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Team 515: Nuclear Reactor Canister for Space

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# Abstract

After almost a 60-year break, NASA has decided to refocus their attempts on using nuclear thermal propulsion (NTP) as a more efficient way to advance space exploration. The NTP process uses uranium to heat hydrogen to create thrust. This process is more efficient than conventional rocket engines. NASA’s research has restarted with the Transient Reactor Test Facility (TREAT). The TREAT reactor is used to test different fuels for NTP. The TREAT reactor can rapidly heat the fuel to test NTP engine startup. The objective is to design, build, and test a canister for the TREAT reactor. The canister is inside the SIRIUS (an acronym with no meaning) module. The SIRIUS module will provide the hydrogen to the canister. The SIRIUS module will be inside Big BUSTER (Broad Use Specimen Transient Experiment Rig), which goes into the TREAT reactor. The canister holds uranium in the center of the canister that will heat the hydrogen flow to test the different fuels.

The design choices were based around the fuel and hydrogen in the canister. The materials used for the canister is tungsten and zirconium carbide to ensure it will not fail at high temperatures. The tungsten can withstand the high temperatures and the zirconium carbide keeps the hydrogen from sticking to the canister. There are multiple small flow channels allows for a high and constant flow rate of hydrogen through the canister.

To test the canister, a heating device is placed inside our experimental canister. This allows for a small-scale simulation of a nuclear heating without using dangerous and unobtainable materials. Argon will function as liquid hydrogen due to its ease of use and availability. Thermocouples will measure the temperature difference and allow for calculations to be made to relate the results from testing to a full-scale test that will be done by NASA.

# Acknowledgement

This project would not have been able to be completed without the support of NASA and their phenomenal engineers. In particular, a large thank you is due to Marvin Barnes and Harold Gerrish. Both of which played a large part in giving the background information on nuclear thermal propulsion and the workings of the involvement of Big Buster and the SIRIUS module at the Idaho National Laboratory.

The team’s advisor was Dr. Eric Hellstrom, who has an extensive background in material science and was a valuable asset during the project’s duration. The material selection process in this project was an important aspect of the overall picture, and Dr. Hellstrom’s insight was not only useful but also significant in the success of the project.

The designed canister was not able to be machined using conventional techniques due to its long length and small diameter holes. The canister’s room for error was also extremely small to obtain reasonable results. Due to these concerns, Lundy Enterprise was chosen to gun barrel drill the canister. Lundy Enterprise was able to supply a fantastically machined canister with a tolerance low enough to confidently perform the experiments.

Lastly, Dr. Shayne McConomy assisted the team in the correct direction of the project by offering advice and networking in order to help the team when at crossroads. At times of confusion and concern, Dr. McConomy was available and willing to use his experience as an expert and professor to aid the team.

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# Nomenclature

|  |  |
| --- | --- |
| NASA | = The National Aeronautics and Space Administration |
| TREAT | = Transient Reactor Test |
| INL | = Idaho National Lab |
| NTP | = Nuclear Thermal Propulsion |
| BUSTER | = Broad Use Specimen Transient Experiment Rig |
| K | = Kelvin |

# Chapter One: EML 4551C

## Project Scope

### Project Description

Our client, Marvin Barnes at NASA, needs a canister that can be incorporated in their “Big Buster” project. The Big Buster project involves NASA testing multiple types of elements as a baseline fuel for a nuclear reactor. The canister will go into the section of the Big Buster where the fission reaction occurs and produces a level of heat that is typically around half that of the sun. To achieve this, the canister needs to be made from a material that can withstand 3000 K. Within NASA’s Big Buster project, the fluid reacting to the baseline fuel is hydrogen, this indicated that the material our canister is made of cannot be able to react with hydrogen any temperatures. The Big Buster project is used for testing at the transient reactor testing facility (TREAT Facility) in Idaho Falls, Idaho.

### Key Goals

The main objective of this project is to design and develop a canister that will safely contain the nuclear reaction between the baseline fuel and the fluid it reacts with. The baseline fuel will start out as uranium nitride if successful multiple other baseline fuels will be tested. The biggest obstacle will be the reaction temperature of a fission reaction and the lack of a reaction between the walls of the canister and the fluid.

### Market

Our canisters' primary and sole market is for NASA to use in their Big Buster project. The contact at NASA for development is Marvin Barnes who has worked at NASA for 35 years and worked on multiple nuclear reaction propulsion projects. During development of the canister, dimensions of Big Buster will be given, and the canister’s volume and dimensions will be based off Big Buster’s dimensions.

### Assumptions

Most assumptions will come from the fact that the use of our canister will occur in Idaho Falls, Idaho. Another key aspect is knowing that after each use of the nuclear reactor, there is a down period of roughly three to five months of inactivity and the average temperature of a fission reaction that creates the most energy is 3,000 K and that the material needs to withstand that temperature. It is safe to assume that the weight of the canister will not affect the use or efficiency of the overall system given that the canister is for testing purposes. The Big Buster, where the canister is involved, is mounted on the ground and not for use in space, meaning weight is not a concern. Another assumption made is that the correct ratio of baseline fuel and hydrogen will be offered within the canister and that everything else in Big Buster is working according to plan. Even though nuclear reactions create a radioactive product, the assumption will be made that we do not need to have a material that absorbs radioactivity. This is due do the short run time of the testing, the five months down period, and the precautions taken by NASA to prevent interactions with radioactive material. If the reaction was tested for a longer time, then radioactive absorptivity would be considered when selecting a material.

### Stakeholders

The key stakeholder for this canister project is NASA and the connection to NASA, Marvin Barnes. The advisor for this project is Dr. Eric Hellstrom, another stakeholder, because of his involvement with development. Each member of the development team is a stakeholder as well because of the time and knowledge into this project. Other companies that are in need for a canister that contains a nuclear reaction won’t be a direct stakeholder but can take reference from the work on this project, however, because NASA is the primary stakeholder. The development of the canister will be made for specific use for NASA and the Big Buster and Sirius Module project.

## Customer Needs

### Interpreted Need

To determine the goals for our design, our team interviewed Marvin Barnes, a NASA engineer wanting a canister developed for fuel testing. While NASA is the target demographic, Marvin is acting as the individual customer representing NASA. These questions were designed to allow for more needs to be found from the responses. The questions are open ended to help keep the results unbiased from a specific design. The questions are also open-ended enough for the needs of this device to be usable with other projects either through NASA or contractors.

### Explanation of Results

* The canister will need to fit into the Big Buster project and contain a nuclear reactor reaction that will reach up to 3000K for a period of at least 30 seconds.
* Our device will be used by the TREAT Reactor in the Idaho National Laboratory, Idaho Falls, Idaho and will not be subjected to the limits of weight and density as well as budget is not a concern.
* The device will not be used in space and will be subjected to atmospheric gravity.
* Radiation absorption does not need to be considered even if radioactive materials such as Uranium are used.
* The canister design needs to be able to have a flow through one direction and the interior needs to be sticky resistant.

The information from Table 1 is relayed here. The canister project will be inserted into the Big Buster from the TREAT Reactor in the Idaho National Laboratory, and it will be used as a container for a nuclear fission reactor. Uranium will be used as its fuel source, and it will reach temperatures of 3000K for a time of 30 seconds. Although Uranium is considered radioactive, for the project, radiation absorption will not be considered a high risk. The reaction will be bolstered by a flow of hydrogen into the reactor to create thrust propulsion for the whole Big Buster project. This flow of hydrogen will be inserted in a one-way flow and the canister must be able to resist the hydrogen sticking to the inner surface.

## Functional Decomposition

### Action and Outcome

This project consists of designing and building a form fitted canister that encloses a uranium reaction and fits within specific dimensions of the Big Buster project. It will be made of a specific material that must withstand 3,000K for over a period of 30 seconds, resist radiation effects, and resist hydrogen sticking to prevent hot spots. This canister will be tested with multiple radioactive materials and will be used to test thermal nuclear propulsion systems.

### Smart Integration

The material of the canister is the most vital component of the project. All its subcomponents are directly affected by this attribute. If the material of the canister cannot withstand extreme temperatures, then the device will fail. Hydrogen will need to flow through the canister for the NTP system to operate successfully. The device could fail should the material it is made of react negatively to hydrogen. The canister’s size is rather limited as it will have to fit inside of Big Buster. All these components are core to the NTP system’s reaction process.

### Connection to System

Through Table 1: Functional Decomposition Cross Reference Table, it is shown that every function is integral to the NTP Reaction Process. While fitting in Big Buster is not used in every function, it is the most important aspect of the project, because without the canister being able to fit in Big Buster, the NTP Reaction Process cannot happen. For the process of allowing flow in one direction, the canister will use hydrogen for the NTP reaction to occur. It is very important for the hydrogen to not stick to the interior surface of the canister because the material may become brittle if it encounters high temperature hydrogen.

### Function Resolution

The form fitted canister needs to fit inside Big Buster, withstand 3000K, and allow hydrogen flow in one direction without sticking causing hot spot propagation.

## Functional Decomposition Changes

After further discussion with the sponsor of our project, a design change has been made making Big Buster only pass pure liquid hydrogen to the canister. This eliminates the function for the canister to only allow the flow of hydrogen into the canister. While preventing hydrogen from sticking to our canister is still a function, only hydrogen will be introduced into the canister.

## Target Summary

For the function of the NTP reaction process, this must first be broken down into the basic elements of a nuclear reaction. In a nuclear reaction, a neutron collides with a uranium atom, splitting it releasing energy in the form of heat and radiation. In the case of a nuclear thermal propulsion engine, making sure the neutrons are reflected is key because low enriched uranium will be used as fuel. This creates a target of less than 10% absorption for neutrons. This metric was decided due to the importance of neutrons in the reaction. The thermal energy released from the reaction will destroy the canister if not properly accounted for, leading to a target for the material to withstand 3000K. The metric for this target is temperature. The energy released in the form of radiation can change the molecular structure of the material. This leads to radiation hardening, that can cause the materials properties to be no longer mechanically sound and cause failure. This leads to a target of no greater than an 8 GPa change in hardness over the course of the test. This would be measured with a hardness test. This target will also allow for the canister to be reusable, preventing the canister from becoming to brittle do reuse. A main function of the canister is to fit within Big Buster. While the exact dimensions of the location within Big Buster is not known at the time, the initial target is presented to be 10 inches in length and 2 inches in diameter. The metric of length and diameter were chosen due to the constraints put in place during the design of Big Buster and the TREAT reactor. The uranium used within the test must fit within the canister for the research to be conducted. While the volume of the uranium is not a limiting factor, accounting for different configurations of uranium being used creates unique targets for each configuration, with the initial test using a structural matrix to hold the uranium in place. The exact volume of uranium being used is not known; however, the target can be created assuming the amount of uranium used is equivalent to the size of a marble. This is enough uranium for a one-way trip to Mars, which has a mass of 175 grams and a volume of 9.2 . The flow of hydrogen is critical to the success of the research. The flow of hydrogen provides two purposes in the canister, it adds a level of cooling to the system, due to it entering the system as a cooled liquid, and it produces a net thrust in a thermal nuclear engine. The hydrogen must be continually flowing in one direction, this leads to a target of a net pressure difference in the canister greater than 0. This metric was chosen due to a net pressure difference indicating the flow of the fluid, in this case hydrogen. To sustain the required specific impulse of 900 *seconds* for the nuclear thermal propulsion engine a mass flow rate of 13 is required for the entire engine. Big Buster will be testing the equivalent of one of six fuel rods leading to a target of 2.2 . The metric for this target is mass flow rate. This mass flow rate of liquid hydrogen will also allow for additional cooling to the canister increasing the decreasing the effects of temperature changes. Big Buster will provide pure liquid hydrogen to the canister. As stated in section 1.3.1, this removes the function of allowing only the flow hydrogen into the canister, removing the need for a target due to it no longer being a function of the canister. If the hydrogen has the possibility to stick to the inner surfaces of the canister and create hot spots within the canister. These hot spots can superheat the hydrogen and cause diffusion of the hydrogen into the canister material and cause hydrogen embrittlement. A coating to the canister as well as flow dynamics may be used to reduce the chances of hydrogen sticking however, the coating of the canister and the canister may have different thermal expansion rates. This creates a target for the canister and canister coating to have thermal expansion rates within . This target will also be used when measuring the target dimensions within Big Buster. This metric is used to measure the rate at which a material expands due to the change in temperature. A full table of the functions, their targets and metrics can be shown in Table 4: Complete Target Catalog.

### Methods of Validation

To validate the neutron absorptivity of the canister, a simulation can be run based on the materials chosen and the levels of neutrons being produced by the nuclear reaction. Live tests of the nuclear fuel canister are not feasible as advanced materials such as uranium-235 and liquid hydrogen are not available to the public. The simulations will determine the number of neutrons being emitted from the reaction and the number of neutrons being absorbed from the canister, creating a percentage. To test the maximum temperature of the canister, a list of materials making up the canister will be compiled. From standard tables, melting points can be assessed. The material with the lowest melting point will be measured when determining the maximum temperature the canister can withstand. This method can also be used thermal expansion, given that the material properties are all found through the same methods. Through simulation using both radiation generation and heat generation, values can be generated for thermal expansion and the effects of radiation on the materials. The changes due to radiation and heat generation go hand in hand, due to them both changing the properties of the materials. The flow of hydrogen can be shown through design testing of the canister prototype. Pressure sensors can be placed on both start of the flow and the exhaust allowing a change in pressure to be calculated. This change in pressure can also be used to calculate the mass flow rate of the hydrogen through the canister using Bernoulli’s equation. Through flow simulations the mass flow rate and change in pressure can be tested against the prototype.

### Derivations of Targets and Metrics

Neutron absorptivity of the canister was a target determined by the sponsor due to the process of nuclear fission and how it works for NTP reactions. The target of less than 10% absorption for neutrons was decided to maximize reaction energy while setting a realistic value to attain. This high amount of energy from the reaction can lead to radiation hardening, that can cause a material’s properties to be no longer mechanically sound and cause failure. We want to avoid material hardening so this target was derived from side effects of the nuclear reaction. Temperature resistance is a critical target that is one of the most important targets because the canister must withstand a high temperature or else the canister will fail. This target was provided by the sponsors as they are specifically looking at this target. For this project to work, the canister needs to fit inside of the equipment being used. Therefore, the critical target of fitting inside Big Buster was decided from the constraints put in place during the design of Big Buster and the TREAT facility. The amount of uranium being used in the canister is not a limiting factor but accounting for different configurations of uranium being used creates unique targets for each configuration. Therefore, the target of a marble size amount of uranium being used was created to make a standard number to reference from. The flow of hydrogen is critical to the project and so the critical target of hydrogen needing to continuously flow in one direction was determined by the sponsors as the process of the NTP reaction consists of a one-way hydrogen flow. A secondary effect of this one-way flow is superheated hydrogen can stick to the inner surfaces of the canister. This issue can cause canister failure and so a film will be used to prevent the hydrogen from sticking to the canister. When attempting to reduce hydrogen flow problems, another target was created based on how film coatings for the canister can cause the canister to have different thermal expansion rates. This target was decided internally by the group when doing research for canister coatings.

### Discussion of Measurement and Validation

To validate our targets, simulations, prototypes, and sensors will be used. Most of the advanced materials such as uranium and the liquid hydrogen will be run through simulations due to limited availability. Simulations can also be used to see how heat and radiation is generated. Simulations for flow, mass flow rate, and change in pressure will also be used to see the effects of each property. Prototypes can be used to with a substitute for liquid hydrogen, such as nitrogen, to validate the practicality of the design, and test change in pressure and mass flow rate. These changes in pressure and mass flow rate can be experimentally measured by using sensors within our prototypes. The targets for the material properties can be validated through common tables, however for advanced material properties such as neutron absorption, advanced simulations can determine the levels of neutrons absorbed by each material chosen.

### Critical Targets

There are 5 critical targets that must be met. These are the withstanding the NTP reaction process, fit within the constraints of Big Buster, minimizing the thermal expansion coefficient, minimizing neutron absorption, and allow hydrogen flow. Each of these targets must be fully realized as one of them failing will cause the entire project to fail.

## Concept Generation

Our concepts were generated using multiple processes, including morphological charts, biomimicry, crap shoot, and the anti-problem. A morphological chart was used for 40 ideas that have different materials as the options and similar functions for the ideas created. Materials such as Tantalum, Tungsten, Osmium, and Hafnium were used for most of the ideas because these materials were chosen due to a back and forth comparison between multiple materials and their material properties. Some ideas had influences of biomimicry such as using a honeycomb shaped canister or having the flow of hydrogen mimic the pathways of a human heart and its arteries. The crap shoot was mainly used to generate ideas that are based on cost or weight such as the idea of making an extremely long hollow canister. The anti-problem forces us to think of ways to reduce the canister properties and create ideas that we can reverse so that it will benefit the canister.

### High Fidelity Concept 1.

A base metal that has a melting point beyond 3000 K and can also withstand the effects of the nuclear radiation. The base metal will have a triple passed path for the hydrogen to flow through will its heating from the nuclear reaction, this means the hydrogen will have three opportunities to absorb the heat. These triple looped paths will also have a liner that is made up of a material that can to withstand 3000 K and the nuclear radiation, but will also defy the no-slip condition so hydrogen does not stick to the side of the triple looped path.

### High Fidelity Concept 2.

A base metal that has a melting point beyond 3,000 K and can also withstand the effects of the nuclear radiation. The base metal will have a spiral path for the hydrogen to flow through will its heating from the nuclear reaction. These paths will also have a liner that is made up of a material that can withstand 3,000 K and the nuclear radiation, but will also defy the no-slip condition so hydrogen does not stick to the side of the spiral path.

### High Fidelity Concept 3.

A base metal that has a melting point beyond 3,000 K and can also withstand the effects of the nuclear radiation. The base metal will have a straight path for the hydrogen to flow through will its heating from the nuclear reaction, this means the hydrogen will have one to absorb the heat. This path will also have a liner that is made up of a material that can withstand 3,000 K and the nuclear radiation but will also defy the no-slip condition so hydrogen does not stick to the side of the path.

### Medium Fidelity Concept 1.

This idea further explores the tungsten canister idea, but involves the use of heat-sinks to further absorb heat. It also allows hydrogen to flow through itself.

### Medium Fidelity Concept 2.

A thin cylinder created of tantalum for the base and has cylindrical pin extrusions to allow the hydrogen to flow and gain thermal energy.

### Medium Fidelity Concept 3.

A canister that is has a rotating component that switches bases when the flow path and the material reach a critical temperature.

### Medium Fidelity Concept 4.

Outsource to an outside company to 3-D print a tungsten for the base and infuse the lining with a ceramic material. This method will consist of a spiral path for the hydrogen flow.

### Medium Fidelity Concept 5.

This base metal will be made of tungsten with an odd numbered looped path. These paths are also lined with a zirconium carbide material.

## Change to Project

Due to recent meetings with the Idaho National Lab (INL) and NASA, there have been some changes to the overall goal of the project. With the previous generation of this project using BUSTER, a smaller version of Big BUSTER, tools have been developed to test nuclear fuels inside of BUSTER on a smaller scale. One of these tools that was developed is the SIRIUS-4 capsule. The SIRIUS-4 capsule is a long, thin capsule with multiple parts. The top portion of the capsule is used to attach to BUSTER and to inject fluids to flow through to the bottom of the capsule. The bottom portion of the capsule is where the test fuel is and it is in the middle of the reaction zone in the TREAT reactor. This is where the fluid would flow through test fuel and data would be collected about the fuel’s performance. With the need for testing larger fuel elements and the flow of hydrogen through a fuel element, Big BUSTER was proposed. Big BUSTER is a proposed larger version of BUSTER with the ability for hydrogen to flow through the fuel element to be tested for NTP engines. While the TREAT reactor does not yet have the capability to allow for hydrogen flow through Big BUSTER, the INL has been approved to begin development of a solution to allow for hydrogen flow to be used in Big BUSTER. Big BUSTER is also still not built. Big BUSTER has been approved and the assembly of it will be beginning shortly. Our canister will be a subsystem of a new SIRIUS capsule (SIRUIS-4) that will be scaled to fit in Big BUSTER and allow for hydrogen to flow through the test fuel element. Our canister will be in the bottom section of the SIRIUS capsule which will be placed within Big BUSTER in the test section of the TREAT reactor. With this new information, our targets have been changed for our canister. One of our main targets of the flowrate of hydrogen has been changed to the rough specifications that are currently available through INL of 20 grams per second of hydrogen flow. Our original target was designed without the proper specifications provided by the INL. The target was made based on the information NASA provided about the flow of hydrogen through a NTP engine. Another target that has changed is the radiation hardening. This target has been changed to mitigate the effects of degradation on the canister. Due to our canister having to endure the degradation of both hydrogen and radiation, the canister needs to be of high resistivity to corrosion effects to remain intact for the test. Due to the hydrogen being supplied from Big BUSTER and SIRIUS, the target for net pressure difference within the canister is now removed and as it is a function of both Big BUSTER and SIRIUS. The target of neutron absorption has also been removed due to this being a function of Big BUSTER and the TREAT reactor. The volume targets have also been changed to be no more than 80% volume of the canister is uranium particles. This is chosen due to the particles needing the move around the canister to complete the reaction process. The dimensions for Big BUSTER have yet to be released to us, while there are rough dimensions given of about 3.5cm in diameter with a range of 5 to 18 inches in length. This is still not definitive given that Big BUSTER has yet to be made and the definite dimensions have yet to be released to us. Given that most of the project has yet to be finalized, many of the targets can still change based on the direction that the project takes. It is also important to note that many of the components for Big BUSTER and SIRIUS are still in the design and development stage which can lead to future changes based on the needs of INL and NASA.

## Concept Selection

### House of Quality

The customer needs were analyzed using a binary pairwise comparison chart. Each need was weighed against the others and judged based on which need was more important, receiving either a 1 for more important or a 0 for less important. An importance weight factor for each customer need was developed from the comparison chart showing that withstanding 3000K to be the most important need.

Table 1:Binary Pairwise Comparison Chart

This importance weight factors are then used in the House of Quality to determine the ranking within the functional decomposition. The house of quality compares the function decomposition with the customer needs. Using the importance weight factors, the functions are then ranked based on how each function helps to achieve each customer need. From the House of Quality, the most important function is to withstand high temperatures. The least important function is having a maximum of 80% of the canister is taken up by uranium particles. This will help to evaluate each concept, allowing for the concept that best fits the customer needs the be chosen.

Table 2: House of Quality



### Pugh Chart

The Pugh charts allow for each high and medium fidelity concept to be compared against each other. This is done by first comparing every concept to a similar datum. If a concept is better than the datum it is given a +, worse a -, or if it performs similarly, an “S”. This eliminates one of the concepts. The remaining concepts are then compared against each other with a different concept being the datum eliminating a concept every time until only 3 concepts remain. The remaining 3 concepts are then compared against each other finding the ideal solution.

In the first Pugh chart, all the concepts were compared against SIRIUS-4. SIRIUS-4 was used because previous tests with SIRIUS-4 had the highest similarity in operating procedures. This led to all our concepts except for concept #78 outperforming SIRIUS-4.

Table 3: First Pugh Chart



For the final Pugh chart, concepts #70, #30, and #15 were compared against each other. This comparison led to concept #70 was chosen as the ideal concept. This is due to it being able to allow for more hydrogen to flow through the canister allowing for the canister to withstand higher temperatures due to the increased hydrogen cooling potential.

Table 4: Final Pugh Chart



**AHP Chart**

The analytical hierarchy process was then used to determine if the weights used for judging the concepts had confirmation bias. This process allows for a mathematical method to remove confirmation bias from the weights. This is done by comparing the design criteria against each other. Criteria 1 is compared against criteria 2, rated using values 1,3,5,7, or 9. If criteria 2 is found to be better than criteria 1, then the inverse number is used. Once every criterion is compared, the values are added together to generate total importance values.

Table 5: Analytical Hierarchy Chart



Using the importance values, the weight sum vector and consistency vectors can be calculated.

Table 6: Normalized Criteria Comparison Matrix



Finally, a consistency ratio is calculated, which should be below 0.1.

Table 7: Consistency Ratio Check



This table shows our consistency ratio was below 0.1.

### Final Selection

The final selection chosen is concept #70: Base metal that can withstand 3000k and not react with nuclear radiation and has a straight path for hydrogen to flow down lined with a material that does not react with hydrogen or the reactants. This concept was selected due to it performing the best in the final Pugh chart and being selected without confirmation bias. This concept is also the best fit for customer needs, allowing for variability depending on the changes made to both Big BUSTER and the SIRIUS project.

# Chapter Two: EML 4552C

## 2.1 Spring Plan

### Project Plan.

Shown in Figure 1: Spring Project Plan, is the spring project plan where every assignment is laid out with a corresponding team member is responsible for the completion of each task. The dates that each task will be completed is also laid out with the time each task will take and the progress that should be made to complete each task.

Table

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Figure 1: Spring Project Plan

### Build Plan.

The build plan for the projects begins with completing the full bill of materials that are required for testing the experimental design of the canister. Once the bill of materials is complete, ordering the machined canister can be completed through Lundy Enterprises. The detailed drawing of the machined canister can be seen in Figure 3: Machined Canister. Once the canister is ordered the remaining components for testing can be ordered. Once the components are delivered testing can begin. After initial testing, the thermocouples were determined to be easier to run from two separate Arduinos and computers.

## Restated Project Charter

### Project Scope

#### Project Description

Our client, Marvin Barnes from NASA, needs a canister that can be incorporated in their “Sirius Module and Big Buster” project. This project involves a canister that will test multiple types of elements as a baseline fuel for a nuclear reactor. The canister will go into the section of the Sirius Module and further within Big Buster where the fission reaction occurs and produces a temperature around 3000 K.  Within NASA’s project, the fluid reacting to the baseline fuel is hydrogen. NASA’s project will be used for testing at the transient reactor testing facility (TREAT Facility) in Idaho Falls, Idaho.

#### Key Goals

The main objective of this project is to design and develop a canister that will safely contain the nuclear reaction between the baseline fuel and the fluid it reacts with. The baseline fuel will start out as uranium-235 and if successful multiple other baseline fuels will be tested. The biggest obstacle will be withstanding the reaction temperature of a fission reaction and preventing a reaction between the walls of the canister and the fluid.

#### Market

Our canisters' primary and sole market is for NASA to use in their Big Buster and Sirius Module project. The contact at NASA for development is Marvin Barnes who has worked at NASA for 35 years and worked on multiple nuclear reaction propulsion projects. During development of the canister, dimensions of Big Buster and the Sirius Module will be given, and the canister’s volume and dimensions will be based off the info given.

#### Assumptions

Most assumptions will come from the fact that the use of our canister will occur in Idaho Falls, Idaho. A key aspect is knowing that after each use of the nuclear reactor, there is a down period of roughly three to five months of inactivity and the average temperature of a fission reaction that creates the most energy is 3000 K and that the material needs to withstand that temperature. It is safe to assume that the weight of the canister will not affect the use or efficiency of the overall system. The Sirius Module, where the canister is involved, is mounted on the ground and not for use in space, meaning weight is not a concern. Another assumption made is that the correct ratio of baseline fuel and hydrogen will be offered within the canister and that everything else in Big Buster and Sirius Module is working according to plan. Even though nuclear reactions create a radioactive product, the assumption will be made that we do not need to have a material that absorbs radioactive byproducts. This is due do the short run time of the testing, the five months down period, and the precautions taken by NASA to prevent interactions with radioactive material. If the reaction was tested for a longer time, then radioactive absorptivity would be considered when selecting a material.

## Results

The following sections outline the validation for this project.

### Material Selection

For the material selection for the canister that will be used in the TREAT Reactor, tungsten was chosen. This was chosen due to the material properties of tungsten, having a melting point of 3693 K. This is well above the required melting point that would be experienced in the tests of 3000 K. The canister will also be coated in zirconium carbide. Zirconium carbide also has a melting point of well above 3000 K at 3800 K. The zirconium carbide coating will prevent the hydrogen gas from sticking to the canister preventing hot spot propagation throughout the canister. For the experimental design of the canister, aluminum 6061 was chosen. This was due to the similar thermal conductivity properties is shares with tungsten. This allows for testing to be as close as possible to testing with tungsten and uranium.

### Fission Product

For the canister that will be used in the TREAT Reactor, different configurations of uranium will be used which will vary on the different fuel sources that the researched at NASA and the Idaho National Lab are testing at the time. For the experimental canister a heating element that can reach temperatures of over 100 ­. This will allow for scaling to simulate the use of uranium at high temperatures for calculations.

### Propellant

For the canister that will be used in the TREAT Reactor, liquid hydrogen that will become gaseous will be used for the experiments. For testing with the experimental canister, argon will be used. Argon was chosen due to safety concerns and availability. Argon gas allowed for simpler calculations and controlled gas flow through the experimental canister.

## Discussion

The experimental canister successfully demonstrated a temperature difference between the entrance temperature of the argon gas and the exit temperature of the argon gas when passing though the experimental canister. The temperature difference found from the experimental testing was found to be 16.1 K. Scaling these results for use in the TREAT Reactor showed that there would be a 1200 K temperature difference when using uranium and hydrogen.

### Errors

The experimental canister had a 2.13% error from the theoretical temperature difference of 16.45 K. This difference from the experimental results and the theoretical results was from ignoring friction from the tubing and canister, from losses due to connectors connecting the various tubing to the canister and the argon tank, and from the varying ambient temperature in the lab where the experiment was conducted. To create a more accurate simulation for theoretical results, the temperature in the lab where testing is conducted should be controlled allowing for more accurate results. For calculating theoretical values, an advanced computer analysis should be conducted using exact modeled parts.

## Conclusion

Overall, the experimental canister created a small-scale representation of the canister that will be used for research into NTP that will be conducted by NASA and the Idaho National Lab. The material selection for the proposed canister would meet the requirements for full scale nuclear fuel experimentation using the TREAT Reactor. The research that will be conducted from the canister would allow for improved nuclear fuels to be researched allowing for more efficient and powerful NTP engines. The finalization of Big BUSTER and the SIRIUS module may change the final dimensions of the canister, however based on the material provide, the canister meets the requirements set by NASA.

## Future Work

Moving forward, the creation of the proposed canister would be constructed. This along with the finalization of both Big BUSTER and the SIRIUS module, testing would then be conducted on different nuclear fuel sources. Alternate designs would be tested on a smaller scale using the experimental method would allow for different configurations to be tested and the results compared to the original experimental canister. These results would then allow for different canisters to be used for different types of experiments with nuclear fuels. Alternate designs proposed to NASA would also allow for different types of experiments to be conducted to test different propellants that could be used with NTP allowing for more efficient and powerful NTP engines to be researched and produced.

# Appendices

# Appendix A: Code of Conduct

**Mission Statement:**Our team's goal is to learn valuable skills that will help up in our future careers.

**Outside obligations:**

* + Brian McGough: ASME Exec Board, Building Manager at Oglesby Union twice a week.
  + McAnarney Borngesser: Weekend manager at Tomahawks 51, Dynamics 2 TA
  + Braden Dukes: ASME Exec Board
  + Jaxon Stadelnikas- None

**Team Roles:** Team roles will be decided further along in the project when more information about the project is received. Initial team roles are based upon everyone's specific discipline. As of this point, roles consist of Aeronautics Engineering for McAnarney, Jaxon, and Brian, and Materials Engineering for Brayden. Future team roles will be assigned based on their strengths and weaknesses. Each member will be assigned roles based on the difficulty and time allotted for each assignment.

**Communication:**Text Messages for urgent communication, Microsoft Teams for document sharing, emails for official records. Members should respond to urgent communications within 12 hours.

**Dress Code:**Casual dressing for normal classes and business casual for presentation and sponsor interactions, to be amended.

**Attendance Policy**: In case of absence of a team meeting, the absentee must give notice beforehand or while the meeting is being scheduled. The absentee will read the summary of the meetings.

**How to notify group:** Through the previously established communication methods.  Known conflicts will be recorded through email.  Last minute conflicts will be communicated through text messages.

**How to respond to people in professional meetings**: With courtesy and respect for others.  Present the group in the best manner possible.

**What do we do before Dr. McConomy or TAs**: Communicate with every team member and commutatively decide on a further action.

**At what point do we contact Dr. McConomy**: Once documented proof of a team member failing to contribute is available and the rest of the team commutatively decided to talk to Dr. McConomy.

**What do you want Dr. McConomy to do when you come**: To penalize the member in a meaningful way.

**How to amend**: As a group by majority vote can amend this living document.  No signatures will be required for future amendments.

**Statement of Understanding**: By signing each member has read and agrees to the terms and conditions stated above.

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# Appendix B: Functional Decomposition

Table 8: Functional Decomposition.

Nuclear Reactor Canister

Fit in “Big Buster”

Project

Allows Flow in One Direction

NTP Reaction Process

Capable Material to Withstand Reaction Temperature

Form Fit Uranium

Allows Flow of Only Hydrogen

Prevent Sticking Between Canister and Hydrogen

Resist Radiation Effect

Table 9: Functional Decomposition Cross Reference Table.

|  |  |  |  |
| --- | --- | --- | --- |
| Function | NTP Process Reaction | Fit in “Big Buster” project | Allow Flow in One Direction |
| Capable Material to Withstand Reaction Temperature |  |  |  |
| Capable Material to Resist Radiation Effect |  |  |  |
| Form Fit Uranium |  |  |  |
| Allows Flow of Only Hydrogen |  |  |  |
| Non-Stick Between Canister and Hydrogen |  |  |  |

# Appendix C: Target Catalog

Table 10: Target Catalog

|  |  |  |
| --- | --- | --- |
| **Functions** | **Targets** | **Metrics** |
| Capable Material Able to Withstand Reaction Temperature | 3000K | Temperature |
| Resist Radiation Effects | Less than 8 GPa increase in hardness | Hardness |
| NTP Reaction Process | Absorb less than 10% of neutrons | Percent Absorptivity |
| Form Fit Uranium | 9.2 | Volume |
| Form Fit Uranium | 175 grams | Mass |
| Fit Within Big Buster | 10 inches long by 2 inches diameter | Length and Diameter |
| Fit Within Big Buster | Less than | Thermal Expansion Rate |
| Prevent Sticking Between Canister and Hydrogen | Less than | Thermal Expansion Rate |
| Allow Hydrogen Flow | Net Pressure Difference of greater than 0 | Pressure Difference |
| Flow rate of Hydrogen | 2.2 | Mass Flow rate |

# Appendix D Figures and Tables

A picture containing graphical user interface

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Figure 2: Work Breakdown Structure

Table 11: Customer Needs Customer Needs Questions Answers and Interpretations.

|  |  |  |
| --- | --- | --- |
| Question | Response | Interpreted Need |
| What are the dimensions of the Canister we are designing? | You are designing a reactor canister to be used in project “Big Buster.” | The canister will have to fit in the Big Buster project. |
| Where will this device be used? | Idaho Falls, Idaho at the TREAT Reactor in the Idaho National Laboratory. | Device will not be used in space and atmospheric gravity will be applied. |
| Do we need to be concerned with radioactivity? | The project is tested on the ground and for a short duration. You do not need to worry about radiation. | Radiation absorption does not need to be considered for this device. |
| What will be used as fuel for the nuclear reaction? | Uranium 235 will be used. | Our canister will need to be able to hold and maintain conditions for a reaction of U 235. |
| How will the reactor work in the canister? | The reactor will inject a stream of hydrogen into the canister and heat it to 3000K for around 30 seconds. | The canister will have to be able to withstand 3000K without failure for at least 30 seconds. |
| What will be the reactant flow? | Hydrogen will flow through the canister to react with the U 235. | The canister will need to be able to have a flow go through it in one direction. |
| What are our limiting factors for this project (weight, cost, etc.)? | Weight does not need to be a factor because the canister will not be in space. The budget is unknown so far. | When selecting a material, the weight or density does not need to be taken account for, and as for now a budget does not need to be a concern. |
| How will we keep the hydrogen from reacting with the material chosen for the canister? | Flow dynamics will be used to keep neutrons away from the walls and the walls can have a film to prevent sticking. | The canisters will need to be sticky resistant. |

Table 12: Concept Generation

|  |
| --- |
| 1. Zirconium reactor canister |
| 1. Tantalum reactor canister |
| 1. Reactor canister made of hafnium |
| 1. Canister made out of tungsten |
| 1. Osmium reactor canister |
| 1. Reactor canister made of lead |
| 1. Canister made with oxides |
| 1. Canister that surrounds the entirety of Big Buster |
| 1. Roll-Cage style canister |
| 1. Rectangular Prism Canister |
| 1. Hexagonal reactor canister |
| 1. Two 1-way valves in order to allow hydrogen flow in one direction |
| 1. Octagonal Reactor Canister |
| 1. Heat absorbent filters to keep canister cool |
| 1. Base metal that can withstand 3000k and not react with nuclear radiation and has a triple pass for hydrogen to flow down lined with a material that does not react with hydrogen or the reactants |
| 1. Coolant system to reduce canister material heat |
| 1. Water cooling to transfer heat off canister |
| 1. Heat sink with fan to cool canister material |
| 1. Canister with 1 large hole in the middle for hydrogen flow |
| 1. Canister with many small holes through the canister |
| 1. Reactor canister design after human heart + arteries |
| 1. Canister that allows hydrogen flow by lungs-like apparatus |
| 1. Canister designed after bamboo (shape) |
| 1. Canister designed after an insect’s exoskeleton |
| 1. Honeycomb canister that injects hydrogen in its cells |
| 1. Afterburner style canister that injects hydrogen flow |
| 1. One time use canister that melts at 3000K but contains the heat past the canister |
| 1. Double walled canister like a vacuum bottle, but filled with liquid helium |
| 1. Canister featuring an air vent system to reduce temperature |
| 1. Use double wall canisters to contain or absorb the heat |
| 1. Double walled canister like a vacuum bottle, but filled with liquid nitrogen to keep cool |
| 1. Double walled canister like a vacuum bottle, but filled with liquid oxygen to keep cool |
| 1. Reflective coating to contain the heat within the space |
| 1. Use high pressure system to push the heat out of the canister |
| 1. Hydraulics to open and close heat flaps |
| 1. High pressure seals to block heat transfer |
| 1. Canister using cryogenic equipment |
| 1. Heat shield to block heat from reaching the canister walls |
| 1. Base metal that can withstand 3000k and not react with nuclear radiation and has a spiraled path for hydrogen to flow down lined with a material that does not react with hydrogen or the reactants |
| 1. Water cooled Tungsten |
| 1. Water cooled Tantalum |
| 1. Water cooled Osmium |
| 1. Water cooled Hafnium |
| 1. Heat-sink cooled Tantalum |
| 1. Heat-sink cooled Tungsten with a path for hydrogen |
| 1. Heat-sink cooled Osmium |
| 1. Heat-sink cooled Hafnium |
| 1. Cylindrical canister with many holes through it |
| 1. Honeycomb shaped canister that is made of Tantalum |
| 1. Honeycomb shaped canister that is made of Tungsten |
| 1. Honeycomb shaped canister that is made of Osmium |
| 1. Honeycomb shaped canister that is made of Hafnium |
| 1. Layered Brass that hits melting point under 3000K but is thick enough to not melt entire canister |
| 1. Extremely long hollow canister |
| 1. Layered Iron that hits melting point under 3000K but is thick enough to not melt entire canister |
| 1. Layered Aluminum that hits melting point under 3000K but is thick enough to not melt entire canister |
| 1. Tungsten layered cast iron that hits melting point under 3000K but is thick enough to not melt entire canister |
| 1. Tungsten self-replacing canister that swaps places with another after getting too hot |
| 1. Tungsten insulated Pringles Can |
| 1. Tungsten cylindrical infused ceramic material canister |
| 1. Tungsten canister that spirals around the center fuel rod |
| 1. Tungsten spiral hydrogen path for superheating |
| 1. Tungsten corkscrew hydrogen path for superheating |
| 1. Tungsten thin cylinder pin to pass hydrogen through |
| 1. Layered tungsten to pass hydrogen |
| 1. Meshed tungsten to pass through hydrogen |
| 1. Tantalum Carbide layered cast iron that hits melting point under 3000K but is thick enough to not melt entire canister |
| 1. Tantalum Carbide self-replacing canister that swaps places with another after getting too hot |
| 1. Tantalum Carbide insulated Pringles Can |
| 1. Base metal that can withstand 3000k and not react with nuclear radiation and has a straight path for hydrogen to flow down lined with a material that does not react with hydrogen or the reactants |
| 1. Tantalum Carbide canister that spirals around the center fuel rod |
| 1. Tantalum Carbide spiral with increasing radius hydrogen path for superheating |
| 1. Tantalum Carbide corkscrew hydrogen path for superheating |
| 1. Tantalum thin cylinder pin to pass hydrogen through |
| 1. Layered Tantalum Carbide to pass hydrogen |
| 1. Meshed Tantalum Carbide to pass through hydrogen |
| 1. Osmium layered cast iron that hits melting point under 3000K but is thick enough to not melt entire canister |
| 1. Osmium self-replacing canister that swaps places with another after getting too hot |
| 1. Osmium insulated Pringles Can |
| 1. Osmium cylindrical infused ceramic material canister |
| 1. Osmium canister that spirals around the center fuel rod |
| 1. Osmium spiral hydrogen path for superheating |
| 1. Osmium corkscrew hydrogen path for superheating |
| 1. Osmium thin cylinder pin to pass hydrogen through |
| 1. Layered Osmium to pass hydrogen |
| 1. Meshed Osmium to pass through hydrogen |
| 1. 3D Printed tungsten layered cast iron that hits melting point under 3000K but is thick enough to not melt entire canister |
| 1. 3D Printed tungsten self-replacing canister that swaps places with another after getting too hot |
| 1. 3D Printed tungsten insulated Pringles Can |
| 1. 3D Printed tungsten cylindrical infused ceramic material canister |
| 1. 3D Printed tungsten canister that spirals around the center fuel rod |
| 1. 3D Printed tungsten spiral hydrogen path for superheating |
| 1. 3D Printed tungsten corkscrew hydrogen path for superheating |
| 1. 3D Printed tungsten thin cylinder pin to pass hydrogen through |
| 1. Layered 3D printed tungsten to pass hydrogen |
| 1. Meshed 3D printed tungsten to pass through hydrogen |
| 1. Base of tungsten with a spiral chamber lined with zirconium carbide |
| 1. Base of tungsten with a spiral chamber lined with palladium |
| 1. Base of osmium with a triple passed chamber lined with |
| 100.Base of tungsten with a triple passed chamber lined with *Goo-Gone* |

Table 13: Second Iteration Pugh Chart



Table 14: Third Iteration Pugh Chart



Table 15: Analytical Hierarchy Chart for Final Concepts



Table 16: Analytical Hierarchy Chart for Final Concepts



Table 17: Analytical Hierarchy Chart for Final Concepts



Table 18: Analytical Hierarchy Chart for Final Concepts



Table 19: Analytical Hierarchy Chart for Final Concepts



Table 20: Analytical Hierarchy Chart for Final Concepts



# Engineering Drawings

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Figure 3: Machined Canister

# Operations Manual

**Project Overview**

This project consists of two parts, a proposed design and a testing design. Many of the materials that would be used for the proposed design are extremely harmful and dangerous and unobtainable for this class. The proposed design is the design that would be used if tungsten, uranium, Big BUSTER, the SIRIUS module, and the TREAT reactor could be used. The testing design is an alternative design that can be tested with the available proper equipment and fits within the budget of the senior design team.

**Project Description**

NASA and the Idaho National Laboratory have partnered to conduct research on nuclear thermal propulsion (NTP) engine fuels. This research into NTP would allow for faster and more efficient space travel to and from Mars, allowing for manned missions to Mars. The senior design team project is tasked with designing a device that can fit within Big BUSTER and the SIRIUS module to go into the Transient Reactor (TREAT) to test different nuclear fuels. To do this, the device must be able to withstand the elevated temperatures of the nuclear reaction and allow for the hydrogen propellent to flow through the canister to be heated by the nuclear reaction.

**Project Objective**

The objective of the project is to develop and test a canister to go into Big BUSTER and the SIRUIS module to test nuclear fuel compounds for thermal nuclear propulsion systems in the Transient Reactor (TREAT).

**Key Goals**

There are three key goals for this project. The first goal is for the canister to be temperature resistant. The canister must be able to withstand the high temperatures of the nuclear reaction happening inside of the canister. If the canister cannot withstand the high temperatures it will fail in the experiment. The next goal is that the canister must resist the effects of radiation. During a nuclear reaction, when radiation interacts with materials, it can cause radiation hardening which can cause very durable materials to become very brittle and this can lead to cracks and a failure of the canister. The canister must remain inert to the effects of the radiation and not change material properties. The final key goal is for reusability of the canister. The canister should be able to able to be reused to save on material costs and allow for multiple tests in the TREAT reactor. Further research into NTP may be deterred due to low reusability.

**Assumptions**

There are some key assumptions that are made to complete the project. The first assumption is that Big BUSTER and the SIRIUS module will function according to the specifications given by NASA. This research project is an ongoing project with constant changes to the design of Big BUSTER and the SIRIUS module. Our project will focus on the initial design specifications given to us by NASA about Bit BUSTER and the SIRIUS module. The second assumption that was made is that weight will not be a constraining factor. Given that this project is a custom-made part for testing that will only happen in the Idaho National Laboratory, the project will not be concerned about adapting the design for use in a spacecraft engine. This leads to weight not being a factor when creating the canister. The third assumption is that the temperature range will not exceed 3000K. This is due to the maximum temperature of the nuclear reaction and the fact that liquid hydrogen will be constantly running through the system keeping the canister below 3000K. The final assumption is that radiation containment will be done by Big BUSTER and the TREAT reactor. This means that our canister will not have to contain the radiation from the experiment. The TREAT Reactor and Big BUSTER will make sure that no radiation will reach outside of the reactor and affect the researchers.

**Component/Module Description**

Given that there are two separate components to the project this section will be broken into the proposed design and the testing design.

**Proposed Design**

The proposed design is a cylinder made from 99.99% pure tungsten that is powder coated with zirconium carbide. The cylinder is 14 inches long and has 28, 0.25inch holes that run through the entire canister. The center whole for the canister runs the length of the canister with a pressure fit at the top to seal the uranium in the center whole. The entire assembly would then be placed within the SIRIUS module which goes into Big BUSTER, which goes into the TREAT Reactor. It is then the job of the SIRIUS module, Big BUSTER, and the TREAT Reactor to activate the uranium through controlling the boron drums that reflect the neutrons and trigger the nuclear reaction. The SIRIUS module and Big BUSTER will then supply the liquid hydrogen to run through the canister allowing for the researchers to gather the results from the test. A CAD model of the proposed design is shown in Figure 4: Proposed Design CAD Model.

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Figure 4: Proposed Design CAD Model

**Testing Design**

The testing design consists of a cylinder of identical dimensions as the proposed design; however, it is made of 6061 aluminums. The center hole is replaced with a 7-inch deep with a 0.5 NTP thread. A heating element will act as the uranium. Our canister will be going through purely conduction heat transfer. Instead of using liquid hydrogen, argon will be used. There are two K-type thermocouples that will be used for performing the experiment. Each thermocouple is controlled by an Arduino. Both Arduinos can be run from a single computer. The mass flowrate is determined by the regulator on the argon cylinder. 3-inch diameter tubing will be used along with a 3D printed adapter to connect the argon to the canister. The tubing will also allow for the heated argon to be directed to a place for proper venting. A testing station made from aluminum extrusion was used to keep the canister in a secure and stationary location for testing.

**Integration**

For assembling the experiment, the first step is to assemble a test rig to hold the canister. This can be done in a variety of ways; however, our team built a cradle out of aluminum extrusion for the canister to sit. Once the base is created, the heating element should be screwed into the canister. Making sure the wires for the heating element are running through the tubing, attach and seal the tubing to either side of the canister. From here holes can be made in the tubing to retrieve the wires for the heating element and to insert the thermocouples. These holes need to be sealed to prevent the argon from leaking. Attach and seal the 3D printed adapter to tubing on the side of the heating element and attach the regulator. A diagram of the assembly of can be seen in Figure 5: Testing Diagram.

Diagram

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Figure 5: Testing Diagram

Once the testing rig has been assembled, each Arduino can be wired to the respected thermocouple. A wiring diagram can be shown in Figure 6: Thermocouple Wiring Diagram.

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Figure 6: Thermocouple Wiring Diagram

**Operation**

The first step in the operation of the canister involves assembly of the testing device. The first step is to screw in the heating element into the canister. Once the heating element is screwed into the canister attach the 3-inch diameter tubes on either end of the canister. The next step is to cut slots into the 3-inch diameter tubing to run the heating element wires out of the tubing and insert the thermocouples on either end of the canister. Attack the adapter to the heating element side of the canister and connect the regulator tubing to the adapter. Finally seal the locations of the thermocouples and every point of contact for the tubing. Once everything is sealed, connect the regulator to the argon canister and feed the end of the 3-inch tubing to the ventilation tubing. Once everything is connected attach the heating element to a 120V power supply. Turn on the power supply and wait for an hour until the canister is heated. Once the canister is at temperature, open the regulator to allow 20 grams per second of argon being delivered to the canister. Run the temperature sensor code on the Arduino and begin gathering data points. Once a steady state has been achieved record and save the data. Once the experiment is complete turn off the argon flow and turn off the power supply. Do not move the canister until it is cool to the touch. Ensure proper storage of the argon before, during, and after the experiment and ensure proper ventilation of the experiment room.

**Troubleshooting**

This design has very few parts that require replacement or maintenance. The biggest expense would be the physical canister itself and if there are any flow interruptions or indecisive data that does not correlate with expected results, ensure that the channels are not obstructed and that the tubing is sealed around the canister firmly to ensure correct flow direction. For errors of leaking gas, ensure that the holes for the thermocouples and heating elements are fully sealed and the connections of the tubing to the argon regulator and canister are clamped securely. If incorrect data is being received, ensure the wiring for the thermocouples and the Arduino are secure and that the code for the Arduino is satisfactory. Also, allow for the power supply to correctly input 5V to the Arduino and enough voltage to the heating element to allow for maximum heating. Parts that would break would be the heating element, tubing, or the thermocouples however, these parts are easily replaceable as they are inexpensive. For other parts such as the argon tank, regulator, and canister, these parts would need to be handled with extreme care to ensure they do not break.

Below is the code used in the Arduinos connected to their respective thermocouple. The code converts the voltage change from the thermocouples to the relevant temperature and displays the currently measured temperature in Celsius.

A picture containing graphical user interface

Description automatically generated

# Calculations

Assumption that Argon Cp is constant:

Initial Surface Temperature of Canister:

Inlet Temperature of the Flow:

Final Surface Temperature of Canister

Mass flow Rate is 20Liters/minute, or:

Converting 20L, Mass:

Need to find Surface Area for all 28 channels:

Thermal Conductivity Coefficient:

Coefficient of Viscosity for Argon:

For the inner and outer diameter of the Canister: and

Find Hydraulic Diameter:

Find Nusselt Number:

Find Enthalpy:

Expected Final Temperature for Canister:

Theoretical Temperature Change, need to assume:

Mass:

Specific Heat for a Constant Volume: or

Change in Temperature from the initial and expected:

Finding the Heat Transfer with Expected ∆T:

To find theoretical ∆T:

We need to find :

Therefore:

This means that our theoretical change in temperature of (16.451˚C) is very similar to our expected change in temperature of (16.451˚C). Our actual average change in temperature at (16.1˚C) and was very similar to both the expected and theoretical values. The errors can be connected to the assumptions of basing the properties at standard ambient conditions for argon gas and experimental faults such as possible leaks and inconsistent procedural methods. Constant Cp for Argon gas, ignoring fanno flow, boundary layers and friction.

Using error calculator:

# Risk Assessment

**FAMU-FSU College of Engineering**

**Project Hazard Assessment Policy and Procedures**

**INTRODUCTION**

University laboratories are not without safety hazards. Those circumstances or conditions that might go wrong must be predicted and reasonable control methods must be determined to prevent incident and injury. The FAMU-FSU College of Engineering is committed to achieving and maintaining safety in all levels of work activities.

**PROJECT HAZARD ASSESSMENT POLICY**

Principal investigator (PI)/instructor are responsible and accountable for safety in the research and teaching laboratory. Prior to starting an experiment, laboratory workers must conduct a project hazard assessment (PHA) to identify health, environmental and property hazards and the proper control methods to eliminate, reduce or control those hazards. PI/instructor must review, approve, and sign the written PHA and provide the identified hazard control measures. PI/instructor continually monitor projects to ensure proper controls and safety measures are available, implemented, and followed. PI/instructor are required to reevaluate a project anytime there is a change in scope or scale of a project and at least annually after the initial review.

**PROJECT HAZARD ASSESSMENT PROCEDURES**

It is FAMU-FSU College of Engineering policy to implement followings:

1. Laboratory workers (i.e. graduate students, undergraduate students, postdoctoral, volunteers, etc.) performing a research in FAMU-FSU College of Engineering are required to conduct PHA prior to commencement of an experiment or any project change in order to identify existing or potential hazards and to determine proper measures to control those hazards.
2. PI/instructor must review, approve and sign the written PHA.
3. PI/instructor must ensure all the control methods identified in PHA are available and implemented in the laboratory.
4. In the event laboratory personnel are not following the safety precautions, PI/instructor must take firm actions (e.g. stop the work, set a meeting to discuss potential hazards and consequences, ask personnel to review the safety rules, etc.) to clarify the safety expectations.
5. PI/instructor must document all the incidents/accidents happened in the laboratory along with the PHA document to ensure that PHA is reviewed/modified to prevent reoccurrence. In the event of PHA modification a revision number should be given to the PHA, so project members know the latest PHA revision they should follow.
6. PI/instructor must ensure that those findings in PHA are communicated with other students working in the same laboratory (affected users).
7. PI/instructor must ensure that approved methods and precautions are being followed by :
   1. Performing periodic laboratory visits to prevent the development of unsafe practice.
   2. Quick reviewing of the safety rules and precautions in the laboratory members meetings.
   3. Assigning a safety representative to assist in implementing the expectations.
   4. Etc.
8. A copy of this PHA must be kept in a binder inside the laboratory or PI/instructor’s office (if experiment steps are confidential).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Project Hazard Assessment Worksheet** | | | | |
| PI/instructor: Dr. Shayne McConomy | Phone #: 850-410-6624 | Dept.: Mechanical | Start Date: 3/8/22 | Revision number: 2 |
| Project: Team 515 Nuclear Canister for Space | | | Location(s): FAMU FSU College of Engineering (COE), FSU Innovation Hub, Idaho National Laboratory  Idaho National Laboratory, 1955 N Fremont Ave, Idaho Falls, ID 83415 | |
| Team member(s): Brian McGough, Braden Dukes, McAnarney Borngesser, Jaxon Stadelnikas | | | Phone #: 904-535-1464 | Email: [bem17@my.fsu.edu](mailto:bem17@my.fsu.edu) |
|  | | |  |  |

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Experiment Steps** | **Location** | **Person assigned** | **Identify hazards or potential failure points** | **Control method** | **PPE** | **List proper method of hazardous waste disposal, if any.** | **Residual Risk** | **Specific rules based on the residual risk** |
| Simulation and CAD | Remote/COE | Brian McGough | Eye Strain | Take breaks every 20 to 30 minutes to prevent unnecessary strain | N/A | N/A | HAZARD: 1  CONSEQ:  Negligible | Safety is planned by the worker and the supervisor. Proceed with supervisor authorization. |
| Residual:  Low |
| Cutting / Drilling Plywood / Aluminum | COE Machine Shop | McAnarney Borngesser | Cuts, Splinters, Dust Inhalation, Ear Damage | Most metal work will be done out of house. For smaller projects the senior design lab will be used. When using power tools, the appropriate protection measures will be taken. | Work Gloves, Safety Glasses, Respirator, Ear Protection | N/A | HAZARD: 3  CONSEQ:  Significant | After approval a written hazard control must be approved before continuing. Limit the number of people working in the hazard zone. Have at least 2 people present when performing any work in the event of an injury. |
| Residual:  Medium |
| 3D Printing | Innovation Hub | Braden Dukes | Hazardous Fumes, Burning | Innovation hub policies will be followed | N/A | N/A | HAZARD: 1  CONSEQ:  Negligible | Safety is planned by the worker and the supervisor. Proceed with supervisor authorization |
| Residual:  Low |
| Laser Cutting | Innovation Hub | Jaxon Stadelnikas | Eye Hazzard, Skin Hazzard, Fire Hazzard, | Innovation hub policies will be followed | Eye Protection | N/A | HAZARD: 3  CONSEQ:  Significant | After approval a written hazard control must be approved before continuing. Limit the number of people working in the hazard zone. Have at least 2 people present when performing any work in the event of an injury. |
| Residual:  Med High |
| Uranium Handling | Idaho National Laboratory | Idaho National Laboratory | Radiation Exposure, Radiation Burns | The Idaho National Laboratory policies will be followed | N/A | N/A | HAZARD: 4  CONSEQ:  Severe | The Idaho National Laboratory will use the procedures that they have put in place when handling radioactive elements. |
| Residual:  High |
| High Temperatures | COE | Brian McGough | Burns, Skin Irritation | During the use of high temperatures, every person in the vicinity should be alerted that a hot object is in use. Limit exposure and wait until cooled until handling. | Protective Gloves | N/A | HAZARD:1  CONSEQ:  Minor | After approval a written hazard control must be approved before continuing. Limit the number of people working in the hazard zone. Have at least 2 people present when performing any work in the event of an injury. |
| Residual:  Low Med |
| Argon Usage | COE | McAnarney Borngesser | Mental Impairment, Breathing Problems | During the use of argon, alert people in the room that the gas will be used. | Regulator | Venting to outside | HAZARD: 2  CONSEQ:  Minor | After approval a written hazard control must be approved before continuing. Limit the number of people working in the hazard zone. Have at least 2 people present when performing any work in the event of an injury. |
| Residual:  Low Med |

**Principal investigator(s)/ instructor PHA:** I have reviewed and approved the PHA worksheet.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Name** | **Signature** | **Date** | **Name** | **Signature** | **Date** |
| \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ | \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ | \_\_\_\_\_\_\_\_\_\_\_\_ | \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ | \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ | \_\_\_\_\_\_\_\_\_\_\_\_ |

**Team members:** I certify that I have reviewed the PHA worksheet, am aware of the hazards, and will ensure the control measures are followed.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Name** | **Signature** | **Date** | **Name** | **Signature** | **Date** |
| Brian McGough |  | 03/08/22 | McAnarney Borngesser |  | 03/08/22 |
| \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ | \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ | \_\_\_\_\_\_\_\_\_\_\_\_ | \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ | \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ | \_\_\_\_\_\_\_\_\_\_\_\_ |
| **Name** | **Signature** | **Date** | **Name** | **Signature** | **Date** |
| Braden Dukes |  | 03/08/22 | Jaxon Stadelnikas | Icon  Description automatically generated | 03/08/22 |
| \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ | \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ | \_\_\_\_\_\_\_\_\_\_\_\_ | \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ | \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ | \_\_\_\_\_\_\_\_\_\_\_\_ |

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**DEFINITIONS**:

**Hazard:** Any situation, object, or behavior that exists, or that can potentially cause ill health, injury, loss or property damage e.g. electricity, chemicals, biohazard materials, sharp objects, noise, wet floor, etc. OSHA defines hazards as “*any source of potential damage, harm or adverse health effects on something or someone".* A list of hazard types and examples are provided in appendix A.

**Hazard control:** Hazard control refers to workplace measures to eliminate/minimize adverse health effects, injury, loss, and property damage. Hazard control practices are often categorized into following three groups (priority as listed):

1. **Engineering control:** physical modifications to a process, equipment, or installation of a barrier into a system to minimize worker exposure to a hazard. Examples are ventilation (fume hood, biological safety cabinet), containment (glove box, sealed containers, barriers), substitution/elimination (consider less hazardous alternative materials), process controls (safety valves, gauges, temperature sensor, regulators, alarms, monitors, electrical grounding and bonding), etc.
2. **Administrative control:** changes in work procedures to reduce exposure and mitigate hazards. Examples are reducing scale of process (micro-scale experiments), reducing time of personal exposure to process, providing training on proper techniques, writing safety policies, supervision, requesting experts to perform the task, etc.
3. **Personal protective equipment (PPE):** equipment worn to minimize exposure to hazards. Examples are gloves, safety glasses, goggles, steel toe shoes, earplugs or muffs, hard hats, respirators, vests, full body suits, laboratory coats, etc.

**Team member(s):** Everyone who works on the project (i.e. grads, undergrads, postdocs, etc.). The primary contact must be listed first and provide phone number and email for contact.

**Safety representative:** Each laboratory is encouraged to have a safety representative, preferably a graduate student, in order to facilitate the implementation of the safety expectations in the laboratory. Duties include (but are not limited to):

* Act as a point of contact between the laboratory members and the college safety committee members.
* Ensure laboratory members are following the safety rules.
* Conduct periodic safety inspection of the laboratory.
* Schedule laboratory clean up dates with the laboratory members.
* Request for hazardous waste pick up.

**Residual risk:** Residual Risk Assessment Matrix are used to determine project’s risk level. The hazard assessment matrix (table 1) and the residual risk assessment matrix (table2) are used to identify the residual risk category.

The instructions to use hazard assessment matrix (table 1) are listed below:

1. Define the workers familiarity level to perform the task and the complexity of the task.
2. Find the value associated with familiarity/complexity (1 – 5) and enter value next to: HAZARD on the PHA worksheet.

**Table 1. Hazard assessment matrix.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | | **Complexity** | | |
| Simple | Moderate | Difficult |
| **Familiarity Level** | Very Familiar | 1 | 2 | 3 |
| Somewhat Familiar | 2 | 3 | 4 |
| Unfamiliar | 3 | 4 | 5 |

The instructions to use residual risk assessment matrix (table 2) are listed below:

1. Identify the row associated with the familiarity/complexity value (1 – 5).
2. Identify the consequences and enter value next to: CONSEQ on the PHA worksheet. Consequences are determined by defining what would happen in a worst case scenario if controls fail.
   1. Negligible: minor injury resulting in basic first aid treatment that can be provided on site.
   2. Minor: minor injury resulting in advanced first aid treatment administered by a physician.
   3. Moderate: injuries that require treatment above first aid but do not require hospitalization.
   4. Significant: severe injuries requiring hospitalization.
   5. Severe: death or permanent disability.
3. Find the residual risk value associated with assessed hazard/consequences: Low –Low Med – Med– Med High – High.
4. Enter value next to: RESIDUAL on the PHA worksheet.

**Table 2. Residual risk assessment matrix.**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Assessed Hazard Level** | **Consequences** | | | | |
| Negligible | Minor | Moderate | Significant | Severe |
| 5 | Low Med | Medium | Med High | High | High |
| 4 | Low | Low Med | Medium | Med High | High |
| 3 | Low | Low Med | Medium | Med High | Med High |
| 2 | Low | Low Med | Low Med | Medium | Medium |
| 1 | Low | Low | Low Med | Low Med | Medium |

**Specific rules for each category of the residual risk:**

Low:

* Safety controls are planned by both the worker and supervisor.
* Proceed with supervisor authorization.

Low Med:

* Safety controls are planned by both the worker and supervisor.
* A second worker must be in place before work can proceed (buddy system).
* Proceed with supervisor authorization.

Med:

* After approval by the PI, a copy must be sent to the Safety Committee.
* A written Project Hazard Control is required and must be approved by the PI before proceeding. A copy must be sent to the Safety Committee.
* A second worker must be in place before work can proceed (buddy system).
* Limit the number of authorized workers in the hazard area.

Med High:

* After approval by the PI, the Safety Committee and/or EHS must review and approve the completed PHA.
* A written Project Hazard Control is required and must be approved by the PI and the Safety Committee before proceeding.
* Two qualified workers must be in place before work can proceed.
* Limit the number of authorized workers in the hazard area.

High:

* The activity will not be performed. The activity must be redesigned to fall in a lower hazard category.

**Appendix A: Hazard types and examples**

|  |  |
| --- | --- |
| **Types of Hazard** | **Example** |
| Physical hazards | Wet floors, loose electrical cables objects protruding in walkways or doorways |
| Ergonomic hazards | Lifting heavy objects Stretching the body  Twisting the body  Poor desk seating |
| Psychological hazards | Heights, loud sounds, tunnels, bright lights |
| Environmental hazards | Room temperature, ventilation contaminated air, photocopiers, some office plants acids |
| Hazardous substances | Alkalis solvents |
| Biological hazards | Hepatitis B, new strain influenza |
| Radiation hazards | Electric welding flashes Sunburn |
| Chemical hazards | Effects on central nervous system, lungs, digestive system, circulatory system, skin, reproductive system. Short term (acute) effects such as burns, rashes, irritation, feeling unwell, coma and death.  Long term (chronic) effects such as mutagenic (affects cell structure), carcinogenic (cancer), teratogenic (reproductive effect), dermatitis of the skin, and occupational asthma and lung damage. |
| Noise | High levels of industrial noise will cause irritation in the short term, and industrial deafness in the long term. |
| Temperature | Personal comfort is best between temperatures of 16°C and 30°C, better between 21°C and 26°C.  Working outside these temperature ranges: may lead to becoming chilled, even hypothermia (deep body cooling) in the colder temperatures, and may lead to dehydration, cramps, heat exhaustion, and hyperthermia (heat stroke) in the warmer temperatures. |
| Being struck by | This hazard could be a projectile, moving object or material. The health effect could be lacerations, bruising, breaks, eye injuries, and possibly death. |
| Crushed by | A typical example of this hazard is tractor rollover. Death is usually the result |
| Entangled by | Becoming entangled in machinery. Effects could be crushing, lacerations, bruising, breaks amputation and death. |
| High energy sources | Explosions, high pressure gases, liquids and dusts, fires, electricity and sources such as lasers can all have serious effects on the body, even death. |
| Vibration | Vibration can affect the human body in the hand arm with `white-finger' or Raynaud's Syndrome, and the whole body with motion sickness, giddiness, damage to bones and audits, blood pressure and nervous system problems. |
| Slips, trips and falls | A very common workplace hazard from tripping on floors, falling off structures or down stairs, and slipping on spills. |
| Radiation | Radiation can have serious health effects. Skin cancer, other cancers, sterility, birth deformities, blood changes, skin burns and eye damage are examples. |
| Physical | Excessive effort, poor posture and repetition can all lead to muscular pain, tendon damage and deterioration to bones and related structures |
| Psychological | Stress, anxiety, tiredness, poor concentration, headaches, back pain and heart disease can be the health effects |
| Biological | More common in the health, food and agricultural industries. Effects such as infectious disease, rashes and allergic response. |

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**Project Hazard Control- For Projects with Medium and Higher Risks**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Name of Project: NASA Nuclear Canister** | | | | **Date of submission: 11/16/21** | | | |
| **Team member** | | **Phone number** | | **e-mail** | | | |
| **Brian McGough** | | **904-535-1464** | | [**Bem17@my.fsu.edu**](mailto:Bem17@my.fsu.edu) | | | |
| **Braden Dukes** | | **239-272-8475** | | [**Bsd18b@my.fsu.edu**](mailto:Bsd18b@my.fsu.edu) | | | |
| **Jaxon Stadelnikas** | | **941-650-3572** | | [**js18e@my.fsu.edu**](mailto:js18e@my.fsu.edu) | | | |
| **McAnarney Borngesser** | | **904-347-5636** | | [**msb18e@my.fsu.edu**](mailto:msb18e@my.fsu.edu) | | | |
|  | |  | |  | | | |
| **Faculty mentor** | | **Phone number** | | **e-mail** | | | |
| **Dr. Eric Hellstrom** | | **850-645-7489** | | [**hellstrom@asc.magnet.fsu.edu**](mailto:hellstrom@asc.magnet.fsu.edu) | | | |
| **Dr. Shayne McConomy** | | **850-645-7489** | | [**smcconomy@eng.famu.fsu.edu**](mailto:smcconomy@eng.famu.fsu.edu) | | | |
| **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”).** | | | | | | | |
| Cutting and drilling aluminum and plywood are necessary for prototyping and running real life simulations of our canister. This was determined to be a medium risk due to the use of power tools, splinters, and dusk inhalation. Proper safety measures for this will involve proper training before the use of any power tools, appropriate PPE, and having at least 2 people present during any work in case of an injury.  Laser cutting smaller, precise components will be required for our canister. This will be performed at the innovation hub. This is labeled a medium/high risk due to the lasers having the ability to cause permanent eye damage. The innovation hub will monitor all laser cutting and proper training is required before use. Eye protection should be worn to prevent eye damage. At least 2 people should be present during any work in case of an injury.  High temperatures due to heating elements will be an integral part of testing components of the canister. This was determined a low/medium risk due to the heating element having the ability to cause burns and skin irritation. Proper safety measure for this will involve alerting all members that a heating element is in use. The heating element should be allowed ample time to cool after use. Protective gloves should be used when handling the heating element after use. At least 2 people should be present during any work in case of an injury.  The use of argon is required for testing components of our canister. This is determined to be a low/medium risk due to inhalation of pure argon causing mental impairment and breathing problems. Proper safety measure for this will involve using a regulator and alerting all members in the vicinity that argon will be in use. At least 2 people should be present during any work in case of an injury. | | | | | | | |
| **Thinking about the accidents that have occurred or that you have identified as a risk, describe emergency response procedures to use.** | | | | | | | |
| * **Remove the injured person from the scene** * **Contact appropriate authority (911, Supervisor, FSUPD)** * **Shut down the cause of the injury** * **Secure the area to prevent other injuries** * **Create an accident report will all the information about the accident and how to prevent future accidents.** * **Share accident report with supervisor or PI** | | | | | | | |
| 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 | | Member Name | | Faculty or other COE emergency contact | | Phone number |
| **Ed McGough** | **904-748-6832** | | **Brian McGough** | | **Dr. Shayne McConomy** | | **850-410-6624** |
| **Diana Stadelnikas** | **941-321-6633** | | **Jaxon Stadelnikas** | | **Dr. Rajan Kumar** | | **850-645-0149** |
| **Todd Dukes** | **239-293-3145** | | **Braden Dukes** | | **Dr. Dorr Campbell** | | **850-410-6610** |
| **Anne Bean** | **904-392-9236** | | **McAnarney Borngesser** | | **Dr. Shayne McConomy** | | **850-410-6624** |
| Safety review signatures | | | | | | | |
| Team member | Signature | | | | Date | Faculty mentor | Date |
| **Brian McGough** |  | | | | **3/8/22** |  |  |
| **McAnarney Borngesser** |  | | | | **3/8/22** |  |  |
| **Jaxon Stadelnikas** | **Icon  Description automatically generated** | | | | **3/8/22** |  |  |
| **Braden Dukes** |  | | | | **3/8/22** |  |  |
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|  |  | | | |  |  |  |

**Report all accidents and near misses to the faculty mentor.**

# References

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Finseth, J. (1991). *Rover Nuclear Rocket Engine Program: Overview of Rover Engine Tests.* Huntsville: Sverdrup Technology.

J. Kenneth Shultis, R. E. (2002). *Fundamentals of Nuclear Science and Engineering.* Manhattan: Marcel Dekker Inc.