2 and 62 was derived from the FOSS system and incorporated a 3D image based on the tomography of the tank. Concepts 8 and 53 take advantage of an RMF transmitter to aid in measuring tank levels either in units of mass or a percentage. This idea was conceptually one of the better ones but the room for error in our measurement would deviate from the actual levels of fuel within the tank. Concept 59 made use of a piston as a physical parameter in the tank that would use displacement of fuel exiting to measure what would be submitted.

1.5.3 High Fidelity Concepts

High fidelity concepts were also selected from the generated concept list. These are the concepts that the design team has more initial confidence in and will be scrutinized during concept selection.

|  |  |
| --- | --- |
| Concept Number | High Fidelity Concept |
| # 1 | 3D printed fiber optic cable combined with stainless steel, single helical sweep. Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image |
| # 33 | RMF transmitter on bottom and top of tank Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key |
| # 78 | Multiple suspended fiber optic cables anchored at both ends of tank Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image |

These concepts each include what is concluded to be the best and most viable concepts to utilize in the project. Concepts 1 & 78 utilize the fiber optic cables to get the mass tomography however their orientation differs greatly from one another. The process of using them is well known (the FOSS system) and the fiber optic casings will not be too difficult to build in house. Concept 33 uses an RMF transmitting, explained in the Biomimicry section, to find the fluid tomography. This is an alternative to using the FOSS system and is the most viable version of the RMF concepts generated due to it requiring a low number of sensors and the readout of the tomography being done using a 2D graph. This 2D graph will be very intuitive and easy to understand rather than a 3D modeling.

## 1.6 Concept Selection

1.6.1 Introduction

To determine which of the medium and high-fidelity concepts is the best choice to pursue for design, we will use three different selection tools: house of quality, Pugh charts, and the analytical hierarchy process. These tools allow objectives and attributes to be translated into quantifiable values so that the comparison of the design concepts can be quantified and compared.

1.6.2 Binary Pairwise Comparison

Binary Pairwise Comparison is a tool used to support the importance rankings of the sponsor requirements in the house of quality. If the sponsor requirement in the right vertical axis is more important than the sponsor requirement in the top horizontal axes then a value of 1 is assigned if it is not more important, then a value of 0 is assigned. These values for each row are added up and are used to determine the importance rankings of each sponsor requirement. The binary pairwise comparison table can be seen below.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Sponsor Requirements | Cost under $5000 | Reusable | Accurate Output Values | Displays Output Values | Total |
| Cost under $5000 | - | 0 | 0 | 0 | 0 |
| Reusable | 1 | - | 0 | 0 | 1 |
| Accurate Output Values | 1 | 1 | - | 0 | 2 |
| Displays Output Values | 1 | 1 | 1 | - | 3 |

As show by the Pairwise Comparison above, it is determined that the “displays output values” requirement is the most important requirement provided by the sponsor. This logically makes sense because without being able to properly display the output values to the user, there is no use to accurately calculate the output values repeatedly as the user will be unaware of them.

1.6.3 House of Quality

A house of quality chart first translates the sponsor requirements into actual design specifications. The sponsor requirements are presented on the right vertical axis of the table and each requirement is assigned a value of importance. The value of importance is represented by a scale of 1-5 where one is a lenient requirement and 5 is an extremely important requirement. The top horizontal axis of the table is the engineering characteristic a designer will reference when working on the device. The numbers in the intersecting cells of the chart are the relativity between the sponsor requirements and the engineering characteristics. Ranked exponentially as 0, 3, and 9 where zero is no relation between the two, 3 has a loose relationship, and 9 meaning the two are coupled together and are almost dependent on each other. The bottom horizontal axis is the ranking system of the chart. Raw score is the summation of all the relativity scores multiplied by the importance ranking. The relative weight is the percentage of how each individual engineering characteristic compares to the total, and the rank order is the ranking of the highest relative weight and raw score.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |
|  | Improvement Direction |  |  |  |  |
| Sponsor Requirements | Importance Rating | Withstand Extreme Temperatures | Durability | Measures Mass in Zero Gravity | Measures Tomography |
| Cost Under $5000 | 2 | 3 | 3 | 3 | 3 |
| Reusable | 3 | 3 | 9 | 0 | 0 |
| Accurate Output Values | 4 | 0 | 0 | 9 | 9 |
| Displays Output Values | 5 | 3 | 3 | 3 | 3 |
|  | Raw Score (135) | 30 | 48 | 57 | 57 |
|  | Relative Weight % | 22.2% | 35.6% | 42.2% | 42.2% |
|  | Rank Order | 4 | 3 | ½ (tie) | ½ (tie) |

Table 1: House of Quality

Above is the ranking of the project functions vs the importance rating chosen for the sponsor requirements. In the row labeled “Relative Weight %” it is shown that both “Measures Mass in Zero Gravity” and “Measures Tomography” tied for the highest ranking. It can be concluded that in relation to what the sponsor believes to be most important, ensuring that the device can measure mass in zero gravity and measure tomography as well as possible is of highest priority. This checks out logically as the main purpose of the device is to accurately measure these values and display them to the user.

1.6.4 Pugh Chart

The Pugh chart compares the concepts relative to a selected datum concept. A “+” symbol means that that concept would do better in the given selection criteria that the datum concept. An “s” symbol means that concept would have the same efficiency as the given selection criteria. A “-” symbol means that that concept would do worse in the given selection criteria. Eight total Pugh charts were created using the medium and high-fidelity concepts, each iteration using a different design concept as the datum.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Selection Criteria | Concept #2  DATUM | Concept #8 | Concept #59 | Concept #62 | Concept  #83 | Concept #1 | Concept #33 | Concept #78 |
| Cost |  | - | + | S | - | + | - | - |
| Withstand Extreme Temperatures |  | + | + | S | + | S | S | - |
| Measures Mass in Zero Gravity |  | S | S | - | S | S | S | S |
| Measures Tomography |  | S | - | - | S | - | - | S |
| Durable |  | + | + | S | - | S | S | - |
| # of Pluses |  | 2 | 3 | 0 | 1 | 1 | 0 | 0 |
| # of Minuses |  | 1 | 1 | 2 | 2 | 1 | 2 | 3 |

Table 2: Pugh Chart 1

Based on the data collected from the Pugh Charts (Appendix E) and shown above, there are two concepts that are tied with the highest (+) and (-) differential, concepts 8 and 59. Concept 8 has 11 (+) and 5 (-), while concept 59 has 15 (+) and 9 (-). Based on those values, it can be said that these concepts offer the best benefits given their costs. This is an interesting outcome given that both concepts are medium fidelity rather than high fidelity. Concept 59, a piston-based concept, satisfies almost all selection criteria more than the other concepts, except for measuring tomography. This would require an additional component to be added but this would ideally reduce the amount of (-) this concept would have. Concept 8 involves RMF transmitters in the tank, and this concept measures mass better but measures tomography worse than the fiber optic-based concepts. It is also the most expensive of the designs compared, but its results are more desirable. A modification of this idea with another concept could yield the best result.

1.6.5 AHP Chart

The last tool used for concept selection was the Analytical Hierarchy Process (AHP). AHP is used to determine the importance of sponsor requirements relative to one another. Each row has a corresponding column containing requirements, each cell will be used to cross examine these requirements. In the AHP chart below, the importance of each requirement is cross referenced with the other requirements of the intended design. For example, if “Accurate Output Values” is in the respective column and “Reusable” is the respective row, the corresponding number would be 0.333 because light weight is only one third as important as keeping the device working for three days. Inversely, if “Accurate Output Values” is in the row and “Reusable” is in the column, the corresponding value would be 3 because accurate output values are 3 times more important than reusability.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Sponsor Requirements | Cost under $5000 | Reusable | Accurate Output Values | Displays Output Values | Total | Average |
| Cost under $5000 | 1 | 3 | 9 | 7 | 20 | 5 |
| Reusable | 0.333 | 1 | 5 | 5 | 11.333 | 2.833 |
| Accurate Output Values | 0.111 | 0.2 | 1 | 3 | 4.311 | 1.078 |
| Displays Output Values | 0.143 | 0.2 | 0.333 | 1 | 1.676 | 0.419 |
| Total | 1.587 | 4.4 | 15.333 | 16 |  |  |
| Average | 0.39675 | 1.1 | 3.833 | 4 |  |  |

Table 3: AHP Chart

This chart determined that “Displays Output Values” is the most important requirement the sponsor has, from there the second most important is “Accurate Output Values”. The least important requirement is “Cost under $5000” and the second least important requirement is “Reusable”. It is determined that “Displaying Output Values” is the most important sponsor requirement and will be most considered when choosing the final concept.

Shown below is the Normalized Criteria Comparison Matrix, Final Rating Matrix, and Alternative Value Matrix, respectively. Using the values found in the Binary Pairwise Comparison they were ranked against the sponsor requirements and how well they fulfilled each one relative to the importance of the requirement.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Normalized Criteria Comparison Matrix [Norm C]** | | | | | | |
|  | A Cost under $5000 | Reusable | Accurate Output Values | Display Output Values | Design Alternative Priorities {Pi} | Criteria Weights  {W} |
| Cost under $5000 | 0.079 | 0.032 | 0.011 | 0.022 | 0.051 | 0.036 |
| Reusable | 0.102 | 0.127 | 0.131 | 0.104 | 0.061 | 0.116 |
| Accurate Output Values | 0.457 | 0.512 | 0.533 | 0.557 | 0.514 | 0.515 |
| Display Output Values | 0.362 | 0.329 | 0.325 | 0.317 | 0.374 | 0.333 |
| Sum | 1 | 1 | 1 | 1 | 1 | 1 |

Table 4: NormC Matrix

|  |  |  |  |
| --- | --- | --- | --- |
| **Final Rating Matrix** | | | |
| Selection Criteria | Concept #1 | Concept #33 | Concept #78 |
| Cost under $5000 |  |  |  |
| Reusable | 0.429 | 0.142 | 0.429 |
| Accurate Output Values | 0.634 | 0.106 | 0.26 |
| Display Output Values | 0.615 | 0.093 | 0.292 |

Table 5: Final Rating Matrix

|  |  |
| --- | --- |
| **Alternative Value Matrix** | |
| Concept #1 | 0.604 |
| Concept #33 | 0.106 |
| Concept #78 | 0.290 |

Table 6: Alternative Value Matrix

Concept #1 is the winner with the highest Alternative Value, meaning it best satisfies the customer requirements that were deemed to be most important in comparison to the other two ideas measured. This concept selection tools strongly point towards a CRYOFOSS design being implemented, that of concept 1. However, we will still consider other designs as further research is done as the values from the Pugh Charts indicate that a fusion of two concepts could prove noteworthy.

## 1.8 Spring Project Plan

# Chapter Two: EML 4552C

## 2.1 Spring Plan

### Project Plan.

### Build Plan.

# Appendices

# Appendix A: Code of Conduct

# Appendix B: Functional Decomposition

# Appendix C: Target Catalog

**Appendix D: 100 Concepts**

1. 3D printed fiberoptic cable combined with stainless steel, single helical sweep. Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

2. 3D printed fiberoptic cable combined with stainless steel, multiple small helical sweeps suspended from top of tank all the same size and operating parallel to each other Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

3. Multiple suspended fiber optic cables, anchored at both ends of tank Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

4. Both vertical and horizontal fiberoptic cables anchored to one side of tank Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

5. 3D printed fiberoptic cable combined with stainless steel, a prism constructed of triangular based pyramids Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

6. A helical sweep fiberoptic cable supported by vertical stainless steel rods Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

7. Multiple small RMF transmitters on the inner sides and bottom of the tank Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

8. RMF transmitter on bottom and top of tank Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

9. Piston like system that compresses the space available for the fluid based on pressure readings so that the 3D image is determined by space available Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

10. Fiber optic cable rings supported by horizontal stainless steel rods Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

11. Multiple probe sensors, stationary from top of tank Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

12. Small 3D printed fiberoptic cable/stainless steel helical sweep that is small enough to enter top of tank after construction that has extended probes of the helical sweep to get readings besides from center of tank Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

13. A vertical stainless rod supporting a fiberoptic bale in the center of the tank segments of fiberoptic cable extend perpendicularly from rod like branches for readings Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

14. Multiple 3D printed helical sweeps of descending size layered so as many measurements as possible can be taken to increase accuracy Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

15. Multiple helical sweeps of descending size layered, all supported by vertical stainless steel rods Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

16. Combination of RMF and 3d printed fiberoptic cable, vertical fiberoptic cables and RMF transmitters on each end of the tank. Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

17. Combination of stationary probe sensors and RMF transmitter at end of the tank Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

18. Combination of stationary probe sensors, they are also used to support a single fiberoptic cable helical sweep. Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

19. Multiple small cameras are installed with the tank and the photos taken produce a tomography graph/3D rendering and based on that rendering and the dimensions/fuel thermal properties a program calculates the mass of the fuel, the mass of the fuel is only recalculated if fuel is added or drawn from tank and processing power is dedicated to tomography Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

20. A combination of probes and multiple cameras is used to measure mass and tomography Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

21. A combination of RMF and cameras is used to determine mass and tomography Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

22. A combination of a helical fiberoptic sweep supported by stainless steel rods and multiple cameras along the inside of the tank is used to gather measurements Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

23. Anchored fiberoptic cables and RMF is used to take measurements Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

24. Anchored fiberoptic cables and multiple cameras is used to take measurements Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

25. A piston like device to provide a limited range when fluid is drawn from the tank and a 3D printed flexible fiberoptic helical sweep is used for measurements Displays the tank fuel levels in percentage full and the tomography is shown as a 3D image

26. 3D printed fiberoptic cable combined with stainless steel, single helical sweep Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

27. 3D printed fiberoptic cable combined with stainless steel, multiple small helical sweeps suspended from top of tank all the same size and operating parallel to each other Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

28. Multiple suspended fiber optic cables, anchored at both ends of tank Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

29. Both vertical and horizontal fiberoptic cables anchored to one side of tank Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

30. 3D printed fiberoptic cable combined with stainless steel, a prism constructed of triangular based pyramids Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

31. A helical sweep fiberoptic cable supported by vertical stainless steel rods Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

32. Multiple small RMF transmitters on the inner sides and bottom of the tank Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

33. RMF transmitter on bottom and top of tank Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

34. Piston like system that compresses the space available for the fluid based on pressure readings so that the 3D image is determined by space available Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

35. Fiber optic cable rings supported by horizontal stainless steel rods Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

36. Multiple probe sensors, stationary from top of tank Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

37. Small 3D printed fiberoptic cable/stainless steel helical sweep that is small enough to enter top of tank after construction that has extended probes of the helical sweep to get readings besides from center of tank Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

38. A vertical stainless rod supporting a fiberoptic bale in the center of the tank segments of fiberoptic cable extend perpendicularly from rod like branches for readings Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

39. Multiple 3D printed helical sweeps of descending size layered so as many measurements as possible can be taken to increase accuracy Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

40. Multiple helical sweeps of descending size layered, all supported by vertical stainless steel rods Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

41. Combination of RMF and 3d printed fiberoptic cable, vertical fiberoptic cables and RMF transmitters on each end of the tank. Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

42. Combination of stationary probe sensors and RMF transmitter at end of the tank. Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

43. Combination of stationary probe sensors, they are also used to support a single fiberoptic cable helical sweep. Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

44. Multiple small cameras are installed with the tank and the photos taken produce a tomography graph/3D rendering and based on that rendering and the dimensions/fuel thermal properties a program calculates the mass of the fuel, the mass of the fuel is only recalculated if fuel is added or drawn from tank and processing power is dedicated to tomography. Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

45. A combination of probes and multiple cameras is used to measure mass and tomography Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

46. A combination of RMF and cameras is used to determine mass and tomography Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

47. A combination of a helical fiberoptic sweep supported by stainless steel rods and multiple cameras along the inside of the tank is used to gather measurements. Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

48. Anchored fiberoptic cables and RMF is used to take measurements Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

49. Anchored fiberoptic cables and multiple cameras is used to take measurements Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

50. A piston like device to provide a limited range when fluid is drawn from the tank and a 3D printed flexible fiberoptic helical sweep is used for measurements Displays the tank fuel levels in percentage full and the tomography is shown as a 2D graph that displays the 3rd plane as a variation in color with a color key

51. 3D printed fiberoptic cable combined with stainless steel, single helical sweep. Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

52. 3D printed fiberoptic cable combined with stainless steel, multiple small helical sweeps suspended from top of tank all the same size and operating parallel to each other Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

53. Multiple suspended fiber optic cables, anchored at both ends of tank Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

54. Both vertical and horizontal fiberoptic cables anchored to one side of tank Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

55. 3D printed fiberoptic cable combined with stainless steel, a prism constructed of triangular based pyramids Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

56. A helical sweep fiberoptic cable supported by vertical stainless-steel rods Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

57. Multiple small RMF transmitters on the inner sides and bottom of the tank Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

58. RMF transmitter on bottom and top of tank Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

59. Piston like system that compresses the space available for the fluid based on pressure readings so that the 3D image is determined by space available Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

60. Fiber optic cable rings supported by horizontal stainless-steel rods Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

61. Multiple probe sensors, stationary from top of tank Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

62. Small 3D printed fiberoptic cable/stainless steel helical sweep that is small enough to enter top of tank after construction that has extended probes of the helical sweep to get readings besides from center of tank Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

63. A vertical stainless rod supporting a fiberoptic bale in the center of the tank segments of fiberoptic cable extend perpendicularly from rod like branches for readings Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

64. Multiple 3D printed helical sweeps of descending size layered so as many measurements as possible can be taken to increase accuracy Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

65. Multiple helical sweeps of descending size layered, all supported by vertical stainless steel rods Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

66. Combination of RMF and 3d printed fiberoptic cable, vertical fiberoptic cables and RMF transmitters on each end of the tank. Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

67. Combination of stationary probe sensors and RMF transmitter at end of the tank. Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

68. Combination of stationary probe sensors, they are also used to support a single fiberoptic cable helical sweep. Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

69. Multiple small cameras are installed with the tank and the photos taken produce a tomography graph/3D rendering and based on that rendering and the dimensions/fuel thermal properties a program calculates the mass of the fuel, the mass of the fuel is only recalculated if fuel is added or drawn from tank and processing power is dedicated to tomography Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

70. A combination of probes and multiple cameras is used to measure mass and tomography. Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

71. A combination of RMF and cameras is used to determine mass and tomography. Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

72. A combination of a helical fiberoptic sweep supported by stainless steel rods and multiple cameras along the inside of the tank is used to gather measurements. Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

73. Anchored fiberoptic cables and RMF is used to take measurements Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

74. Anchored fiberoptic cables and multiple cameras is used to take measurements Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

75. A piston like device to provide a limited range when fluid is drawn from the tank and a 3D printed flexible fiberoptic helical sweep is used for measurements Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

76. 3D printed fiberoptic cable combined with stainless steel, single helical sweep Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

77. 3D printed fiberoptic cable combined with stainless steel, multiple small helical sweeps suspended from top of tank all the same size and operating parallel to each other Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

78. Multiple suspended fiber optic cables, anchored at both ends of tank Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

79. Both vertical and horizontal fiberoptic cables anchored to one side of tank Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

80. 3D printed fiberoptic cable combined with stainless steel, a prism constructed of triangular based pyramids Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

81. A helical sweep fiberoptic cable supported by vertical stainless steel rods Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

82. Multiple small RMF transmitters on the inner sides and bottom of the tank Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

83. RMF transmitter on bottom and top of tank Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

84. Piston like system that compresses the space available for the fluid based on pressure readings so that the 3D image is determined by space available Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

85. Fiber optic cable rings supported by horizontal stainless steel rods Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

86. Multiple probe sensors, stationary from top of tank Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

87. Small 3D printed fiberoptic cable/stainless steel helical sweep that is small enough to enter top of tank after construction that has extended probes of the helical sweep to get readings besides from center of tank Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

88. A vertical stainless rod supporting a fiberoptic bale in the center of the tank segments of fiberoptic cable extend perpendicularly from rod like branches for readings Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

89. Multiple 3D printed helical sweeps of descending size layered so as many measurements as possible can be taken to increase accuracy Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

90. Multiple helical sweeps of descending size layered, all supported by vertical stainless steel rods Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

91. Combination of RMF and 3d printed fiberoptic cable, vertical fiberoptic cables and RMF transmitters on each end of the tank. Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

92. Combination of stationary probe sensors and RMF transmitter at end of the tank. Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

93. Combination of stationary probe sensors, they are also used to support a single fiberoptic cable helical sweep. Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

94. Multiple small cameras are installed with the tank and the photos taken produce a tomography graph/3D rendering and based on that rendering and the dimensions/fuel thermal properties a program calculates the mass of the fuel, the mass of the fuel is only recalculated if fuel is added or drawn from tank and processing power is dedicated to tomography Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

95. A combination of probes and multiple cameras is used to measure mass and tomography Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

96. A combination of RMF and cameras is used to determine mass and tomography Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

97. A combination of a helical fiberoptic sweep supported by stainless steel rods and multiple cameras along the inside of the tank is used to gather measurements. Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

98. Anchored fiberoptic cables and RMF is used to take measurements Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

99. Anchored fiberoptic cables and multiple cameras is used to take measurements Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

100. A piston like device to provide a limited range when fluid is drawn from the tank and a 3D printed flexible fiberoptic helical sweep is used for measurements. Displays the tank fuel levels in mass units available and the tomography is shown as a 3D image

**Appendix E: 8 Pugh Charts**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Selection Criteria | Concept #2  DATUM | Concept #8 | Concept #59 | Concept #62 | Concept  #83 | Concept #1 | Concept #33 | Concept #78 |
| Cost |  | - | + | S | - | + | - | - |
| Withstand Extreme Temperatures |  | + | + | S | + | S | S | - |
| Measures Mass in Zero Gravity |  | S | S | - | S | S | S | S |
| Measures Tomography |  | S | - | - | S | - | - | S |
| Durable |  | + | + | S | - | S | S | - |
| # of Pluses |  | 2 | 3 | 0 | 1 | 1 | 0 | 0 |
| # of Minuses |  | 1 | 1 | 2 | 2 | 1 | 2 | 3 |

Pugh Chart 1

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Selection Criteria | Concept #2 | Concept #8  DATUM | Concept #59 | Concept #62 | Concept  #83 | Concept #1 | Concept #33 | Concept #78 |
| Cost | + |  | + | + | S | + | S | - |
| Withstand Extreme Temperatures | - |  | S | - | S | - | S | - |
| Measures Mass in Zero Gravity | S |  | - | S | S | S | S | S |
| Measures Tomography | S |  | - | + | S | S | S | + |
| Durable | - |  | S | - | S | - | S | - |
| # of Pluses | 1 |  | 1 | 2 | 0 | 1 | 0 | 1 |
| # of Minuses | 1 |  | 2 | 2 | 0 | 2 | 0 | 3 |

Pugh Chart 2

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Selection Criteria | Concept #2 | Concept #8 | Concept #59  DATUM | Concept #62 | Concept  #83 | Concept #1 | Concept #33 | Concept #78 |
| Cost | - | - |  | - | - | - | - | - |
| Withstand Extreme Temperatures | - | S |  | - | S | - | S | - |
| Measures Mass in Zero Gravity | S | + |  | S | S | S | S | S |
| Measures Tomography | + | + |  | + | + | + | + | + |
| Durable | - | S |  | - | S | - | - | - |
| # of Pluses | 1 | 2 |  | 1 | 1 | 1 | 1 | 1 |
| # of Minuses | 3 | 1 |  | 3 | 1 | 3 | 2 | 3 |

Pugh Chart 3

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Selection Criteria | Concept #2 | Concept #8 | Concept #59 | Concept #62  DATUM | Concept  #83 | Concept #1 | Concept #33 | Concept #78 |
| Cost | S | - | + |  | - | + | - | - |
| Withstand Extreme Temperatures | S | + | + |  | + | S | + | - |
| Measures Mass in Zero Gravity | + | S | S |  | S | + | S | S |
| Measures Tomography | + | - | - |  | - | + | - | S |
| Durable | S | + | + |  | + | + | + | - |
| # of Pluses | 2 | 2 | 3 |  | 2 | 4 | 2 | 0 |
| # of Minuses | 0 | 2 | 1 |  | 2 | 0 | 2 | 3 |

Pugh Chart 4

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Selection Criteria | Concept #2 | Concept #8 | Concept #59 | Concept #62 | Concept  #83  DATUM | Concept #1 | Concept #33 | Concept #78 |
| Cost | + | S | + | + |  | + | S | - |
| Withstand Extreme Temperatures | - | S | S | - |  | - | S | - |
| Measures Mass in Zero Gravity | S | S | S | S |  | S | S | S |
| Measures Tomography | S | S | - | + |  | + | S | + |
| Durable | + | S | S | - |  | - | S | - |
| # of Pluses | 2 | 0 | 1 | 2 |  | 2 | 0 | 1 |
| # of Minuses | 1 | 0 | 1 | 2 |  | 2 | 0 | 3 |

Pugh Chart 5

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Selection Criteria | Concept #2 | Concept #8 | Concept #59 | Concept #62 | Concept  #83 | Concept #1  DATUM | Concept #33 | Concept #78 |
| Cost | - | - | + | - | - |  | - | - |
| Withstand Extreme Temperatures | S | + | + | S | + |  | + | - |
| Measures Mass in Zero Gravity | S | S | S | - | S |  | S | S |
| Measures Tomography | + | S | - | - | - |  | - | S |
| Durable | S | + | + | - | + |  | + | - |
| # of Pluses | 1 | 2 | 3 | 0 | 2 |  | 2 | 0 |
| # of Minuses | 1 | 1 | 1 | 4 | 2 |  | 2 | 3 |

Pugh Chart 6

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Selection Criteria | Concept #2 | Concept #8 | Concept #59 | Concept #62 | Concept  #83 | Concept #1 | Concept #33  DATUM | Concept #78 |
| Cost | + | S | - | - | + | - |  | + |
| Withstand Extreme Temperatures | S | S | S | - | S | S |  | S |
| Measures Mass in Zero Gravity | S | S | - | - | S | - |  | S |
| Measures Tomography | - | S | S | S | S | S |  | S |
| Durable | + | S | + | + | S | + |  | + |
| # of Pluses | 1 | 0 | 1 | 1 | 1 | 1 |  | 2 |
| # of Minuses | 2 | 0 | 2 | 3 | 0 | 2 |  | 0 |

Pugh Chart 7

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Selection Criteria | Concept #2 | Concept #8 | Concept #59 | Concept #62 | Concept  #83 | Concept #1 | Concept #33 | Concept #78  DATUM |
| Cost | + | + | + | + | - | + | - |  |
| Withstand Extreme Temperatures | + | + | + | S | + | S | + |  |
| Measures Mass in Zero Gravity | S | S | S | - | S | S | S |  |
| Measures Tomography | S | - | - | - | - | - | - |  |
| Durable | + | + | + | S | + | S | + |  |
| # of Pluses | 3 | 3 | 3 | 1 | 2 | 1 | 2 |  |
| # of Minuses | 0 | 1 | 1 | 2 | 2 | 1 | 2 |  |

Pugh Chart 8

See publication manual of the American Psychological Association page 62

# References

**There are no sources in the current document.**