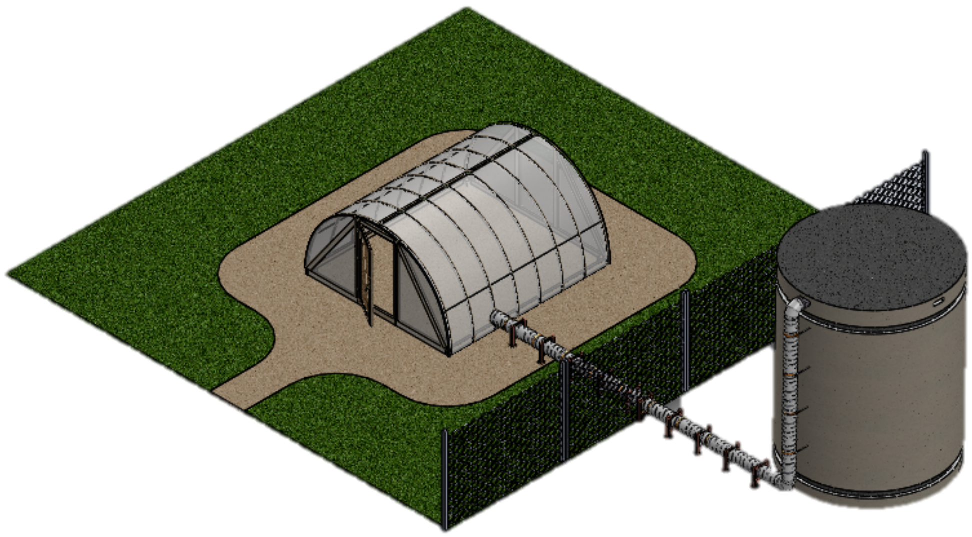
Capturing Heat From Spent Nuclear Fuel



WN21 ME 450 Team 17

Section 5: Professor Steven Skerlos

June Ahn

Kyra Kothawala

Jared Rosenberg

Quan Usher

Jordan Wallace

Sponsored by Dr. Marianna Coulentianos

April 26, 2021

TABLE OF CONTENTS

EXECUTIVE SUMMARY **3**

BACKGROUND **4**

Spent Nuclear Fuel Storage 4

Greenhouse 5

PROBLEM DEFINITION **5**

Project History 5

Problem Statement 6

REQUIREMENTS AND SPECIFICATIONS **6**

CONCEPT EXPLORATION **8**

Concept Generation 8

Concept Convergence 9

SOLUTION DEVELOPMENT **13**

Site Selection 14

Design Selection 14

Mathematical Model 18

Mathematical Model Calculations 20

SOLUTION VERIFICATION **23**

Verification of Cask Outlet Temperature 23

COMSOL Background 23

COMSOL Model Development 23

Results of the COMSOL Simulation and Comparison to MATLAB Model 24

Comparison of Assumed Outlet Temperature to Measured Outlet Temperature 25

Sensitivity Analysis 26

Requirements and Specifications 26

COST ANALYSIS **27**

SOCIAL CONTEXT CONSIDERATIONS **28**

Engineering Standards 28

Engineering Inclusivity 28

Environmental Context Assessment 29

Social Context Assessment 30

Ethical Decision Making 30

DISCUSSION AND RECOMMENDATIONS **31**

Funding and Immediate Next Steps 31
Expansion of Infrastructure 32
Future Recommendations 32
Alternative Solution Spaces 32
Additional Considerations 33

AUTHORS **34**

ACKNOWLEDGEMENTS **36**

REFERENCES **37**

APPENDICES **40**
Appendix A - Group Brainstorming Mind Map 40
Appendix B - Cask Outlet Temperature Documents 41
Appendix C - List of Applicable Regulations for Capturing SNF Heat 43

EXECUTIVE SUMMARY

Spent Nuclear Fuel can be placed in dry cask storage, where it emits waste heat into the atmosphere. Our sponsor, Dr. Marianna Coulentianos, identified an opportunity to capture this heat for a beneficial application. Our team evaluated the feasibility of our sponsor's previously proposed solutions and designed a system that could transfer heat from the dry cask. We focused specifically on quantifying the amount of heat that would be available for a therothecial application.

In order to determine how much heat would theoretically be available, we constructed both mathematical and computational simulations of heat transfer through a duct system. The system we propose includes a square funnel feature at the cask interface, connected to a round, rigid duct system extending over the perimeter fence. It was observed that the outlet temperature of our proposed system is around 36-65℃, which we determined is most suitable for a greenhouse application.

We calculated a return on investment of 5 years by growing tomatoes in a greenhouse of 1800 ft^2. We are confident that our design is feasible and does not violate any regulations set forth by the Nuclear Regulatory Commission. However, more analysis is needed to further examine discrepancies between field data and our assumptions, as well as the scalability of our proposed solution.

We also considered the social context of this solution. Eating fruits and vegetables grown on a nuclear site is likely to cause skepticism around our solution. While we believe that the radiation levels of this waste heat are too low to realistically affect horticultural applications, all food that is intended for human or animal consumption in the United States must register with the FDA before beginning these activities.

BACKGROUND

We have partnered with UM affiliate Marianna Coulentianos who created the concept of SustainiUM, a design project which proposes to utilize heat emitted by Spent Nuclear Fuel (SNF), contained in dry storage casks, to dry municipal wastewater sludge, hence producing environmentally friendly biomass fuel and/or fertilizer.

Our goal is to explore the potential of operating a cask model on a pilot site for recovering waste heat for a beneficial application.

Spent Nuclear Fuel Storage

Nuclear energy is derived from the fission of uranium atoms. This process generates heat to produce steam, which is used by a turbine to generate electricity. Uranium pellets are placed inside cylindrical fuel rods to use for reactions. The fuel becomes extremely hot and radioactive, and after about five years, the fuel becomes cooler and is considered spent and no longer useful for heating water. Reactor operators are responsible for the heat and radioactivity that remains in the SNF after it's taken out of the reactor.

SNF is a high-level radioactive waste that must be stored and isolated. After being removed from the reactor, it is placed into wet storage. Wet storage submerges the spent rods in a large pool of water to be cooled over the span of 7-10 years. This storage system is displayed below in Figure 1.[1] In the late 1980s, wet storage pools began reaching capacity which led to the development of dry storage.[2]

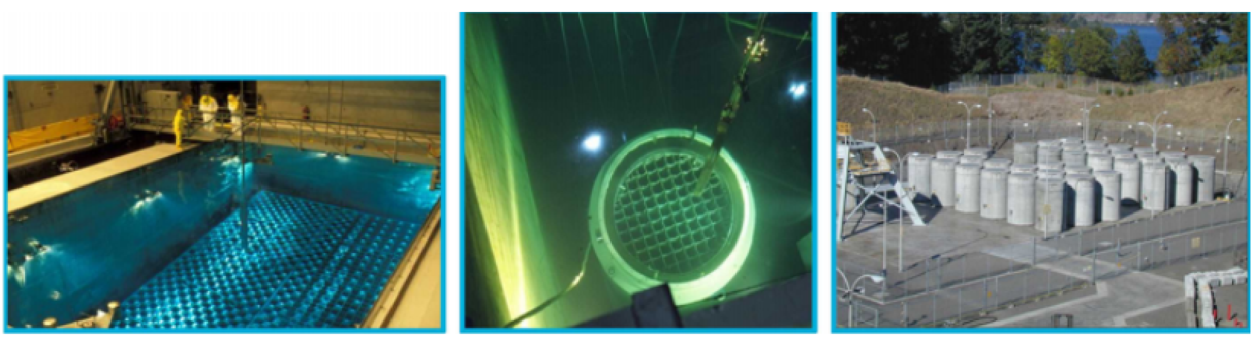


Figure 1. Wet storage (Left), Transfer of fuel rods to canister (Center), and Dry storage (Right)

Dry storage allows the SNF to continue cooling by transferring it from the pool to a canister called a cask. The casks are typically steel cylinders that are either welded or bolted closed. The casks are surrounded by a concrete overpack for additional protection and to serve as a shield from radioactivity. There are multiple different dry cask system designs, some oriented vertically and some stored horizontally or underground. Orientation affects the accessibility of the cask as well as natural convection.

The decay heat from the spent fuel is transferred through the surrounding steel canister and to the atmosphere via convection. Additionally, dry cask canisters are backfilled with an inert cooling gas, usually helium, to promote heat transfer from the SNF to the canister wall. This method allows the SNF in dry casks to be passively cooled and stored. A section view of a typical dry cask can be seen in Figure 2.

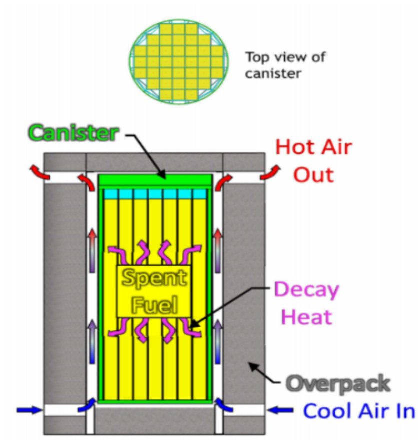


Figure 2. A section view of a typical dry cask storage unit showing the inner canister and outer concrete overpack.

Greenhouse

A greenhouse is a building with either glass or a transparent vinyl wall and roof that allows sunlight to enter. The energy emitted by the sun is used as a source of heat and light to grow plants inside this space. Greenhouses are often used to grow plants despite non-ideal external weather conditions and commonly grown crops are tomatoes, cabbage, potatoes, spinach, and lettuce. Without a greenhouse, some of these plants are only allowed to grow in select regions during colder seasons. Due to its advantage, there are an estimated 9 million acres of greenhouses around the world[3].

PROBLEM DEFINITION

This project was created and developed by Dr. Marianna Coulentianos who is our primary stakeholder. She recognized the potential to use decay heat from SNF for a beneficial application. The project history and current general description of the problem are outlined below.

Project History

This project is sponsored by Dr. Marianna Coulentianos, a recent Ph.D. graduate of the University of Michigan. Some of her early research focused on exploring the nuclear energy and wastewater treatment industries. She found that the wastewater treatment system in the US heavily depends on natural gas for operation, which is expensive and harmful to the environment. She also found that most of the potential energy of nuclear fuel still remains after it is considered spent. These findings led her to develop an initial idea correlating these two industries.

Dr. Coulentianos identified an opportunity to offset the high energy cost of drying wastewater by leveraging unused decay heat from SNF. She found that combining these two industrial waste streams could result in a beneficial product, biomass. Over the past year, Dr. Coulentianos has worked to develop this idea by identifying over 30 stakeholders and evaluating a pilot site located in Pottstown-Limerick, PA. The nuclear site in Limerick, PA produces an estimated 1517.7 kW of decay heat over a 25 year span. The Pottstown wastewater treatment facility produced 6.6 mega gallons of wastewater sludge per year. Financial analysis found that implementing Dr. Coulentianos' proposed solution at the pilot location could be profitable in 3 years. Dr. Coulentianos is knowledgeable on wastewater treatment and drying processes, but there is still a need for further nuclear and heat transfer analysis and consideration of other applications.

Problem Statement

Nuclear energy generation produces spent nuclear fuel (SNF). The energy in this fuel cannot be fully utilized, and in the US only 5% of the energy from the reactor fuel can be harvested before it is considered spent.[4] The SNF is eventually stored for long periods of time in cylindrical containers called dry casks where the decay heat is ventilated and released into the atmosphere using a convection cooling process. This decay heat is currently unused and has many potential applications. Therefore our team has been tasked with developing a solution for capturing this heat for a greenhouse.

REQUIREMENTS AND SPECIFICATIONS

To develop the requirements and specifications we followed a selection process that consisted of researching relevant materials, brainstorming initial requirements and specifications, incorporating stakeholder feedback, and finalizing the requirements and specifications. We considered the topics of dry cask heat transfer, beneficial applications, economics, and ethics. Each of these initial requirements were then paired with a specification based upon our understanding of the project scope and problem statement. The requirements were chosen based on what would most affect our design model and the relevance to the dry casks and capturing SNF heat. The finalized list of requirements and specifications is shown in Table 1.

Table 1: The requirements and specifications of our project, along with their respective sources and remaining questions. Regulations compliance is the highest priority so that our design is eligible for possible implementation at existing nuclear power plants.

Requirement	Specification(s)	Sources
Complies with all applicable nuclear regulations and cask licenses	Must comply with following NRC, 10 CFR Part 50 and Part 72 standards	Compliance regulations for canister storage (Appendix C) Document of applicable regulations for capturing SNF Heat (Appendix C)
Complies with site licenses and logistics	Heat capture design must interface with SNF facility and follow all protocols Design does not require a change in license	General licensing document (Appendix C) Cask storage layout plans for a typical site
Ethics	Hold paramount the safety, health, and welfare of the public	Review and abide by NSPE Code of Ethics
Reliable	Maintain a heat efficiency > 30% Monitoring/sensor system to track heat and airflow at all times	
Easy to maintain and service	Less than 10% custom made parts	Employ use of commercially available HVAC parts
Cost consideration	Design must be profitable within 5 years of installation	

Due to a highly regulated field, our project solution space is constrained and must conform to existing nuclear energy regulations in the United States. The evidence and justifications for specifications directly related to the SNF come from standards published by the US Nuclear

Regulatory Commision, the American Society of Mechanical Engineers, the US Department of Energy, and others. So far, we have identified standards for construction permits, SNF storage and handling, and cask configurations. Other sources of evidence for our specifications come directly from the largest manufacturer of the dry cask systems in use today; Holtec International[5]. They provide drawings of dry cask components and plan views of the concrete pads on which the casks sit.

The primary engineering principles used for the project are heat transfer and thermodynamic analysis. Through many revisions of our requirements and specifications, we have narrowed the scope of the project to designing a way to capture the waste heat from the casks for a beneficial application. By considering criteria such as maintenance, reliability, and minimizing energy losses we have made the device to operate with minimal intervention for the existing dry cask storage systems and apply to nuclear regulations.

CONCEPT EXPLORATION

Our concept explorations consisted of a series of convergent and divergent processes where we generated multiple design concepts then filtered them down to four key concepts. The four design concepts were evaluated based on stakeholder feedback, meetings with heat transfer experts, and compliance to our requirements and specifications. A detailed description of our ideation process is outlined below.

Concept Generation

For the first step of concept generation, each member of the team performed individual research and ideation consisting of brainstorming and sketching. We were encouraged by Marianna, our primary stakeholder, to think outside the box in order to generate innovative solutions. Most of the ideas were centered around existing technologies found in research papers, but applied and combined in novel ways such as duct and chimney systems and solar dryers. The other conventional ideas were expanded upon with research into relevant topics. In order to organize concepts, we created a mind map with ideas categorized by cask interface, heat transfer/transport, and applications. The final version of our mind map can be seen in Appendix A.

After the completion of the mind map, we selected three key ideas from each category that best encompassed the other ideas in that section. These served as the basis for further divergence as we continued exploring our solution space. The topics we chose to research as a group for each category is shown in Table 2.

Table 2. The nine relevant components from the cask interface, heat transfer, and applications categories. These components were further researched and ideated upon.

Category	Concept Name
Cask interface	Vacuum
	Heat sink
	Hose
Heat transfer/transport	Heat exchanger
	Duct
	Heat capacitor material
Applications	Greenhouse
	Thermoelectric generator
	Biosolids dryer

Concept Convergence

After brainstorming individual components of the design, a morphological analysis was completed to form full, stand-alone systems. The morphological functions included cask interface, heat transfer, and applications. After combining different function solutions, stakeholder feedback was considered and a meeting with Dr. Katsuo Kurabayashi, a heat transfer professor, was conducted to determine feasibility and finalize four concepts to continue exploring. The four concepts that were further explored were the underground casks, thermoelectric generator, heat pump and greenhouse duct shown in Figures 3 - 6. After preliminary and economic calculations, we were able to eliminate designs and focus on a final solution using a duct system to transfer heat from the dry cask to a greenhouse.

Underground Casks with Chimney: In order to broaden the solution space, a variety of cask types were considered based on current and long term nuclear storage facilities. The San Onofre site in California stores dry casks underground using Holtec underground containers. Based on Holtec patents, the underground system reclaims the energy from heat emanating from the SNF and provides continuous passive cooling of the loaded canisters by utilizing the chimney-effect[6]. The consideration for a design with casks underground allows natural radiation shielding and special arrangement so that SNF is hotter than what is typically allowed, thereby increasing the amount of energy that can be reclaimed.

Given the logistical challenges of nuclear regulations, it is a priority to have a design which does not require modifications to the existing site licenses. The Holtec system of dry storage casks, connected by pipes, could be slightly modified to create a stack. This would release part of the heated air above ground[7]. Moreover, this design could be applied to a general long term storage facility such as Yucca Mountain. This proposed deep geological repository could be arranged in a similar system as the San Onofre site.

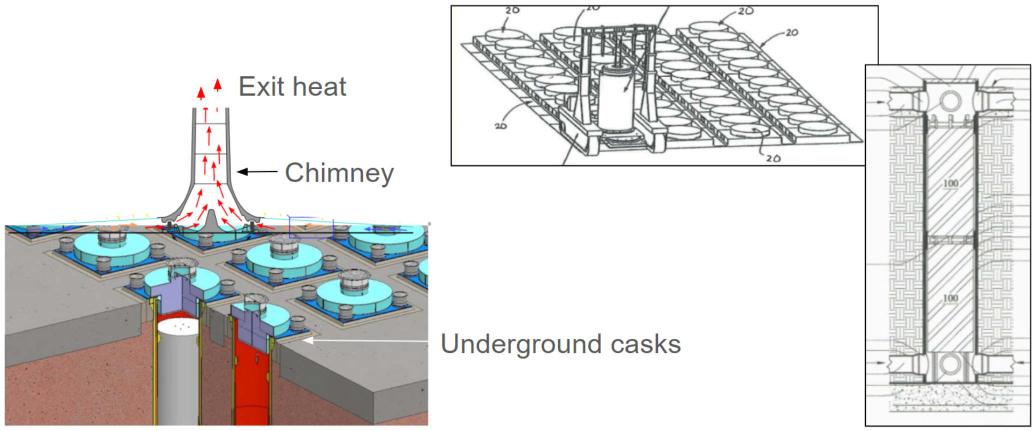


Figure 3. This figure shows a preliminary schematic of the underground casks with chimney concept. The chimney funnels the rising waste heat from a collection of underground casks to power a turbine.

The underground dry cask with chimney was evaluated for feasibility and eventually eliminated due to stakeholder feedback. We concluded that the underground dry cask design was infeasible because of the limited number of underground cask sites in the U.S. and disinterest from our primary stakeholder.

Thermoelectric Generator: After reviewing waste heat recovery technologies and applications, it was determined that thermoelectric methods could be applicable to transform the low-grade heat to electricity. This system benefits from having no moving parts that can fail or wear out . However, this comes with a tradeoff of system efficiency, which tends to range from 2-5%[8].

For space travel, similar methods of using a Radioisotope Thermoelectric Generator have been used to convert heat generated by the decay of plutonium-238 fuel into electricity using thermocouples[9]. The thermocouples generate power by converting the temperature gradient into electric voltage. Multiple packs of thermocouples can be linked together to produce electricity and would be beneficial in relation to dry casks.

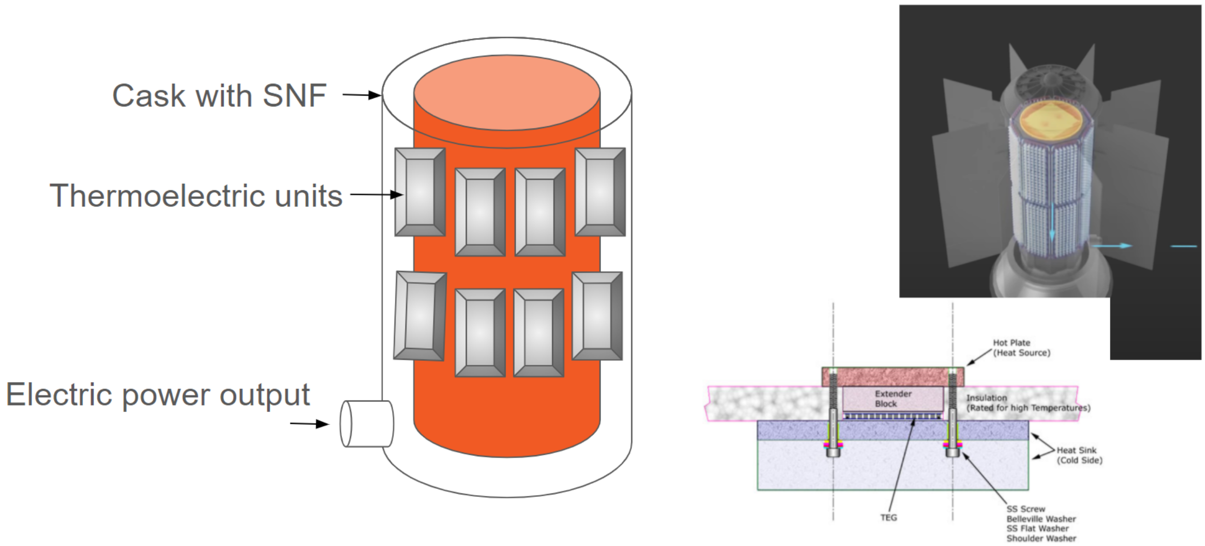


Figure 4. This figure shows a preliminary schematic of the thermoelectric generator concept. This concept converts heat flux into electrical energy. The temperature gradient in a conducting material results in heat flow; this results in the diffusion of charges. This flow of charge carriers between the hot and cold regions in turn creates a voltage difference, generating electricity.This systems allows passive recovery of waste heat, but at a low efficiency, could be offset with larger quantities of dry casks.

To determine the feasibility of the thermoelectric generator concept, we contacted Dr. Kazuaki Yazawa, a professor at Purdue University, who specializes in harvesting energy from wasted heat and using thermoelectrics for power generation. He suggested using the low-grade heat as-is for higher efficiency and only converting the heat energy to electricity if necessary. Since the amount of electricity generated by thermoelectrics would not be sufficient for our project requirements and there is no readily available technology, we did not continue developing this concept.

Heat Pump/Vacuum: We decided to focus a portion of our research on heat transfer devices that could potentially increase the grade of the heat captured. During our ideation phase, we found that heat pump is one of the widely used heat transferring devices. With external power, it is capable of transferring heat from lower temperatures to higher temperature for longer distance, which is considered to be against the laws of thermodynamics. It can be used as either cooling and heating devices and many home appliances that we use nowadays including refrigerators, air conditioners, and dryers have already applied this technology for better efficiency and performance. For residential purposes, heaters with heat pump technology usually operate at temperatures around 4℃ and supply hot air of around 21℃.

Van de Bor et. al.[11] published a study showing that a compression resorption heat pump and a waste stream inlet temperature of 45℃ could attain a maximum outlet temperature of 142℃. The compression resorption also typically yields higher efficiencies[11]. Compression Resorption heat pumps are more technically complex than other heat pumps and can be expensive to install, so ideally we would like to find less expensive alternatives. However, this research affirmed that the conversion of low-grade heat to higher qualities using heat pumps is feasible.

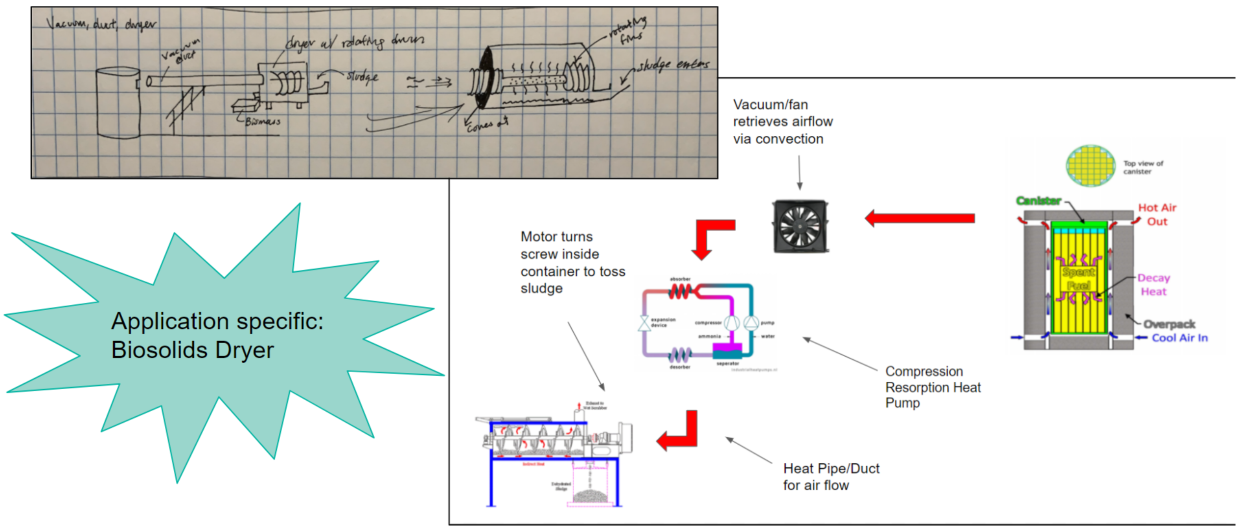


Figure 5. This figure shows a preliminary schematic of the vacuum/heat pump concept. This mechanism aims to suck the hot air out via convections, converting low grade heat to a higher grade. This high grade heat is then transferred to a metal rotating drum with an auger screw to toss and dry sludge.

Due to a lack of publicly available data, we used simulated data from a NRC study [8] to determine that one dry cask has a mass flow rate of approximately 2.53 x 10 kg/s which converts to a volumetric flow rate of 75.58 m^3/hr. For industrial heat pumps, the anticipated volumetric flow rate of the fluid entering the heat pump is expected to be around 10^4 m^3/hr. This confirmed that the unforced volumetric flow rate of one cask was insufficient to operate the heat pump. The idea could be feasible, if there is a minimum of 135 dry casks on site to meet the volumetric flow rate required. While fans could theoretically increase the flow rate, the amount of fans and required fan speed were too large to be feasible. Additionally, the Industrial Heat Pumps Feasibility Check calculator indicated that we could only harvest 10% of the available energy from the dry casks, resulting in a further inefficient system. In conclusion, we decided that this concept, while potentially feasible, was not suited to meet our EROI requirement.

Duct and Greenhouse: In an effort to explore alternative applications, we developed a concept to use the emitted heat as a source for a greenhouse. Many sites do not have the space or funding for large scale greenhouse applications, so this idea uses only the heat emitted from dry casks to run smaller greenhouses close to the storage site. In Min and Yu's study, they found that heat generated during operation at power plants is typically discarded into the sea after being absorbed in cooling water. Recently, several countries have been applying power plant waste heat to horticulture. In France, the Dampierre nuclear power plant has been supplying its waste heat as the only heat source to a large scale horticulture estate of 150 ha in size.[12].

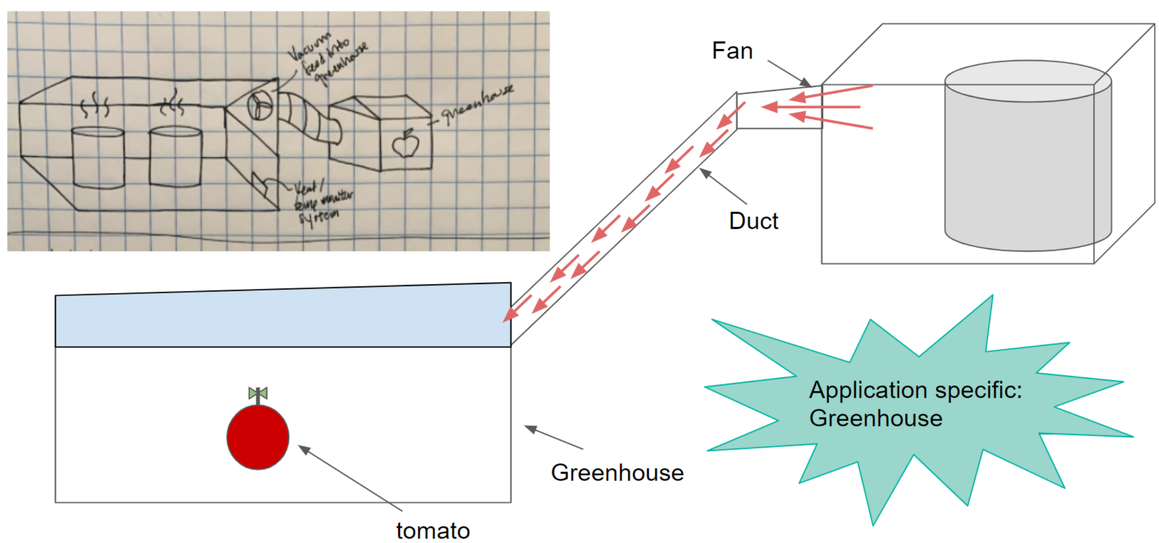


Figure 6. This figure shows a preliminary schematic of the green house concept. This does not directly capture heat, but rather transfers the heat to a separate location for horticultural applications.

The fan and duct interface with greenhouse application provide a solution that can comply with nuclear regulations and site licenses due to its minimally invasive nature. In addition, there is potential for a greater heat transfer efficiency with existing technology that is readily available. Furthermore, there were social benefits achieved with this greenhouse application such as additional space to grow food. Thus, we decided to continue iterating on this concept as our final solution.

SOLUTION DEVELOPMENT

A duct system with a greenhouse was determined to be the best idea to continue developing. The value of our project is delivered through a detailed design, MATLAB mathematical model, and COMSOL simulation to determine our system's performance capabilities. Based on publicly available data, we initially assumed the outlet temperature of the cask was approximately 100 ℃. We recently received data about SNF dry casks at Duke energy and Palo Verde Nuclear Generating Station indicating the cask outlet temperatures were around 50 ℃ shown in Appendix B. Resultantly, we have made design calculations and decisions based on both of these scenarios and recommend gaining more data from various spent nuclear fuel sites. The results of this effort are further detailed below.

Site Selection

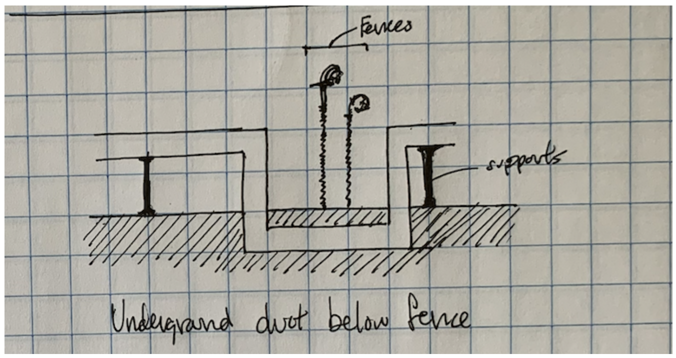
In order to create a model, we determined a pilot location where our model would be based. There are over 70 nuclear power generation sites across the country, so we had a variety of options in which we could select. Given the high regulation of this industry and limited access to publicly accessible cask and site information, we refined our search to locations in which our stakeholder had pre-existing relationships formed. Resultantly, our pilot site was determined to be the Palo Verde Generation Station in Tonopah, AZ. This site, and our projected physical solution space, is shown in Figure 7 below.

Figure 7. The Palo Verde Generation Station in Tonopah, AZ site used for dependent variables in our mathematical model. The red annotations indicate our physical solution on site, highlighting the (1) dry storage casks, (2) duct-fan system for heat transport, and (3) application area.

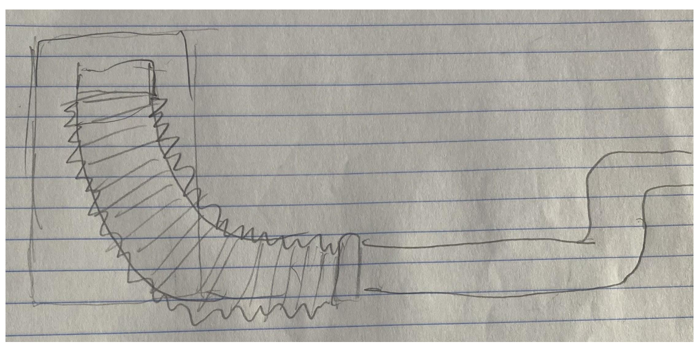
We focused our attention on Palo Verde generating station because they are the largest intermittent SNF storage facility in the US with the most available dry casks (152). It was also confirmed by site personnel that the satellite imagery available on Google Maps is up to date, which we have referenced for our solution development. However, we realized that the ambient temperature around the site is almost suitable for a greenhouse without the use of waste heat[13] since the yearly average ambient temperature in Tonopah, AZ is 21℃[10]. Factoring in the concentration of heat within the greenhouse from direct sun exposure, using the cask waste heat for a greenhouse at the Palo Verde is inefficient. Therefore, in the future it would be necessary to choose a secondary representative site as the basis of our model parameters.

Design Selection

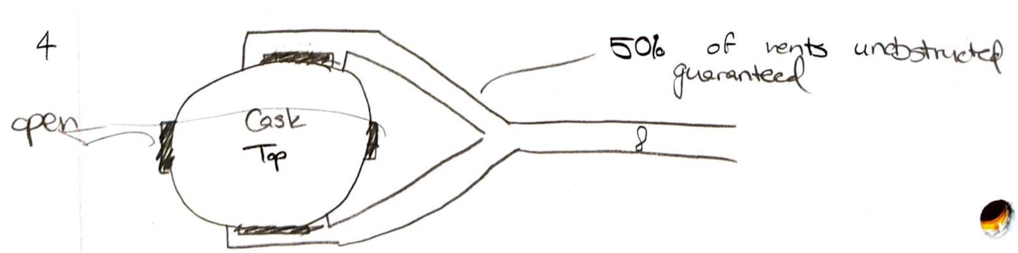
With a pilot location selected, the required design constraints, such as site logistics and cask design, were finalized and a tailored solution was developed. Through conversations with our primary stakeholder, we understood that the value of our solution would be directly tied to the cask interface and heat transport. As a result, we conducted a second round of concept divergence and convergence to create the optimal solution for our pilot site. To achieve this, we began by ideating around various cask interface possibilities given the key constraints of the site. From conversations with site personnel, we determined that the main constraints were that the system could not obstruct more than 50% of the cask outlet vents and that the greenhouse needed to be beyond the pad's fenced perimeter. With these in mind, we generated the ideas shown in Figure 8 below.



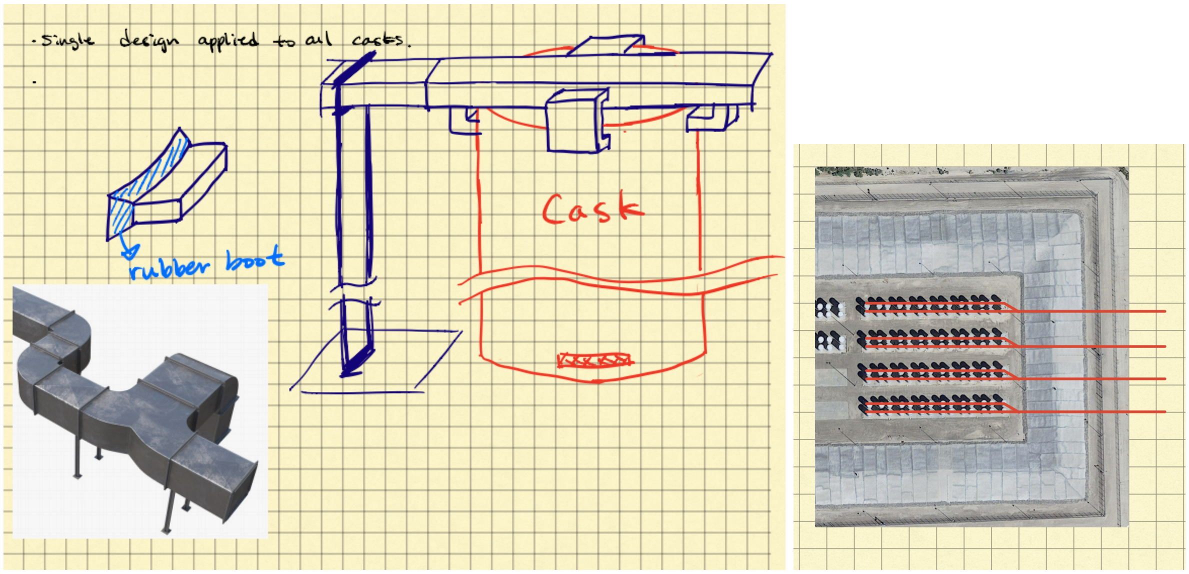
(a)



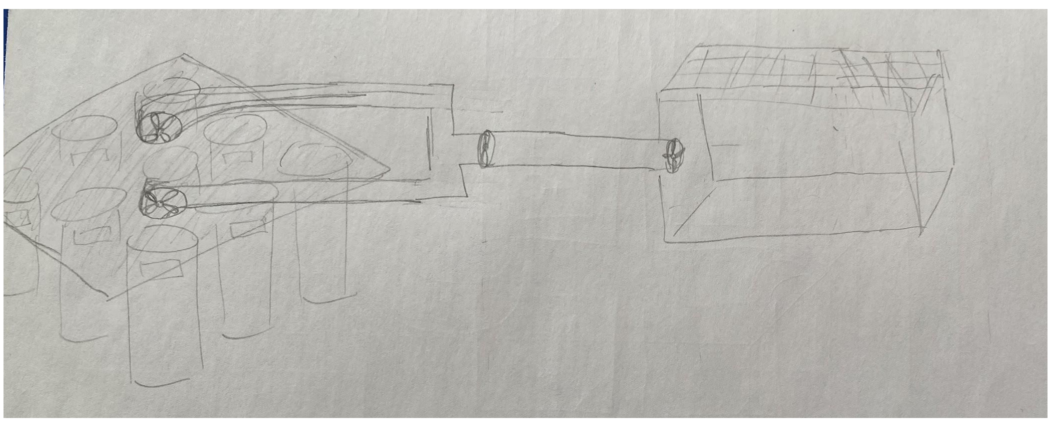
(b)



(c)



(d)



(e)

Figure 8. The initial drawings detailing ideas for the heat transport. **(a)** An image depicting an underground fence interface with rigid supports. **(b)** A flexible duct system connecting to a rigid duct for flexibility at the cask interface. **(c)** A 50% coverage system that works to engage opposing vents, using the other two as emergency outlets. **(d)** A scaled up system for full engagement of all vents extending across multiple casks on a storage pad. **(e)** A funnel system covering the top surface of casks to encapsulate all heat generated around the storage pad.

The concepts above served to introduce many system components for evaluation and potential implementation into a final solution. As a result, these components were listed by category for an optimal solution to be developed. The results are shown below in Table 3.

Table 3. The idea generated components evaluated to create the most efficient duct system considering the fence interface, system supports, casks interface, and duct type and routing.

Category	Idea
Fence Interface	Through the fence
	Over the fence
	Underground past the fence
System Support	Rigid supports
	Sandbag supports
	Telescoping leg supports
Cask Interface	Off center coverage
	Funnel
	Magnetic Strips
	Flexible Round
Duct Type	Flexible Square
	Rigid Round
	Rigid Square

With the components listed out, our team underwent a series of checks to determine the best one in each category. The evaluation process consisted of a feasibility check, comparison to our requirements and specifications, and an understanding of our pilot site's logistics. By doing so, we determined that the optimal design would include a square funnel feature at the cask interface, connected to a round, rigid duct system extending over the perimeter fence, ultimately connecting to our greenhouse application. The rigid round duct design was chosen based on its high efficiency, low maintenance, weather proof nature, and fan compatibility.[14] In addition, this duct type is less likely to grow mold and other organisms on its surfaces because of non-porous and smooth material. Rigid supports were chosen due to their strength and adjustability to different heights and configurations. We also decided that going over the fence would be the best fence interface decision due to the minimal obstruction it would create for existing systems. To communicate these elements as a cohesive system, we developed a CAD model in Solidworks. The result is shown below in Figure 9.

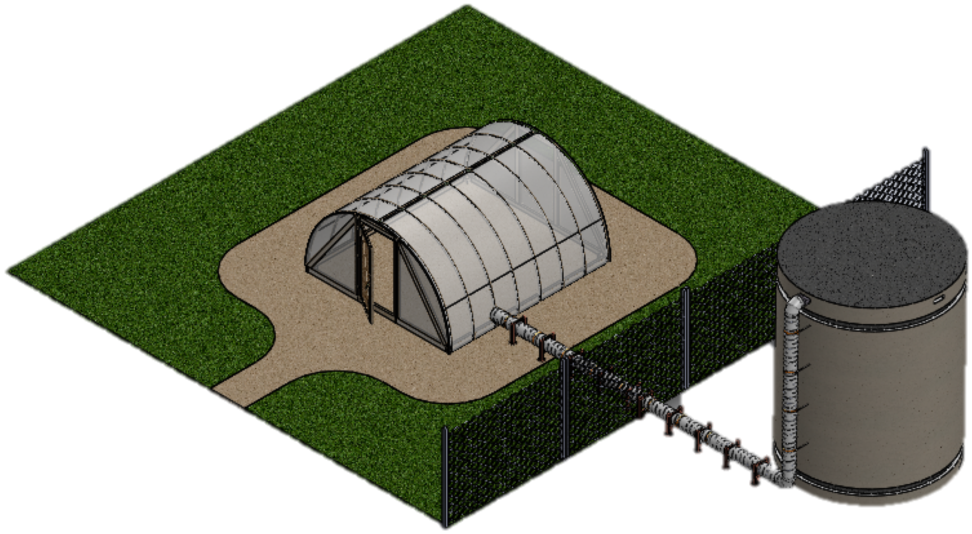


Figure 9. Overall design solution rendered in Solidworks. Shown is the cylindrical dry cask connected to a single outlet duct, rigidly supported along its path through the fence connecting to the greenhouse. This rendering serves as a visual aide, and omits specific design details for simplicity.

The CAD model simplifies our system in showing the connection to a cask at a single vent. The model is primarily used to visually represent the concept generated, as it omits some of the system complexities such as the dual vent engagement and going over the fence. This simplification was made to communicate the idea clearly and show the overall system logistics.

Mathematical Model

We determined that a mathematical model would be most appropriate due to the complex nature of the heat transfer and thermodynamics of our proposed system in addition to our stakeholders' required focus on heat transport. The optimal range of temperatures for the chosen application of a greenhouse is approximately 70 - 80℉ (21-27℃)[13]. With the inlet temperature and desired outlet temperature known, the duct transport system was designed under these constraints. It is imperative, then, that we determined the temperature distribution inside a duct of arbitrary parameters as a function of its length and inlet (cask outlet) temperature. This is the primary focus of our mathematical model. The duct outlet (greenhouse inlet) temperature, and corresponding mass flow rate of heated air will inform the design of the greenhouse in order to achieve optimal performance.

Assumptions: Over the course of the project, we have struggled to find accurate sources of information for the geometries, materials, and heat generation rate inside of the dry cask. Either the information was not publicly available, or it was not kept by the operators of the SNF storage facilities. Therefore, the mathematical model we have developed used the cask outlet temperature and mass flow rate of air as the only inputs from the dry cask. If these two values are known either via measured or simulated data, we can proceed without regard for the internal heat transfer processes of the dry cask.

To simplify the modelling process, there are several assumptions that we have made about the system. These assumptions, along with their corresponding sources and justifications, are presented below in Table 4.

Table 4. Assumed model parameter values for each stage of the heat transfer process along with their level of certainty and sources. Green, yellow, and red indicate high, medium, and low certainty respectively of assumed values. Note that we are most uncertain of the mass flow rate which is a critical value with great influence over the duct outlet temperature.

	Model Parameter	**Value Range**	**Certainty**	**Source**
Cask	Outlet Temperature	80 - 100 [℃]		Holtec Int. patents[6]/safety reports[7], NRC simulation data[8]
	Mass Flow Rate	20 - 60 [g/s]		NRC simulation data[8]
Ambient Conditions	Ambient Temperature	10 - 30 [℃]		Historical weather data[10]
	Wind Speed	0 - 9 [m/s]		Historical weather data[10]
Heat Transport	Duct Diameter	0.15 - 0.3 [m]		Commercial benchmarks[15]
	Duct Thickness	0.3 - 2 [mm]		Commercial benchmarks[15]
	Duct Thermal Conductivity	0.5 - 100 [W/m-k]		Commercial benchmarks[15]
	Insulation Thermal Conductivity	.02 - .07 [W/m-K]		Industry Standards[19]
	Insulation Thickness	65 - 80 [mm]		Industry Standards[19]

Outlet temperature is labelled green because of agreement between multiple primary sources. It is necessary to assume a range of temperatures rather than one value because we suspect that the actual surface temperature of the canister varies slightly even within a single cask. It is also dependent upon the length of the cask, of which there are multiple configurations available, as well as ambient temperatures which fluctuate hourly and seasonally.

We are least certain of the mass flow rate range because it is dependent on the internal heat transfer processes of the cask, which we are not concerned with. Therefore, we must rely on publicly available data or model predictions. So far, we have only found one source of simulated mass flow rate data from the Nuclear Regulatory Commision, and without a second source to compare against, we cannot be certain of the validity of their model data. Those sourced from commercial benchmarks and industry standards are well documented and therefore are labelled green.

There are specific assumptions which simplify the modelling process itself. These are: fully developed internal flow without an entrance region, no radial velocity or temperature gradient, and a duct which is flush to the cask outlet. The radial velocity and temperature assumptions are believed to be valid, but we will continue to assess their validity with our heat transfer stakeholder.

Mathematical Model Calculations

This model uses the concepts of heat transfer to predict the duct outlet temperature for a given set of cask air and atmospheric weather conditions. The model is complicated by the presence of both internal and external flow within and around the duct, which must be combined in order to arrive at a single closed form solution. These steps are explained below.

Internal Flow: Looking first at the internal flow of air within the duct, the Reynolds number can be calculated using the Eq. 1 shown below,

$$Re_D = \frac{VD}{\upsilon} \qquad (1)[16]$$

where V is the velocity of the flow within the duct [m/s], D is the diameter of the duct [m], and ν is the kinematic viscosity of the flow [m^2/s]. Once the Reynolds number has been calculated, it is used in conjunction with the Prandtl number to calculate the Nusselt number using the appropriate Nusselt correlation. In general, the Nusselt correlation relates all of the relevant flow parameters to a single convection coefficient which is ultimately used to calculate the heat rate. Selection of the appropriate Nusselt correlation depends on flow regime (i.e. laminar or turbulent), system geometry, Reynolds number magnitude etc. The appropriate correlation for the internal flow of the duct is given by Gnielinski and is shown below in Eq. 2,

$$Nu_D \equiv \frac{hD}{k_f} = \frac{(f/8)(Re_D - 1000)Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)} \qquad (2)[16]$$

where Re_D is the Reynold's number, Pr is the Prandtl number, and f is the friction factor associated with the surface roughness of the duct. While specific correlations may be analytically or empirically derived for specific flow conditions, the definition of the Nusselt number, which is always true, is shown as the middle term in Eq 2. Here, h is the convection coefficient [W/m^2-K], D is the diameter of the duct [m], and k_f is the thermal conductivity of the fluid [W/m^2-K]. The friction factor for an assumed smooth surface condition is given by Petukhov and is shown in Eq. 3 below.

$$f = [0.790 \cdot ln(Re_D) - 1.64]^{-2} \tag{3}[16]$$

Once the Nusselt number is calculated, the convection coefficient may also be calculated.

External Flow: Turning now to external flow of ambient air around the duct, all flow properties must be evaluated at the film temperature of the system. The film temperature T_f is defined as the average of the ambient air temperature T_∞ and the average surface temperature of the duct T_s in Kelvin. Because the duct surface temperature is nonuniform and directly related to the desired output of the model, we cannot know T_s in advance. To overcome this obstacle, we can arbitrarily guess T_s to allow us to calculate the film temperature of the system and evaluate the required flow properties. This guess propagates all the way to the output of the model, which we can then use to calculate T_s. This guessing process is repeated until the two different values of T_s converge. Guessing T_s and calculating the film temperature, all flow properties (ν, Pr, k_f) can be evaluated and the Reynolds number calculated in the same manner as above using Eq 1.

The appropriate Nusselt correlation for external cross flow over a round duct is given by Churchill and Bernstein and is shown in Eq. 4 below.

$$Nu_D = 0.3 + \frac{0.62Re_D^{1/2}Pr^{1/3}}{[1+(0.4/Pr)^{2/3}]^{1/4}}[1 + (\frac{Re_D}{282{,}000})^{5/8}]^{4/5} \tag{4}[16]$$

Once the Nusselt number is calculated, the convection coefficient may also be calculated.

Combining the Two Flows: Now that both internal and external convection coefficients are known, they can be combined into an overall heat transfer coefficient which also accounts for conduction heat transfer through the duct wall. The overall heat transfer coefficient is defined in Eq 5 shown below,

$$U = [\frac{1}{h_i} + \frac{r_1}{k_d} \cdot ln(\frac{r_2}{r_1}) + \frac{r_1}{r_2}\frac{1}{h_e}]^{-1} \tag{5}[17]$$

where h_i is the internal convection coefficient [W/m^2-K], h_e is the external convection coefficient [W/m^2-K], r_1 is the internal radius of the duct [m], r_2 is the external radius of the duct [m], and k_d is the thermal conductivity of the duct material [W/m-K]. Finally, the overall heat transfer coefficient is used to find the duct outlet temperature as a function of its length, defined below in Eq. 6,

$$T_o = T_\infty - (T_\infty - T_i)e^{(-\frac{UD\pi x}{\dot{m}c_p})} \tag{6}[17]$$

where T_o is the duct outlet temperature [K], T_i is the duct inlet (cask outlet) temperature [K], T_∞ is the ambient air temperature [K], D is the diameter of the duct [m], $\dot{m}$ is the mass flow rate through the duct [kg/s], c_p is the specific heat of air [kJ/kg-K], U is the overall heat transfer coefficient [m^2-K/W], and x is the length of the duct [m]. A plot of this equation is shown below in Figure 10.

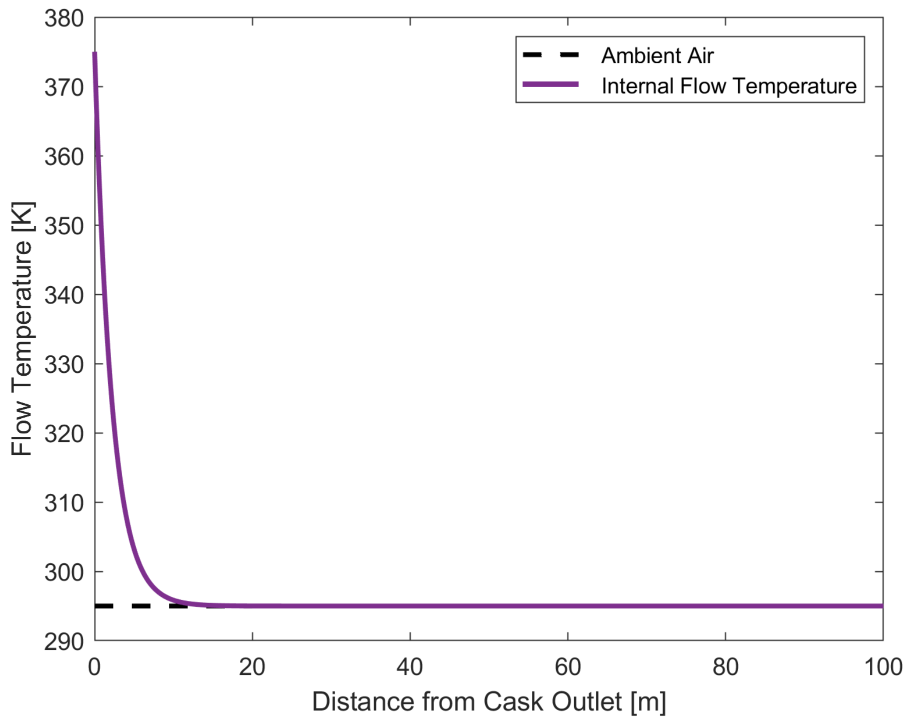


Figure 10. Predicted internal flow temperature along duct length for a given set of flow conditions and duct configuration (Eq 6). Ambient air is constant at 295K (22℃), and the flow temperature decays exponentially as it travels through the duct. Maximum flow temperature is 375K (102℃) corresponding to the cask outlet, and the internal temperature decays to ambient at a distance of about 10 meters, far sooner than the required 100 meter length.

Equation 6 predicts the duct outlet temperature as a function of the inlet temperature and mass flow rate, and it can be used to determine the validity of the assumed fluid properties as explained above.

The rate of heat loss as predicted by the mathematical model is greater than expected, possibly due to the uncertainty surrounding critical flow characteristics such as mass flow rate and cask outlet temperature. The model predicts that the duct flow will decay to ambient temperature at a distance of about 10 meters, which is far too soon for our needs. The accuracy of this model is discussed in greater context in Results of the COMSOL Simulation and Comparison to MATLAB Model on page 24.

SOLUTION VERIFICATION

We will not be constructing a physical prototype of our proposed system; therefore, verification is completed using a secondary modelling process. We have chosen to use COMSOL to study the temperature distributions and heat losses present in the system. The methods and results of the COMSOL simulation, comparison to the analytical MATLAB model, and translation to real world operation are discussed in the following sections.

Verification of Cask Outlet Temperature

As discussed previously, we have assumed a temperature range of 80-100℃ for the air exiting the top of the dry casks. The amount of heat energy available for capture is directly proportional to the temperature of this air. Therefore, it is critical to the feasibility and success of our system that the outlet temperature is known to the highest degree possible.

Through interviews with Luke McIntyre, Engineer at Palo Verde Nuclear Site, and Steven Edwards, Manager at Duke Energy, it was found that the average measured temperature of the air at the cask outlets is about 48℃ at our Palo Verde pilot site. This data disproves our assumption, and it is supported by a secondary theoretical source provided to us. These sources for the outlet temperature are more credible than those that were previously available to us because they come directly from facility personnel and include the only measured data that we have seen thus far.

The cause of the large discrepancy between predicted and measured temperature is not known with certainty, but it is possible that the data from the Palo Verde site is not typical due to ambient conditions, age, or packing arrangement of the fuel inside the canister. There may be other SNF storage facilities with cask outlet temperatures different from the Palo Verde site. While the measured temperature is much lower than anticipated, we can now move forward knowing the accurate temperature for our pilot site with the highest possible certainty. The outlet temperature documents provided to us are shown in Appendix B.

COMSOL Background

COMSOL is a finite element analysis tool which uses geometry and assigned boundary conditions to provide detailed data values for all parts of a model. In our case, it reports temperature along the duct given appropriate internal and external boundary conditions. COMSOL operates using built in heat transfer mechanics and therefore provides results that are high in accuracy and unbiased by underlying assumptions.

COMSOL Model Development

It was decided that the COMSOL simulation would solely model the straight duct portion of the design in order to enable a one to one comparison of the MATLAB model results. A straight circular duct with a concentric layer of insulation 100 meters in length (required length at pilot site) was created in Solidworks and imported into COMSOL. Identical boundary conditions were applied to both the COMSOL and analytical model, and the solution to the configuration was computed. The cask outlet temperature was set at 375K (102℃) to align with the MATLAB model.

In addition to the outlet temperature, we also accounted for two key parameters which define the performance of insulation: thermal conductivity and thickness. The former was defined as a nominal value among several popular insulation materials[18] and was assigned a value of .05 W/mK. The appropriate thickness was determined to be 76 mm from documentation provided by the North American Insulation Manufacturers Association[19].

Results of the COMSOL Simulation and Comparison to MATLAB Model

Once the COMSOL model was solved, the temperature distribution within the duct along its length could be produced. The resulting temperature distribution is shown below in Figure 11.

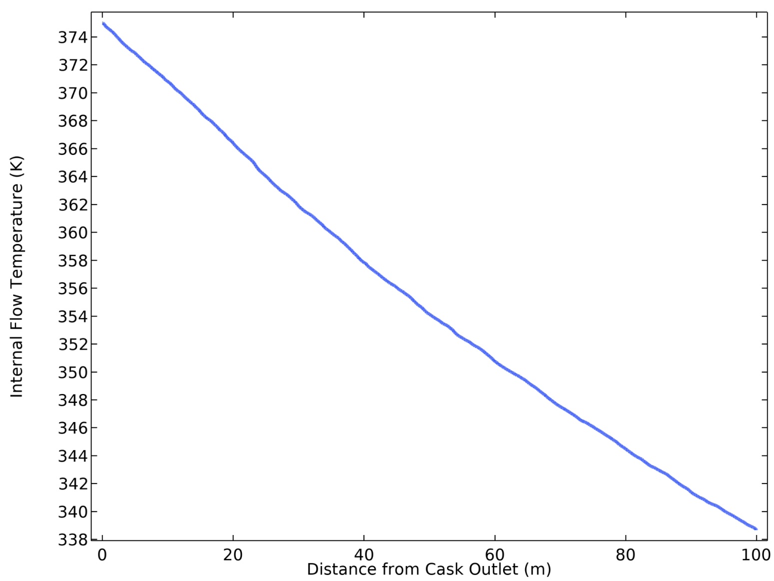


Figure 11. Airflow temperature in Kelvin inside an insulated circular duct as a function of its length in meters. The maximum temperature value of 375K corresponds to the duct inlet closest to the cask outlet. The flow temperature appears to decrease linearly with length and reaches a minimum value of 339K at the duct outlet. The duct outlet is coincident to the greenhouse inlet.

The rate of the temperature decay differs between the COMSOL and MATLAB models. The analytical model formulated in the above sections, and plotted in Figure 11 predicts an exponential decay of the temperature. However, the COMSOL simulation shows a temperature drop which appears to be linear. More importantly, the temperature drop according to the COMSOL model is much smaller than that of the MATLAB model. We believe that the COMSOL model is more accurate than the analytical model because while both used the same boundary conditions, the COMSOL model does not include any simplifying assumptions such as laminar versus turbulent flow, choice of Nusselt correlation, or neglect of entrance region. It is reasonable then to believe that the COMSOL model is producing more accurate results. The difference may be due to one or several of these factors.

Comparison of Assumed Outlet Temperature to Measured Outlet Temperature

Throughout this report, we have assumed a cask outlet temperature of 100℃, which is much higher than values measured at the Palo Verde site. The assumption of the higher temperature allows us to prove the conceptual feasibility of the proposed design, and the difference in these temperatures can be readily reduced when implementing the physical solution by exploring the possibility of capturing heat from more than one cask. Additional COMSOL simulations are performed to show the difference in duct outlet temperatures when the cask outlet temperature is adjusted to its measured value of 321K (48℃). The resulting temperature distribution is compared to the assumed temperature condition below in Figure 12.

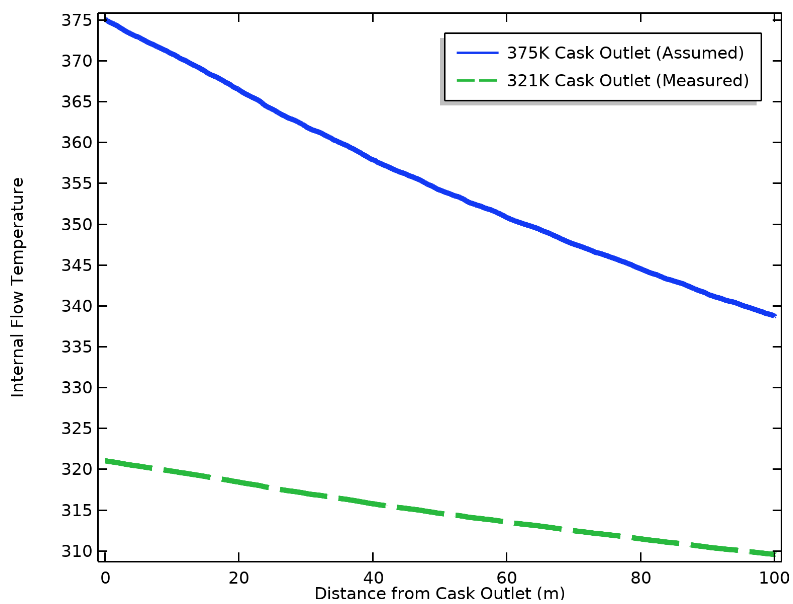


Figure 12. Airflow temperature in Kelvin inside an insulated circular duct as a function of its length in meters. The solid line represents the assumed initial value of 375K (102℃), while the dashed line represents the measured initial value of 321K (48℃) and all other conditions are held constant. Although the assumed cask outlet condition appeared linear when plotted alone, it now appears to be nonlinear. Internal flow temperature decreases with duct length, and duct outlet temperature increases with cask outlet temperature.

The assumed temperature distribution appears to be nonlinear, which suggests that both distributions are nonlinear, which implies a higher level of agreement between the two modeling methods than originally assumed. If all plots are exhibiting exponential decay as predicted by the

MATLAB model, then the discrepancy between them is explained by an incorrect parameter value, causing the distribution to decay more quickly than it should.

Sensitivity Analysis

To investigate how different parameters affect the temperature distributions predicted by COMSOL, a sensitivity analysis was performed. By changing the value of a single model parameter while keeping all others constant, the effects of that parameter can be isolated. The effects of cask outlet temperature on the distribution in the duct for a selection of values are shown below in Figure 13.

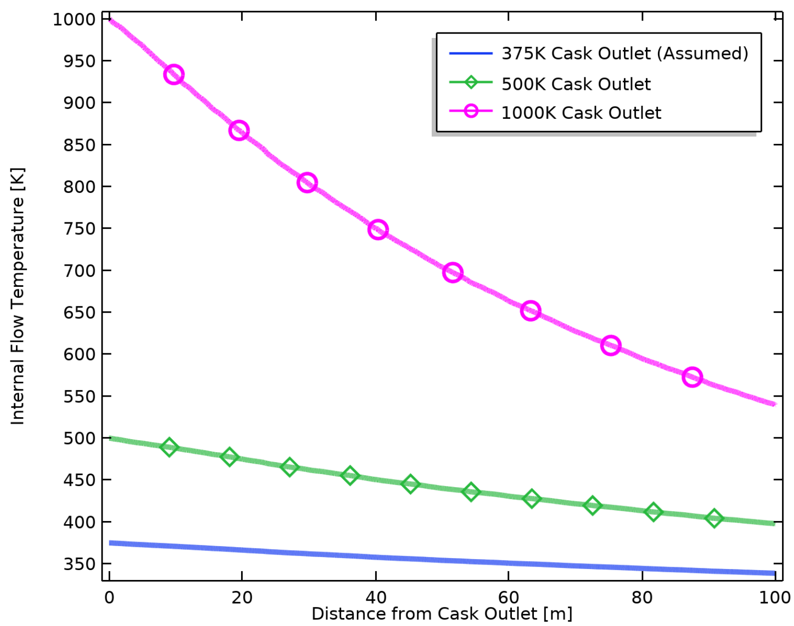


Figure 13. Airflow temperature (K) inside an insulated circular duct as a function of its length (m). Heat losses along the duct are much greater at higher inlet temperatures and the exponential nature of the decay is much more apparent.

The percentage change between inlet and outlet temperatures for 375K (102ºC), 500K (227ºC), and 1000K (727ºC) inlet conditions are -9.6%, -20.4%, and -46.1% respectively. Regardless of the scale of the vertical axis, it is clear that the heat losses increase as the cask outlet temperature increases. All else held constant, heat losses of any magnitude can be reduced by either increasing the thickness or decreasing the thermal conductivity of the insulation surrounding the duct.

Requirements and Specifications

Over the course of this project, we have strived to fulfill our requirements and specifications shown previously in Table 1. Some of these requirement verifications are addressed in other sections. Compliance with nuclear regulations is detailed in Engineering Standards, with references to NRC 10 CFR Part 72 as well as the specific certificates of compliance relevant to the Palo Verde site. A discussion of Ethics is presented in Ethical Decision Making, where we consider the radiation exposure of plant workers and the risks of environmental impact of our solution, among others. Cost consideration is explored in depth in the Cost Analysis section, where the ROI is found to be under 5 years.

The specifications we developed for the Reliability requirement were that the heat transport from the cask to the application area must achieve a thermal efficiency of at least 30%, and the system must include a monitoring system to track temperature and airflow at all times. The thermal efficiency of the duct system can be calculated as the quotient of duct outlet temperature to inlet temperature. The predicted efficiency for the assumed situation of 100℃ inlet is 90.3%. The predicted efficiency for the measured inlet temperature of 48℃ is 96.4%. Both of these efficiencies far exceed the specification of 30% or greater.

We propose that the temperature is consistently monitored using resistance temperature detectors (RTD): temperature sensors that contain a resistor that changes resistance value as its temperature changes. RTDs have high accuracy and repeatability, both desirable characteristics for our passive system. Additionally, we learned from one of our stakeholders, Luke McIntyre, that RTDs are also used for dry cask temperature monitoring, we believe that this affirms that using such sensors is permissible under NRC regulations.

COST ANALYSIS

Given the amount of unused space at the Palo Verde generation station, we assumed our greenhouse to be at an industrial scale of production, with a footprint of 1800 ft^2. Initial research indicated that the most profitable greenhouse crop to grow is a tomato[20]. Using this as our crop of choice, and assuming one plant per 6 ft^2 and 20lbs of tomato per plant yearly, we determined that the greenhouse will generate an average of $13 of profit per ft^2, which is roughly $23,000 annually. Regarding cost, we determined the construction costs of the ducts[21], fans[22], humidifiers[23], irrigation[24] and greenhouse[25] to be roughly $98,000. Maintenance costs weren't able to be determined yet, and are currently omitted as a result, so the overall estimated ROI was five years as is shown in Table 5.

Table 5. This is the ROI calculation for the greenhouse application. It assumes no maintenance costs and accounts for key greenhouse inputs. The estimated ROI is five years.

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
Humidifier	$2,000	$0	$0	$0	$0	$0
Fans	$12,000	$0	$0	$0	$0	$0
Duct	$34,190	$0	$0	$0	$0	$0
Irrigation	$4,800	$0	$0	$0	$0	$0
Construction	$45,000	$0	$0	$0	$0	$0
Cost	**$97,990**	**$0**	**$0**	**$0**	**$0**	**$0**
Revenue	**$0**	**$23,000**	**$23,000**	**$23,000**	**$23,000**	**$23,000**
Profit	-$97,990	-$74,990	-$51,990	-$28,990	-$5,990	$17,010

SOCIAL CONTEXT CONSIDERATIONS

As engineers, we have both visible and hidden power when we design systems. It is paramount to the welfare of society as a whole that we consider the social, environmental, and economic facets of our proposed design, so as to not create inequities in the lives of those directly and indirectly affected by any system which may be built.

Engineering Standards

The storage of SNF is a heavily regulated process which consists of regulatory requirements, licensing, and routine inspections. In order to ensure that our design complied with NRC regulations, the team compiled a list of relevant standards involving the inspection and operation of dry casks and the storage site. These standards are from NRC Regulations Title 10, Code of Federal Regulations. The standards were used as a benchmark to gauge feasibility throughout the ideation process and for verification of the final design concept. Two of the primary standards referenced were the *Standards for construction permits, operating licenses, and combined licenses* (NRC, 10 CFR 50.45 Part 50) and *Changes, tests, and experiments* (NRC, 10 CFR 72.48 Part 57). In order to comply with these standards, outlet blockage of dry casks had to be kept at a 50% maximum, and minimal changes were made to the existing infrastructure to allow routine inspections to occur without issue. Additionally, any changes to existing infrastructure could require a reissuing of a site license. As such, the team placed emphasis on finding a solution that could be minimally invasive. A full list of standards and certificates of compliance concerning dry cask operations relevant to our application can be found in Appendix C.

Engineering Inclusivity

Nuclear energy is a highly scrutinized field, and the team and stakeholders both acknowledged that the public may not have interest in or decline eating food that may have been exposed to any form of radiation. In order to make this design more inclusive, we have considered labeling food that is grown via this method in order to achieve complete transparency with the public. Alternatively, we've considered making the food source limited to only plant workers who are more knowledgeable of the risks and safety precautions. In both cases, there is a need to educate the consumer base on the safety of the product.

Working with the SNF can be potentially hazardous as well, so the employees who would be tasked with constructing and maintaining this design were also taken into consideration during our design process. Temperature sensors would be installed in the design to absolve the need to send a person to check the status of the design. Additionally, the ductwork consists of lightweight materials with minimally invasive supports to reduce interference with existing infrastructure. This will allow for easy construction and deconstruction for maintenance staff if dry casks need to be accessed or moved.

Throughout our design process, we have specifically attempted to address issues of uncertainty and potential misinformation. We gathered a variety of information from a pool of six different stakeholders from varying backgrounds and perspectives. This gave us a broader perspective of the nuclear field holistically, and we used this knowledge to make an informed decision on our application selection. We believe that there are more conversations to be had before our design concept could be reasonably implemented, such as interviews regarding public interest and perception, and solidifying company incentives.

Environmental Context Assessment

The solution developed in this project has both an environmental and a social impact. It does not inherently pose additional environmental hazards, and serves to create benefit where none existed before. Our system has the potential to reduce the global dependence on fossil fuels by increasing the amount of energy that is able to be extracted from an already existing energy source. Our system capitalizes on this potential by capturing the heat in dry casks to assist with maintaining adequate temperatures in a greenhouse, which otherwise may be sourced from a power plant and generate heat through environmentally problematic or damaging sources.

Our proposed solution does require external sources of energy to power the fans which drive airflow in the system. While in our pilot case we anticipate this power draw to be less than the power required for conventional greenhouse heating systems, depending on the sites and logistics, it is possible that the necessity for a fan could essentially be doing more harm than good. Additionally, while studies prove the likelihood to be minimal[26], growing crops on a nuclear site could potentially cause risk to consumers in the case of an accident or poor management of equipment. Both undesirable scenarios exist; however, they are unlikely outcomes. Therefore we believe our solution is adequate in addressing concerns surrounding environmental context.

Social Context Assessment

The social elements of this solution are not as sustainable as we hoped. The solution that was developed is based on assumptions that were proven incorrect in the final weeks of the project. Our system is built for outlet temperatures above 100℃ and actual data from our pilot site displayed outlet temperatures around half of this value. Our data set comes from a single site and it is possible that newer, hotter SNF exists at other sites and would provide the necessary outlet temperatures for our system to work. Additionally, if the crops are sold under a larger brand as opposed to independently to customers, this could bypass any ability for the public to discern which of their produce was grown using nuclear waste heat and their ability to make informed decisions about their food.

While these are the implications of the greenhouse, our project focuses more on the capture and transport of heat to the greenhouse. This system could be used for other applications as well. Therefore, it can be concluded that there are potential applications that we have not considered and are more attractive and likely to be adopted and self-sustaining in the market. If so, the economic success is not likely to be so successful to the point of making planetary and social systems worse off. This system is not a consumer product and would be high cost for an individual. Additionally, the heat dissipated by the SNF is very stable and will persist for decades without interruption. Thus, we believe that these factors would prevent any potential issues with disruptions in business as usual.

Lastly, it is important to mention that this project exists in a field with potential for serious change. Current storage sites are technically temporary holding locations for SNF with long term plans in place to consolidate and move all of these casks to a central location such as the Yucca Mountain Nuclear Waste Repository[27]. While this plan has been in effect for years and has not seen any progress in being approved, the intent and existence of the plan indicates a potential block in the sustainability of our solution. That said, the work that we have outlined could be altered and scaled to serve a similar purpose at a long term storage location as well.

Ethical Decision Making

Ethics play a large role in our project, especially during the concept selection process. Nuclear energy has a justified negative public perception because of the risks and historical precedence of reactor meltdowns. As a result, nuclear energy is a highly regulated field. In this project, many of our concerns regarding ethics were centered around the safety of personnel operating our proposed system in addition to the safety of the food designated for consumption by the public. In terms of personnel safety, we found that many of the existing systems and regulations in place were created to prioritize safety. Therefore, a critical design specification of ours was to comply with existing site regulations. This choice displays the ethical influence in our decision making process.

Similarly, our team considered the ethics of growing food for public consumption on a nuclear site. Radiation can have adverse effects on food and it would be unethical to propose a system that produces food unsafe for consumption. As a result, our team found radiation data for the dry casks and determined that even in the direct vicinity of a cask, radiation is minimal[26]. To further increase the safety of the produce, we recommend that prior to selling food produced in the greenhouse, some standardized verification is taken to check the food for defects. Perhaps using USDA health checks or another similar system could ease any concerns surrounding the effects of growing crops on a nuclear site.

Lastly, our team considered how the success of this solution could cause adverse effects in communities. Nuclear energy, while cleaner than many current energy production methods, has negative impacts on communities surrounding plants. The energy production itself isn't harmful, but there is a large negative impact from the potential failure or meltdown of a nuclear site. We believe that the benefits from this project could promote continued or increased use of nuclear energy in the future. As a result, this could be an unethical solution when accounting for the failure risks of these nuclear sites, but we believe the benefits of promoting continued use of nuclear power outweigh the risks.

DISCUSSION AND RECOMMENDATIONS

With the immense amount of information presented, it is important to discuss some of the key findings provided throughout this report. The following sections seek to provide further context on project elements as well as provide recommendations for future work.

Funding and Immediate Next Steps

If given a budget, we would likely run trials at our pilot site. These trials would encompass preliminary installation of a prototype duct system. The system would be monitored via RTDs, so we would be able to obtain temperature data from various points in our system. This would allow us to retroactively improve the validity of our computational models. Given that these results still demonstrate that a greenhouse application is feasible, there is a need to quantify theoretical crop yields and validate their safety for consumption. Food irradiation (the application of ionizing radiation to food) is a technology that improves the safety and extends the shelf life of foods. The Food and Drug Administration (FDA) is responsible for regulating the sources of radiation that are used to irradiate food. The FDA approves a source of radiation for use on foods only after it has determined that irradiating the food is safe[28]. Some root vegetables like potatoes also possess natural quantities of uranium from the soil they are grown from[29]. The uranium levels of food grown in this greenhouse would be compared to those of natural vegetables and submitted for approval by the FDA.

Expansion of Infrastructure

Although we have conducted a cost analysis of the greenhouse system with 1800 ft^2 with the assumption of utilizing all of the casks in Palo Verde Generating Station, the design and feasibility analysis only applies to a single-cask system. To continue the project, the initial concept could be scaled up through extending the duct system to engage multiple casks onsite. More dry casks in use would potentially allow for a larger greenhouse or potentially higher heat output, opening the door for additional design applications such as a biosolids dryer. There would be various ways to connect multiple casks by varying the number of casks to be connected in series or parallel or even by the location of the greenhouse. More detailed research on the duct system including the connection between them and the overall design for the most efficient flow and least heat loss will be required to finalize the duct design. The preliminary materials were found for an individual design, but on a larger industrial scale may want to be considered and the cost analysis adjusted accordingly.

Future Recommendations

Regarding future work related to our project, we recommend conducting additional COMSOL modeling to evaluate the fans at the cask interface pulling in cold air as well as the heat from the dry cask and how that would affect the system. The heat transfer analysis model would need to answer the following questions: At what ambient temperatures does the system still provide adequate heat? What is the minimum level of insulation required to produce adequate heat? How would multiple inputs and more complex duct geometry affect the system output?

Other considerations for the project include if using SNF that has been recently inserted into a dry cask would provide heat at a higher outlet temperature or if different nuclear storage sites have varying temperature ranges between the outlet and inlet temperatures. Additionally, how sites with a cooler climate will affect the heat transfer and application.

Alternative Solution Spaces

There could be potential for adjusting how SNF is used prior to dry cask storage. This project was conducted under the assumption that heat would be collected from SNF inside dry casks. However according to an article[30] from DW, there has been recent advancement in developing a solution that uses direct spent nuclear fuel rods to heat cities. Instead of using coal as an energy source to power stations, a system can be developed to use heat from SNF to heat water. There is considerable interest in this due to the cost effectiveness and existing infrastructure that could be fitted to this need. Therefore, directly using SNF rods in a smaller scale nuclear reactor like the Teplator could be a solution-space that would be interesting for further exploration related to this project.

Additional Considerations
Although we have performed extensive research and analysis to present our proposed system as completely as possible, there still remain areas of uncertainty which we recommend are further explored. As mentioned previously, we are uncertain of cask outlet temperatures, and additional sources of measured data are needed to construct a robust range of outlet temperatures. We recommend reaching out to SNF storage facilities in several regions of the United States to see how cask outlet temperatures are affected by varying environments and weather conditions.

We have alluded to the possibility of performance improvements expanding our system to capture heat from multiple dry casks. These improvements are facilitated by the close proximity of casks to each other, and the many commercially available configurations for our selected duct type. Some of the concepts which were brainstormed and presented in Figure 8d are designed with modularity in mind. Additional ideation aimed specifically at multi-cask systems should be performed.

For the future of this project, we believe that there is great value in working directly with relevant SNF storage facilities such as we have done to gain greater insights into regulatory and logistical challenges which may not be anticipated by a third party design team.

CONCLUSIONS
Throughout this project, our team has worked to provide quantifiable solutions for capturing and transferring heat from SNF in dry cask storage. We have successfully designed a heat transfer system and developed a mathematical model and COMSOL simulation to determine the heat transfer capabilities of our proposed system. Our finalized analytical model and design, while meeting many of our initially set requirements and specifications, failed to produce accurate results when compared with the COMSOL simulation. Additionally, we determined our outlet temperature assumptions inconsistent with data recieved. As a result, we believe that further system analysis and development is required for this system. With regard to our chosen application, if a greenhouse is implemented, there is a need to demonstrate the end product's safety and value. Quantifying theoretical crops yields and performing tests to examine the levels irradiation would be next steps to achieving these goals. Irradiated food is more commonplace than what is publicly perceived, and given FDA approval, the application has potential to proceed further in development and even expand with larger infrastructure. In order to proceed, we recommend creating a physical, small scale prototype, exploring additional locations with other SNF storage configurations, and potentially exploring other applications, such as using SNF directly as a heating source, as is done in the Czech Republic[30]. These areas can be further explored with additional time and capital, and we encourage further development in these areas. Even with the potential for further development, this project was successful in outlining a realistic system design and quantifying the amount of heat accessible through our duct system, and serves as a strong foundation for future developments in this field.

AUTHORS

June Ahn

Junyoung(June) Ahn is a senior Mechanical Engineering student at the University of Michigan originally from Seoul, South Korea, but spent most of his childhood in the southern part of the US while eating crawfish. He takes care of one dog and two cats, which makes him both a dog lover and a cat lover. He spends most of his time either traveling with his car or tearing it apart and his dream job is to become a car engineer designing modular platforms and chassis for cars.

Kyra Kothawala

Kyra Kothawala is a senior Mechanical Engineering student at the University of Michigan and originally from Portage, MI. She is passionate about learning and sustainable design where she can apply her creative, analytical, and problem-solving skills. Kyra is involved in a socially-engaged design team called BLUElab India Project and is also the Social Officer for the Society of Women Engineers on campus. In her free time she enjoys traveling, reading, and playing any kind of sport.

Jared Rosenberg

Jared Rosenberg is a senior Mechanical Engineering student from Los Angeles, CA. He has enjoyed going to amusement parks from a young age, frequenting Cedar Point in the summers. His dream job is to become a roller coaster engineer or work somewhere in the amusement industry. During lockdown he began experimenting with 3D printers, and in his spare time he enjoys watching movies and going on walks. His favorite part of this project has been learning so much about a unique field such as nuclear waste handling.

Quan Usher
Quan Usher is a senior Mechanical Engineering student at the University of Michigan and originally from Atlanta, GA. He is passionate about empowerment of marginalized communities and shattering biases. His dream is to become a successful engineer made entrepreneur, and use that knowledge to educate others about the power of financial literacy and generational wealth. Quan is a recipient of the Ron Brown, Hamilton, and Simon Scholarships and has served as Manufacturing Lead for the BLUElab Thailand. In his free time, he enjoys gaming and exploring new investment opportunities.

Jordan Wallace
Jordan Wallace is a senior Mechanical Engineering student from Evanston, IL. He is passionate about the energy industry and hopes to contribute to developing energy solutions through clean and alternative sources throughout his career. On campus, Jordan serves as the Vice President for the National Society of Black Engineers and is also a Departmental Ambassador for Engineering 110. In his free time he enjoys playing basketball and golf and plans to travel post-pandemic.

ACKNOWLEDGEMENTS
Our team would like to acknowledge the following individuals who provided resources and supported our work throughout the duration of this project. Our work would not be possible without their contributions.

Dr. Marianna Coulentianos	*Project Founder & Sponsor*
Professor Steven Skerlos	*ME 450 Faculty Advisor*
Professor Heather Cooper	*ME 450 Course Coordinator*
Professor Katsuo Kurabayashi	*Heat Transfer Expert*
Luke McIntyre	*Engineer at Palo Verde Nuclear Site*
Steven Edwards	*Manager at Duke Energy*
Jacob Ladd	*Founding Team Member*
Luyao Li	*Founding Team Member*

REFERENCES

[1] Tilghman, M. (2012). *Using Nuclear Waste Heat as Power Source*. Large.Stanford.Edu.

[2] *Dry Cask Storage*. (2020). Nrc.Gov.

[3]McNutty, J. (2017). *Solar greenhouses generate electricity and grow crops at the same time, UC Santa Cruz study reveals*. USC Newscenter.

[4]Bunch, S., Kort, K. (2017). *Water and Wastewater Annual Price Escalation Rates for Selected Cities across the United States.* 7.

[5]Holtec International. (2021). *Spent Fuel Management*.

[6]Singh, K., Griffiths, J., Mitra-Majumdar, D. (2019). *System and Method for Reclaiming Energy from Heat Emanating from Spent Nuclear Fuel*(U.S. Patent No.10,418,136 B2). U.S. Patent and Trademark Office. https://holtecinternational.com/wp-content/uploads/2019/09/Patent-10418136-B2.pdf

[7]Holtec International. (2009). *Final Safety Analysis Report for the Holtec International Storage, Transport, and Repository Cask System (HI-STAR 100 Cask System) Docket 72-1008.* https://www.nrc.gov/docs/ML0930/ML093070147.pdf

[8]Durbin, S., Lindgren, E. (2018). *Thermal-Hydraulic Experiments Using A Dry Cask Simulator.* U.S.NRC.

[9]*Power Systems.* Rps.Nasa.Gov.

[10]USA.COM. http://www.usa.com/palo-verde-az-weather.htm

[11]Van de Bor, D., Infante Ferreira, C., Kiss. A. (2015). *Low Grade Waste Heat Recovery Using Heat Pumps and Power Cycles.* Elsevier.

[12]Yu, M., Nam. Y., (2016). *Feasibility Assessment of Using Power Plant Waste Heat in Large Scale Horticulture Facility Energy Supply System.* MDPI.

[13]AerIndustires. (2019). *Greenhouse Temperature Considerations.*

[14]*Thermaround™ is the round outdoor duct solution for exterior applications.* Thermaduct. https://www.thermaduct.com/products/thermaround-outdoor-spiral-ductwork-solution

[15]Switzerland Air: Air conditioning & Heating. *The Different Types of Ductwork Material.* https://www.switzerlandairandheating.com/blog/the-different-types-of-ductwork-material/

[16]Gerhart, P., Gerhart, A., Hochstein, J., (2016). *Munson, Young, and Okiishi's Fundamentals of Fluid Mechanics 8th edition.* Wiley.

[17]Bergman, T., Lavine, A., Incropera, F., Dewitt, D., (2011). *Fundamentals of Heat and Mass Transfer.* John Wiley & Sons.

[18]Engineering ToolBox, (2003). *Thermal Conductivity of some selected Materials and Gases*. https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html.

[19]*A Guide to Insulated HVAC Duct Systems.*(2003). North American Insulation Manufacturers Association. http://insulationinstitute.org/wp-content/uploads/2015/11/AH121.pdf

[20] *How to Make $40,000 Growing Heirloom Tomatoes.* Profitable Plants. https://www.profitableplants.com/how-to-make-40000-growing-heirloom-tomatoes/#:~:text=Most%20commercial%20growers%20allow%20about,about%20%2480%20at%20retail%20prices.

[21] FIXR. (2020, March 27) *Ductwork Installation Cost: Cost to Install Ductwork for Central Air.* Fixr.com. www.fixr.com/costs/ductwork#:~:text=Expect%20to%20pay%20%2435%2D%24,on%20your%20home%27s%20unique%20layout.

[22] *Commercial & Industrial Duct Fans: Inline Exhaust Fans: Tube Axial Fans.* Industrial Fans Direct. www.industrialfansdirect.com/collections/duct-inline-exhaust-fans.

[23] *2021 Average Greenhouse Misting System Installation Prices: How Much Does a Greenhouse Misting System Cost?.* CostOwl.com. www.costowl.com/home-improvement/landscaping-greenhouse-misting-system-costs.html#:~:te

xt=A%20quality%2C%20high%2Dpowered%20greenhouse,costs%20approximately%20%2475 0%20to%20%241%2C250.

[24] Pro Lawn Care (2014, May 14). *How Much Does Drip Irrigation Cost?* CostHelper. home.costhelper.com/drip-irrigation.html.

[25] Allied Steel Buildings. (2020). *How Much Does It Cost to Build A Commercial Greenhouse?.* Allied Steel Buildings. www.alliedbuildings.com/commercial-greenhouse/#:~:text=Typical%20mid%2Dsized%20comm ercial%20greenhouses,cost%20nearly%20%2425%2C000%20and%20above.

[26]*Final Safety Analysis Report*. (2004). https://www.nrc.gov/docs/ML0930/ML093070147.pdf

[27]*Examining the potential of national nuclear waste repository site.* BECHTEL. https://www.bechtel.com/projects/yucca-mountain-nuclear-waste-repository/

[28]*Food irradiation: What you need to know.* Center for Food Safety and Applied Nutrition. https://www.fda.gov/food/buy-store-serve-safe-food/food-irradiation-what-you-need-know#:~:te xt=How%20Will%20I%20Know%20if,irradiation%E2%80%9D%20on%20the%20food%20lab el.

[29]*Uranium.* (2015). Agency for Toxic Substances and Disease Registry. https://www.atsdr.cdc.gov/sites/toxzine/uranium_toxzine.html#:~:text=Root%20crops%20such% 20as%20potatoes,of%20uranium%20to%20the%20diet.&text=People%20may%20also%20be% 20exposed,found%20in%20the%20drinking%20water.

[30]*Czech researchers develop revolutionary nuclear heating plant.* DW. https://www.dw.com/en/czech-researchers-develop-revolutionary-nuclear-heating-plant/a-57072 924

APPENDICES

Appendix A - Group Brainstorming Mind Map

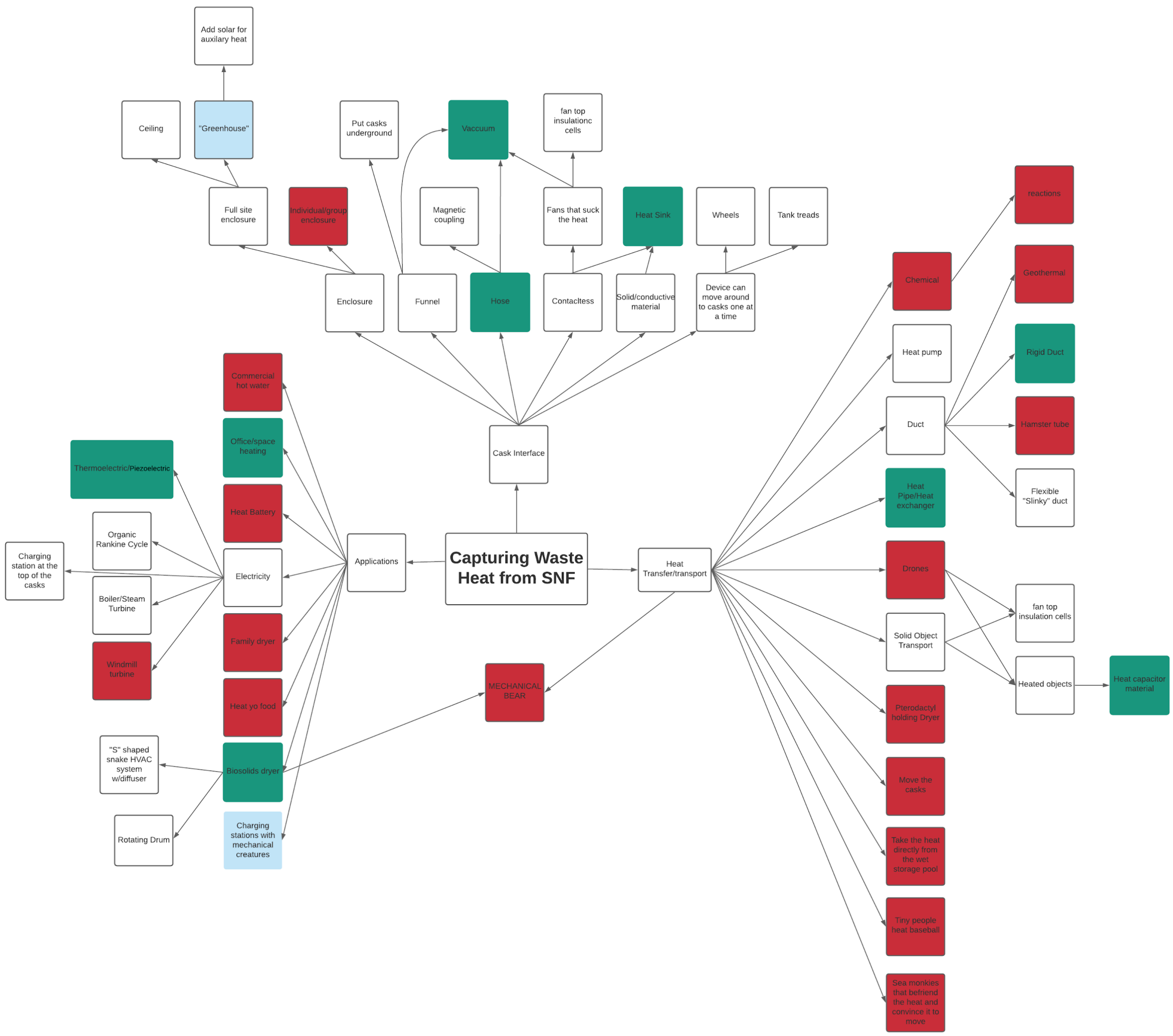


Figure A-1. The iterated group brainstorming mind map. There are three categorical structures with a total of 35 ideas. Those highlighted in red were eliminated with a gut and feasibility check. Those highlighted in green (three from each category) were selected as representative ideas to further research. Ideas highlighted in blue (greenhouse, charging station with mechanical creatures) were particularly interesting to our primary stakeholder.

Appendix B - Cask Outlet Temperature Documents

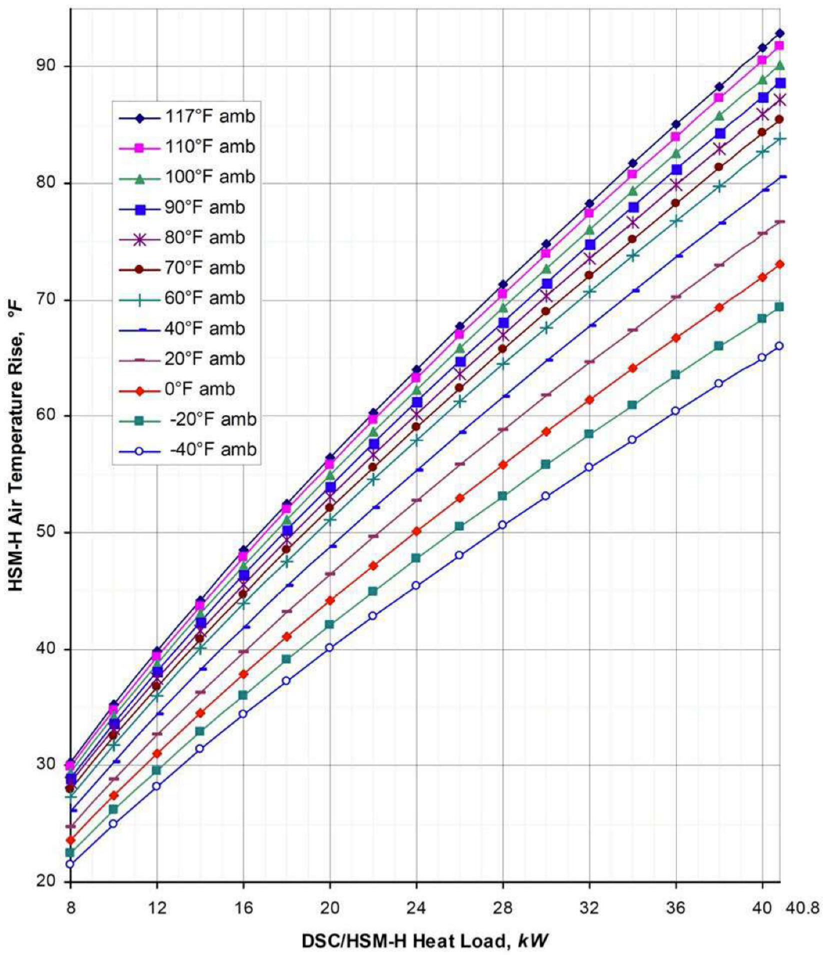


Figure B-1. Predicted temperature rise above ambient temperature for air exiting the top of the dry cask (ºF) as a function of ambient temperature and fuel loads.

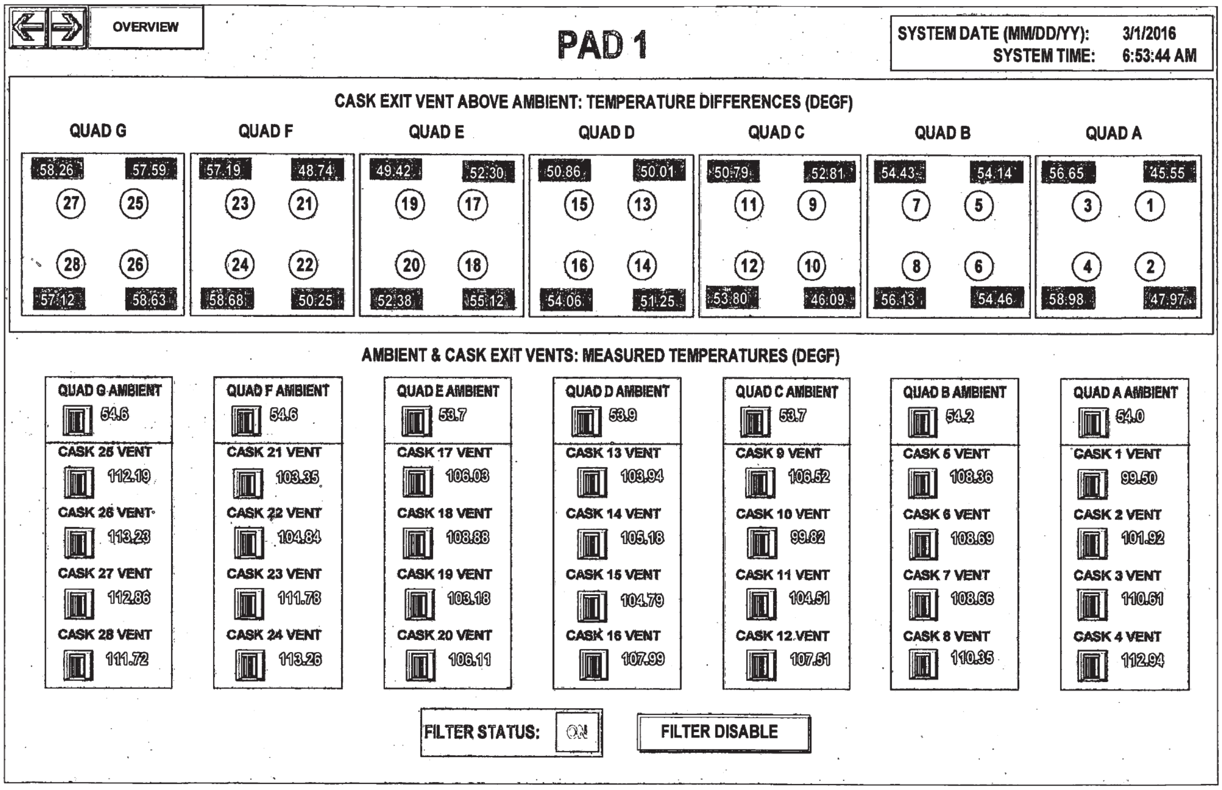


Figure B-2. Real time temperature data of individual casks at the Palo Verde Generating Station site. Reported values include the ambient temperature measured at each cask grouping, cask outlet temperature, and temperature rise above ambient. All values are reported in degrees Fahrenheit.

Appendix C - List of Applicable Regulations for Capturing SNF Heat

Regulation (NRC, 10 CFR) Part 50

Domestic licensing of production and utilization facilities

The regulations in this part are promulgated by the Nuclear Regulatory Commission pursuant to the Atomic Energy Act of 1954, as amended (68 Stat. 919), and Title II of the Energy Reorganization Act of 1974 (88 Stat. 1242), to provide for the licensing of production and utilization facilities. This part also gives notice to all persons who knowingly provide to any licensee, applicant, contractor, or subcontractor, components, equipment, materials, or other goods or services, that relate to a licensee's or applicant's activities subject to this part, that they may be individually subject to NRC enforcement action for violation of § 50.5.

50.45 Standards for construction permits, operating licenses, and combined licenses

(a) An applicant for an operating license or an amendment of an operating license who proposes to construct or alter a production or utilization facility will be initially granted a construction permit if the application is in conformity with and acceptable under the criteria of §§ 50.31 through 50.38, and the standards of §§ 50.40 through 50.43, as applicable.

(b) A holder of a combined license who proposes, after the Commission makes the finding under § 52.103(g) of this chapter, to alter the licensed facility will be initially granted a construction permit if the application is in conformity with and acceptable under the criteria of §§ 50.30 through 50.33, § 50.34(f), §§ 50.34a through 50.38, the standards of §§ 50.40 through 50.43, as applicable, and §§ 52.79 and 52.80 of this chapter.

Regulation (NRC, 10 CFR) Part 72

Licensing requirements for the independent storage of spent nuclear fuel, high-level radioactive waste, and reactor-related greater than class C waste

72.48 Changes, tests, and experiments

(c)

(1) A licensee or certificate holder may make changes in the facility or spent fuel storage cask design as described in the FSAR (as updated), make changes in the procedures as described in the FSAR (as updated), and conduct tests or experiments not described in the FSAR (as updated), without obtaining either:

(i) A license amendment pursuant to § 72.56 (for specific licensees) or

(ii) A CoC amendment submitted by the certificate holder pursuant to § 72.244 (for general licensees and certificate holders) if:

(A) A change to the technical specifications incorporated in the specific license is not required; or

(B) A change in the terms, conditions, or specifications incorporated in the CoC is not required; and

(C) The change, test, or experiment does not meet any of the criteria in paragraph (c)(2) of this section.

(2) A specific licensee shall obtain a license amendment pursuant to § 72.56, a certificate holder shall obtain a CoC amendment pursuant to § 72.244, and a general licensee shall request that the certificate holder obtain a CoC amendment pursuant to § 72.244, prior to implementing a proposed change, test, or experiment if the change, test, or experiment would:

(i) Result in more than a minimal increase in the frequency of occurrence of an accident previously evaluated in the FSAR (as updated);

(ii) Result in more than a minimal increase in the likelihood of occurrence of a malfunction of a system, structure, or component (SSC) important to safety previously evaluated in the FSAR (as updated);

(iii) Result in more than a minimal increase in the consequences of an accident previously evaluated in the FSAR (as updated);

(iv) Result in more than a minimal increase in the consequences of a malfunction of an SSC important to safety previously evaluated in the FSAR (as updated);

(v) Create a possibility for an accident of a different type than any previously evaluated in the FSAR (as updated);

(vi) Create a possibility for a malfunction of an SSC important to safety with a different result than any previously evaluated in the FSAR (as updated);

(vii) Result in a design basis limit for a fission product barrier as described in the FSAR (as updated) being exceeded or altered; or

(viii) Result in a departure from a method of evaluation described in the FSAR (as updated) used in establishing the design bases or in the safety analyses.

72.104 Criteria for radioactive materials in effluents and direct radiation from an ISFSI or MRS

(a) During normal operations and anticipated occurrences, the annual dose equivalent to any real individual who is located beyond the controlled area must not exceed 0.25 mSv (25 mrem) to the whole body, 0.75 mSv (75 mrem) to the thyroid and 0.25 mSv (25 mrem) to any other critical organ as a result of exposure to:

(1) Planned discharges of radioactive materials, radon and its decay products excepted, to the general environment,

(2) Direct radiation from ISFSI or MRS operations, and

(3) Any other radiation from uranium fuel cycle operations within the region.

72.122 Overall requirements

(d) *Sharing of structures, systems, and components*. Structures, systems, and components important to safety must not be shared between an ISFSI or MRS and other facilities unless it is shown that such sharing will not impair the capability of either facility to perform its safety functions, including the ability to return to a safe condition in the event of an accident.

(h) *Confinement barriers and systems*.

(1) The spent fuel cladding must be protected during storage against degradation that leads to gross ruptures or the fuel must be otherwise confined such that degradation of the fuel during storage will not pose operational safety problems with respect to its removal from storage. This may be accomplished by canning of consolidated fuel rods or unconsolidated assemblies or other means as appropriate.

(k) *Utility or other services*.

(1) Each utility service system must be designed to meet emergency conditions. The design of utility services and distribution systems that are important to safety must include redundant systems to the extent necessary to maintain, with adequate capacity, the ability to perform safety functions assuming a single failure.

(4) An ISFSI or MRS which is located on the site of another facility may share common utilities and services with such a facility and be physically connected with the other facility; however, the sharing of utilities and services or the physical connection must not significantly:

(i) Increase the probability or consequences of an accident or malfunction of components, structures, or systems that are important to safety; or

(ii) Reduce the margin of safety as defined in the basis for any technical specifications of either facility.

72.126 Criteria for radiological protection

(c) *Effluent and direct radiation monitoring*.

(1) As appropriate for the handling and storage system, effluent systems must be provided. Means for measuring the amount of radionuclides in effluents during normal operations and under accident conditions must be provided for these systems. A means of measuring the flow of the diluting medium, either air or water, must also be provided.

(2) Areas containing radioactive materials must be provided with systems for measuring the direct radiation levels in and around these areas.

(d) *Effluent control*. The ISFSI or MRS must be designed to provide means to limit to levels as low as is reasonably achievable the release of radioactive materials in effluents during normal operations; and control the release of radioactive materials under accident conditions. Analyses must be made to show that releases to the general environment during normal operations and anticipated occurrences will be within the exposure limit given in § 72.104. Analyses of design basis accidents must be made to show that releases to the general environment will be within the exposure limits given in § 72.106. Systems designed to monitor the release of radioactive materials must have means for calibration and testing their operability.

72.128 Criteria for spent fuel, high-level radioactive waste, and other radioactive waste storage and handling

(a) *Spent fuel and high-level radioactive waste storage and handling systems*. Spent fuel storage, high-level radioactive waste storage, reactor-related GTCC waste storage and other systems that might contain or handle radioactive materials associated with spent fuel, high-level radioactive waste, or reactor-related GTCC waste, must be designed to ensure adequate safety under normal and accident conditions. These systems must be designed with--

(1) A capability to test and monitor components important to safety,

(2) Suitable shielding for radioactive protection under normal and accident conditions,

(3) Confinement structures and systems,

(4) A heat-removal capability having testability and reliability consistent with its importance to safety, and

(5) means to minimize the quantity of radioactive wastes generated.

(b) *Waste treatment*. Radioactive waste treatment facilities must be provided. Provisions must be made for the packing of site-generated low-level wastes in a form suitable for storage onsite awaiting transfer to disposal sites.

72.212 Conditions of general license issued under 72.210

(b) The general licensee must:

(3) Ensure that each cask used by the general licensee conforms to the terms, conditions, and specifications of a CoC or an amended CoC listed in § 72.214.

(5) Perform written evaluations, before use and before applying the changes authorized by an amended CoC to a cask loaded under the initial CoC or an earlier amended CoC, which establish that:

(i) The cask, once loaded with spent fuel or once the changes authorized by an amended CoC have been applied, will conform to the terms, conditions, and specifications of a CoC or an amended CoC listed in § 72.214;

(ii) Cask storage pads and areas have been designed to adequately support the static and dynamic loads of the stored casks, considering potential amplification of earthquakes through soil-structure interaction, and soil liquefaction potential or other soil instability due to vibratory ground motion; and

(iii) The requirements of § 72.104 have been met. A copy of this record shall be retained until spent fuel is no longer stored under the general license issued under § 72.210.

(6) Review the Safety Analysis Report referenced in the CoC or amended CoC and the related NRC Safety Evaluation Report, prior to use of the general license, to determine whether or not the reactor site parameters, including analyses of earthquake intensity and tornado missiles, are enveloped by the cask design bases considered in these reports. The results of this review must be documented in the evaluation made in paragraph (b)(5) of this section.

(9) Protect the spent fuel against the design basis threat of radiological sabotage in accordance with the same provisions and requirements as are set forth in the licensee's physical security plan pursuant to § 73.55 of this chapter with the following additional conditions and exceptions:

(i) The physical security organization and program for the facility must be modified as necessary to assure that activities conducted under this general license do not decrease the effectiveness of the protection of vital equipment in accordance with § 73.55 of this chapter;

(ii) Storage of spent fuel must be within a protected area, in accordance with § 73.55(e) of this chapter, but need not be within a separate vital area. Existing protected areas may be expanded or new protected areas added for the purpose of storage of spent fuel in accordance with this general license;

(iii) For the purpose of this general license, personnel searches required by § 73.55(h) of this chapter before admission to a new protected area may be performed by physical pat-down searches of persons in lieu of firearms and explosives detection equipment;

(iv) The observational capability required by § 73.55(i)(3) of this chapter as applied to a new protected area may be provided by a guard or watchman on patrol in lieu of video surveillance technology;

(v) For the purpose of this general license, the licensee is exempt from requirements to interdict and neutralize threats in § 73.55 of this chapter; and

(vi) Each general licensee that receives and possesses power reactor spent fuel and other radioactive materials associated with spent fuel storage shall protect Safeguards Information against unauthorized disclosure in accordance with the requirements of § 73.21 and the requirements of § 73.22 or § 73.23 of this chapter, as applicable.

Regulations (NRC, 10 CFR) Part 73

Physical protection of plants and materials

(a) Purpose. This part prescribes requirements for the establishment and maintenance of a physical protection system which will have capabilities for the protection of special nuclear material at fixed sites and in transit and of plants in which special nuclear material is used. The following design basis threats, where referenced in ensuing sections of this part, shall be used to design safeguards systems to protect against acts of radiological sabotage and to prevent the theft or diversion of special nuclear material. Licensees subject to the provisions of § 73.20 (except for fuel cycle licensees authorized under Part 70 of this chapter to receive, acquire, possess, transfer, use, or deliver for transportation formula quantities of strategic special nuclear material), §§ 73.50, and 73.60 are exempt from §§ 73.1(a)(1)(i)(E), 73.1(a)(1)(iii), 73.1(a)(1)(iv), 73.1(a)(2)(iii), and 73.1(a)(2)(iv). Licensees subject to the provisions of § 72.212 are exempt from § 73.1(a)(1)(iv).

Palo Verde CoC Information

102-08129-MDD/MSC
ATTN: Document Control Desk
U.S. Nuclear Regulatory Commission
Registration of Dry Spent Fuel Storage Canister - Identification No. AMZDFX157
Page 2

Licensee's Address:

Arizona Public Service Company
P.O. Box 52034
Phoenix, AZ 85072-2034

Reactor:	Palo Verde Nuclear Generating Station, Unit 3
License Number:	NPF-74
Docket Numbers:	STN 50-530 and 72-44
Contact Name and Title:	Michael DiLorenzo, Nuclear Regulatory Affairs Department Leader
Cask Certificate No.:	Certificate of Compliance No. 1031, Amendment No. 7, July 28, 2017
Cask Model No.:	NAC-MAGNASTOR
Cask Identification Nos.:	TSC Identification No. AMZDFX157 VCC Identification No. AMZDNE157