Reliability Analysis of a Freeze Desalination System

by
Francisco Alberto Boschetti Tofano

A THESIS

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degree of

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Deborah Pence

The unsustainable use of fresh water sources and unavailability of fresh water in certain parts of the world have created a demand for water desalination systems. Desalination methods are effective at producing consumable water, but often require large scale setups, high energy consumption, and careful maintenance. A team of students at Oregon State University was tasked to design a functional model for a mobile desalination system to solve this problem. It was determined that indirect freeze desalination represents a scalable and energy efficient desalination method. In order to minimize redesigns in later stages of the design process, reliability analysis methods are applied to the freeze desalination system. A Failure Modes and Effects Analysis (FMEA) is performed using available component data and the current system design. The FMEA results reveal that the most critical components in the system are the pump and the chiller compressor. Recommended actions are suggested to improve system design and reliability.

Key Words: Indirect Freeze Desalination, Reliability Analysis, Failure Modes and Effects Analysis

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I understand that my project will become part of the permanent collection of Oregon State University, Honors College. My signature below authorizes release of my project to any reader upon request.

Francisco Alberto Boschetti Tofano, Author

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1. Introduction

Agriculture in California represents over 13% of the United States' total agricultural value receiving over $50 billion in 2017 [1]. During that year over a third of the nation's vegetables and two-thirds of the fruits and nuts were grown in California [1]. This market has been recently affected by the droughts experienced in the state. During these droughts, agriculture is forced to rely on the use of aquifers to meet its high demand for fresh water [2]. Aquifers supply around 40% of the water used in farms and cities, having nearly 85% of Californians depending on groundwater [3]. This high level of consumption is unsustainable for the aquifers and lead to a decrease in water quality. The high salinity levels in the aquifers created an urgency for a solution to help the agricultural market affected. The solution to this problem is water desalination. Water desalination methods involve treating salt water to reduce its salinity. They are usually driven by thermal energy, electrical energy, or pressure; with thermal energy being the oldest one [4].

A team of students at Oregon State University (OSU) has been tasked to design a mobile freeze desalination system to solve the problem with high salinity water in the aquifers used for agricultural purposes. The team members are: Francisco Boschetti, Joshua Cook, Mason Pratt, and Trevor Whitaker. This desalination system is required to fit in the bed of a pick-up truck and must be partially solar powered to allow the users to transport the system around and treat the water where needed. Most common desalination methods are known to have high energy consumption as well as intense maintenance requirements, hindering the implementation of a mobile system. However, there exists a lower energy desalination method that can be implemented on a portable scale. This method is called freeze desalination. Freeze desalination is based around freezing water to separate it from the salt. It is fairly energy and space efficient in comparison to the other desalination methods at smaller scales [5].

The urgency for unsalted water makes time and cost significant factors contributing to the design of the freeze desalination system. In the design phase of complex systems, considerable losses of time and money arise from needs for improvements during the testing stages. Design engineers have developed a variety of reliability analysis methods due to the impact these losses can have on design projects. These methods are used to produce more robust models from the early stages of the design process. Among these methods, the most popular methods include Failure Modes and Event Analysis (FMEA), Fault Tree Analysis (FTA), and Probabilistic Risk Assessment (PRA). These are basic, yet exhaustive, methods that can give design engineers clear ideas of the critical components and failure modes of the system.

In this thesis, an FMEA of the proposed desalination system is performed to identify the critical failure modes of the system. The results are analyzed to identify the most critical components in the system, allowing the performance of alternative design considerations and system design improvements.

The next chapter presents the background to this research, explaining the need for desalination, the different desalination methods, desalination system design, and reliability analysis methods. The third chapter covers the selection of the reliability analysis method for this study, the steps for this process, and the data used for the analysis. The results and discussions of the analysis are displayed in the fourth chapter, and then conclusions and recommendations are discussed in the fifth chapter.

2. Background

2.1 Aquifers

As water is pulled from aquifers, they will naturally refill with water from the soil around them. If the aquifers are drained too fast, they will instead refill with salt water from the nearby ocean [3]. This has become a relevant issue due to the high demand for fresh water for agricultural purposes. If the water acquired from the aquifers has high levels of salinity, it cannot be used in farms or consumed by people [6]. This problem is the reason why the design for a portable desalination device has become relevant.

2.2 Water desalination

Most thermal desalination processes work by evaporating the water to leave the salt behind, while electrical and pressure methods rely on the separation of ions in the salt water into a membrane –each with different driving mechanisms [4].

Some popular desalination methods include [7]:

- Multi-stage flash desalination: The salt water goes through a series of flash evaporations, and the energy released from the condensation of each step is used in the next iteration of evaporation. In this process, the evaporated water is clean [7].
- Reverse osmosis desalination: The salt water is forced to pass through a specialized membrane with applied pressure. In this process, the impurities remain in the membrane while the water that passes through is clean [4].

While these methods are effective and possess individual upsides, they require high amounts of energy for operation, as well as constant maintenance [4,7,8]. These conditions drive operational costs higher than what most users at larger scales can afford. It also increases the difficulty to operate outside of specialized facilities. The University of California at Davis has been researching methods to solve this problem. They developed a "photovoltaic desalination system" that does not require an external power source as it draws all of its required energy from a thin solar panel. The method works by utilizing the electric fields generated in a solar cell to reject the ions in the water passing through, achieving desalination [9]. Even though the photovoltaic desalination system is portable, a search for more efficient methods of water desalination is underway.

2.3 Desalination System Design

The design requirements for the water desalination system given to the student team at OSU were the following:

- Mobile device that fits on the bed of a pick-up truck (51''x97'')
- Modular and scalable device
- Produces water at low salinity, fit for consumption (50 mg/L)
- Optimized around water production output per day (30 L)
- Energy efficient (20% efficiency)
- Solar assisted (5% of energy used)

Out of these requirements, energy efficiency and size requirements represent the biggest constraints to choosing a suitable water desalination method. Freeze desalination could provide the best fit for these requirements due to the smaller required change in temperature relative to ambient temperature, as well as the difference in change of phase energy required to freeze water instead of evaporating it [10,11,12]. Freeze desalination methods are also insensitive to scaling, enabling small scale operation to be as efficient as large scale, unlike the other thermal desalination methods [7].

Freeze desalination methods work by freezing the salt water and creating ice crystals. These ice crystals are comprised of virtually all pure water [7]. This process generates unsalted ice, and a concentrated salt solution called brine as outputs. After the freezing is complete, the brine is separated and washed away. The ice can then be melted to produce pure water [7].

After the freeze desalination was chosen as the method to be used for the system, two major types of desalination were compared in order to choose the most applicable for the system being designed. These two methods were indirect freeze desalination and direct contact freeze desalination. While both of these methods work by creating ice crystals comprised of pure water [7], the main difference is in the way the refrigerant interfaces with the water being desalinated. In the direct method, as its name suggests, the refrigerant is brought into direct contact with the water and creates bubbles that have desalinated ice formed around them [7]. The indirect method instead uses a surface to separate the refrigerant and the salt water. The refrigerant cools the surface, and desalinated ice forms on it [7]. Both methods are effective and successfully desalinate water, but the direct method has a significant disadvantage in the refrigerant being retained in the ice formed, making the water produced non-potable before treated to separate it from the mixed refrigerant [7]. Consequently, the indirect freeze desalination method was chosen.

The current design for the indirect freeze desalination system is based around a tube-and-shell heat exchanger. The tube-and-shell heat exchanger functionality can be seen below in Figure 1. In the first step the shell is filled with the salt water. A chiller then cools the refrigerant which is then run through the tubes in the heat exchanger, causing the salt water to freeze around the tubes. The products of the process can be seen in the second part of Figure 1, where the produced desalinated ice exists around the tubes, and high salinity brine in the container. This brine is then removed, and the ice is washed to remove any remaining brine. Finally, the clean ice is melted to collect the desalinated water [7].

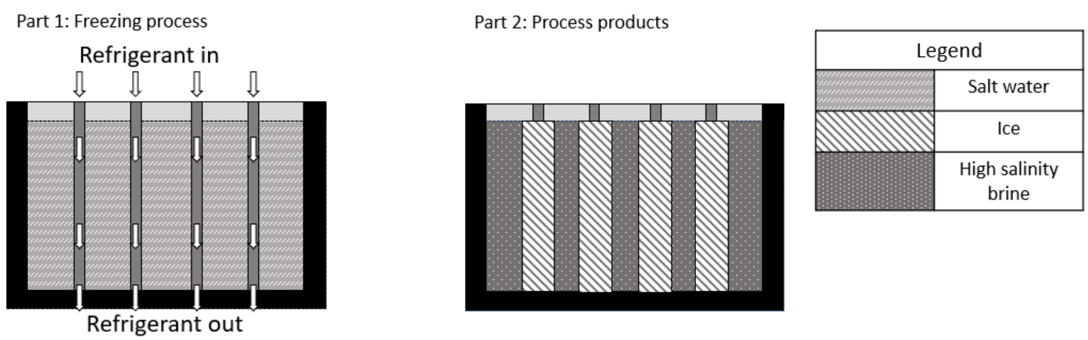

Figure 1: Ice formation in a tube-and-shell indirect freeze desalination system

Figure 2 shows the components and material flows in the freezing process of the system. The washing and melting subsystems were not included as their designs and incorporation into the developed system have not been finalized.

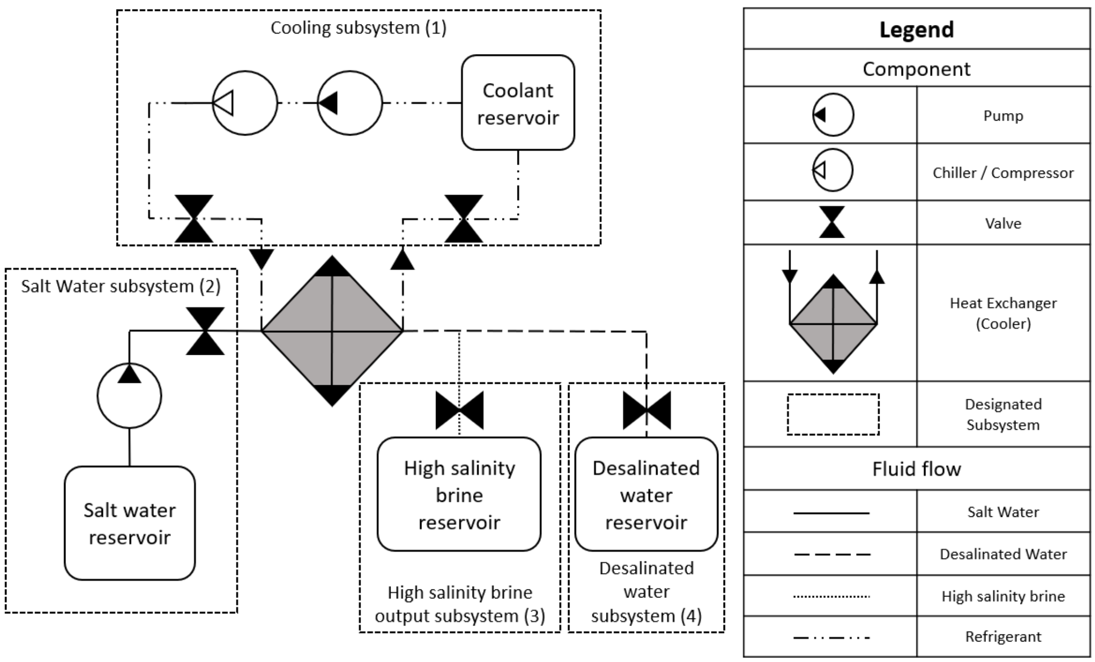

Figure 2: Model of designed freeze desalination system.

The process starts with the input of salt water into the system from the salt water subsystem. The valve is opened, and the pump is then actuated to fill the heat exchanger with salt water. Once this process is done, the valve is closed, and the cooling subsystem begins to operate. Both valves in the subsystem are opened and the chiller, which is modeled as a pump and compressor [13], will cool and pump the refrigerant through the coolant tubes in the heat exchanger. Once this process is finalized and the ice has formed, the chiller is turned off, and the valves are closed. The valves to the high salinity brine reservoir can then be opened to allow the brine to flow out of the heat exchanger, as well as any water used in cleaning the ice. This valve is then closed, and the clean ice can be melted. The desalinated water reservoir valve is opened to collect the produced desalinated water.

The powering elements of the system are also not being considered into this analysis as they will be later chosen to meet the requirements of the selected components.

The system also incorporates different types of sensors in order to detect possible component failures. Across each pump and valve, a pressure differential sensor is located. A temperature sensor is also located at the chiller output. The fluid that flows across each component and the fluid properties, such as pressure and temperature, are known as set points determined from [35]. By knowing the expected flow properties at each location component failure can be detected by comparing the sensor readings with the expected values.

2.4 Reliability Analysis Methods

During the development and design of complex systems, it is known that is it difficult to perform these analyses at the early stages of the design phase due to the system not being fully defined, and lack of system knowledge and probabilities [14]. However, if it is possible to overcome these difficulties, then the early design stages represent a great opportunity to study system irregularities and possible failure modes [15]. This would reduce the monetary and time costs of major re-designs during the testing stages of the system, as well as prevent larger scale problems down the design life of the product that could involve accidents, environmental impacts, and general system malfunction.

These failure modes can be caused by component incompatibility as well as well as undesired system behaviors that can cascade into failure; leading into the system not producing the desired output. To prevent this from happening, design engineers have developed several reliability tools to analyze failure modes in complex systems. Some of the most common reliability analysis methods are Failure Modes and Effects

Analysis (FMEA), Fault Tree Analysis (FTA), and Probabilistic Risk Assessment (PRA).

The FMEA is an exhaustive method with the primary objective of finding all of the failure modes a system can have. It evaluates the most critical failure modes using a Risk Priority Number calculated from the severity, occurrence, and detectability of each of the failure modes. From this analysis, the most important components of a system can be identified, and preventive measures can be taken as needed to improve system performance. FMEAs have two main types: *Process* or *Design*. The Process FMEA focuses on manufacturing processes and the steps of manufacturing a system, while the Design FMEA is based on analyzing a system and its components under operation. While FMEAs can provide design engineers with high amounts of information, it has the downside of requiring knowledge of the system being studied, as well as requiring component data in order to perform a proper analysis [16]. For example, if a bicycle was to be considered for an FMEA, then the Process FMEA would be concerned with the analysis of manufacturing steps like assembling the pedals and how they might be assembled unsuccessfully. The Design FMEA would instead be concerned with the individual components that make up the pedals and their failures and effects during normal operation of the bike.

The FTA is a top-down analysis method with the primary objective of identifying main contributors to the top critical event. It is done by first identifying the critical failure modes of the system, and then breaking them down to their causes using logic gates, creating a tree with base events at the bottom and the major event at the top. This is called an Event Tree. After this Event Tree has been developed, probabilities of failure are added to the base events. The failure probabilities along with the logic gates used in the tree design then allow for the probability of the main event occurring to be calculated. It provides a powerful visual tool that easily displays the events that lead to the top failure mode, as well as a qualitative insight into the failure mode studied [17]. The FTA has the limitation of assuming that each component has two mutually exclusive states that can lead to the top failure event, as well as requiring failure data for each of the base events [18].

PRA is a quantitative method in which failure likelihood and consequences are expressed numerically. It is based around answering three main questions: What can go wrong? How serious are the consequences? And how likely is it to happen? [19]. It integrates fault tree and sequence diagram models to generate the probability of events happening [20]. The probabilistic framework generated is then used to guide the design engineers with the system, but it requires high-fidelity models that are not usually available during early design stages [14].

3. Methodology

3.1 Reliability Analysis Method Selection

The first step to analyze the current design of the indirect freeze desalination system was to determine which reliability method to implement. The FMEA, FTA, and PRA were compared in order to determine which one would give the best insight into the current system design. It was also important to consider the requirements to each method and ensure that it was possible to meet them using proper assumptions and keeping the analysis relevant. Table 1 shows the methods compared, and the criteria evaluated.

Table 1: Comparison of reliability analysis methods

Method	**FMEA**	**FTA**	**PRA**
Type of analysis	Exhaustive system analysis	Top-down single failure analysis	General system failure analysis
Type of results	Component/system failure mode criticality	Probability of top event occurring	Failure probability, and severity
Positives	-Provides individual component insight -Complete system evaluation -Helps with failure mitigation and system improvements	-Provides a visual tool with a clear representation of the top event -Shows component interaction and how each affects the top event	-Provides quantitative results on the probability of general system failure along with the severity of events -Generates a probabilistic framework to aid with design
Negatives	-Component interaction not evaluated -Requires component data and high expertise in the area of study	-Each FTA analyzes a single failure mode -Requires component data	-Very difficult to implement during early stage designs -Requires component data

After all the methods were compared, the FMEA was selected to be the most appropriate and effective method to meet the scope of this study. FMEA was chosen because it gives a general system overview, as well as single component evaluation which will help with component selection in later design stages. It also provides a guide for design engineers to follow for system improvements and considerations which can be used and updated as the system is designed. From the earlier discussed types of FMEAs, the Design FMEA was chosen for this analysis as it is the FMEA type designed to evaluate system performance and individual component reliability. Process FMEA was not considered because it pertains to the manufacturing process of the system, which is not relevant for the present case.

Once it was determined that the FMEA would be the best fit for this project´s scope, it was critical to evaluate the requirements to perform the analysis and determine if these could be met. The data required for all methods was met as data was found for all system components. The only remaining difficulties to perform an FMEA were component interaction and expertise in the area of study. As the system design was discussed during earlier planning stages, it was revealed that even though the freeze desalination system requires proper functioning of all of its components to generate unsalted water, a single component failure would not interact with other components around it [5]. It was also determined that the expertise required to perform the FMEA could be met by committee members Dr. Pence and Dr. Gess.

3.2 Component Data Selection

In order to properly conduct the FMEA, it was necessary to find failure data for the components in the system. Two sources with component data that could be applied to this study were: the OREDA "Offshore Reliability Data Handbook" [21], and the Defense Technical Information Center (DTIC) "Nonelectronic Parts Reliability Data" [22].

For this study, the OREDA handbook was chosen as the component reliability data source. The OREDA handbook presents relevant and up to date data for components used in oil and cooling applications with seawater [21]. This made the OREDA data more relevant to the study as the components in the freeze desalination system could also be exposed to seawater.

3.3 FMEA

The steps followed to perform the FMEA are those covered in Carlson's "Understanding and Applying the Fundamentals of FMEAs", and McDermott's "The Basics of FMEA" [16, 23].

The finalized FMEA table will contain all the sections shown in Table 2, and the steps to fill the table will be covered in the next sections.

Table 2: All sections to be covered in FMEA analysis

Item/ Function	Potential Failure Mode	Potential Effect(s) of Failure	**SEV**	Potential Cause(s) of Failure	**OCC**	Design Control (Detection)	**DET**	**RPN**

3.3.1 FMEA Step 1: System Components

The first step in the FMEA is to identify all the subsystems and components in the analyzed system. For this step, the freeze desalination model was broken down into subsystems around the fluid handled, or the primary function. These were broken down until individual components. The generated list for the freeze desalination system is:

1. Freeze desalination system
    - 1.1. Cooling subsystem
        - 1.1.1. Chiller subsystem
            - 1.1.1.1. Chiller compressor
            - 1.1.1.2. Chiller Pump
        - 1.1.2. Coolant flow valves
        - 1.1.3. Coolant reservoir
    - 1.2. Saltwater transportation subsystem
        - 1.2.1. Saltwater reservoir
        - 1.2.2. Saltwater flow valve
        - 1.2.3. Saltwater flow pump
    - 1.3. High salinity brine output subsystem
        - 1.3.1. High salinity brine reservoir
        - 1.3.2. High salinity brine flow valve
    - 1.4. Desalinated water subsystem
        - 1.4.1. Desalinated water reservoir
        - 1.4.2. Desalinated water flow valve
    - 1.5. Shell and tube heat exchanger
    - 1.6 Piping and connections

For this analysis, it was determined that the different repeating components along the system would hold very similar functionalities with each other. For these repeating components it was also noted that their failure modes and effects would be the same across the different location, with the only significant difference being the fluid flow that it affected in their corresponding subsystems. These factors made it possible to reduce these repeating items to a single element each in the FMEA table, i.e. all the valves are just listed as "valves".

The components selected from the OREDA handbook from which data were acquired include: blowdown ball valve, centrifugal pump, shell and tube heat exchanger, surge tank for the reservoirs, centrifugal electric pump, and piping and connectors. These components were selected as they provided a wide array of failure modes for each component and properly represent their functionality in the analyzed model. The components selected and data used can be updated as the design of the system progresses, and final components are selected.

3.3.2 FMEA Step 2: Component Functionalities

The second step is to determine the function of each identified component for the FMEA. Table 3 shows part of the FMEA after step 2 is finished.

Table 3: Part of the FMEA after completing step 2

Item/ Function	Potential Failure Mode	Potential Effect(s) of Failure	**SEV**	Potential Cause(s) of Failure	**OCC**	Design Control (Detection)	**DET**	**RPN**
Compressor / Refrigerant compression in refrigeration-compression cycle								

3.3.3 FMEA Step 3: Failure Modes

The third step is to identify all the failure modes the listed components can have. Failure modes are when the component is unable to function properly or meet its intended requirements. For this step, the failure modes were taken from the OREDA handbook [21]. Table 4 shows part of the FMEA after step 3 is finished.

Table 4: Part of the FMEA after completing step 3

Item/ Function	Potential Failure Mode	Potential Effect(s) of Failure	**SEV**	Potential Cause(s) of Failure	**OCC**	Design Control (Detection)	**DET**	**RPN**
Compressor / Refrigerant compression in refrigeration-compression cycle	Fail to start on demand							
	High output							

3.3.4 FMEA Step 4: Failure Effects

The fourth step is to identify all the potential effects of the listed failure modes. These indicate how the individual component performance or integrity is affected, as well as its effect on the overall system. For this step, the possible effects were determined from the failure modes and were considered along with their criticality listed in the OREDA handbook [21]. This information along with individual component literature [24-34] enabled the generation of a list of the effects of the listed failure modes. Table 5 shows part of the FMEA after step 4 is finished.

Table 5: Part of the FMEA after completing step 4

Item/ Function	Potential Failure Mode	Potential Effect(s) of Failure	**SEV**	Potential Cause(s) of Failure	**OCC**	Design Control (Detection)	**DET**	**RPN**
Compressor / Refrigerant compression in refrigeration-compression cycle	Fail to start on demand	Complete inability to cool refrigerant						
		Delayed start on refrigerant cooling						
	High output	Unexpected fluid properties						

3.3.5 FMEA Step 5: Severity (SEV)

The fifth step is to develop a severity scale and to assign severity scores to each of the listed effects of failure. The severity scale developed for this analysis can be seen in Table 6.

Table 6: Severity scale

Category (product)	Criteria: Severity of Effect (Effect on Product)	Rank
Unsafe	Unsafe operation without warning	10
	Unsafe operation with warning	9
Major loss of system performance	Unable to produce desalinated water	8
	Output is degraded	7
Minor loss of system performance	Major loss of efficiency	6
	Decrease in system efficiency	5
Minor system disturbances	Moderate component damage	4
		3
	Minimal component damage	2
No Effect	No noticeable effect	1

For the development of this table, it was important to consider the effects of failure at a component, efficiency, and output level without regarding the likelihood of the event, or how easy it would be to detect.

The higher elements on the scale, 10 and 9, are assigned to when the analyzed failure effect can be considered hazardous for the operator or people around the system. The highest is given when the system can cause harm suddenly and without any sort of warning.

The next tier in the scale, scores 8 and 7, are given to failure modes that can affect the system's ability to generate the desired output or production of degraded output, i.e. not enough fresh water volume or too high salinity. The main purpose of the system is to generate desalinated water, so anything that affects the system's capability to do so should be treated with high priority.

The lower categories of the table are divided between the effects of loss in system efficiency and component damage. Effects of loss in system efficiency were given higher severity ranks than just component damage because of the desalination system being energy intensive. The lowest rank of the scale belongs to failures that have no noticeable effect on the system.

Severities were then assigned to each of the previously listed effects of failure with the help of the literature on component failure [24-34], the OREDA handbook [21], and discussion with the thesis committee members. Part of the FMEA after completing step 5 can be seen in Table 7.

Table 7: Part of the FMEA after completing step 5

Item/ Function	Potential Failure Mode	Potential Effect(s) of Failure	**SEV**	Potential Cause(s) of Failure	**OCC**	Design Control (Detection)	**DET**	**RPN**
Compressor / Refrigerant compression in refrigeration-compression cycle	Fail to start on demand	Complete inability to cool refrigerant	**8**					
		Delayed start on refrigerant cooling	**6**					
	High output	Unexpected fluid properties	**5**					

3.3.6 FMEA Steps 6: Failure Causes

The sixth step and seventh step of the process are to determine possible causes for each of the listed failures and develop an occurrence scale to assign an occurrence value to each possible failure cause, respectively. The component failure data from the OREDA handbook [21] includes only failure mode effect occurrence and does not include causes of failure. This step was completed with the use of the component literature [24-34], along with discussions with the thesis committee to develop lists of common causes of failure for each component.

3.3.7 FMEA Step 7: Occurrence (OCC)

The seventh step of the process is to develop an occurrence scale to assign an occurrence value to each possible failure cause determined in step 6. The generated occurrence table can be seen in Table 8.

Table 8: Occurrence scale

Likelihood of failure	**Criteria: Occurrence of Cause (incidents per item)**	**Rank**
Very High	>1 failure per hour	10
	4000 per 10^4 hours - >1 failure per 24 hours	9
High	2000-4000 per 10^4 hours	8
	1000-2000 per 10^4 hours	7
Moderate	500-1000 per 10^4 hours	6
	100-500 per 10^4 hours	5
	50-100 per 10^4 hours	4
Low	10-50 per 10^4 hours	3
	1-10 per 10^4 hours	2
Very low	< 1 per 10^4 hours	1

The ranks in for the occurrence scale were derived using the occurrence data for the selected system components, along with discussions with the thesis committee, and the system analysis done by Trevor Whitaker on his thesis “Freeze Stage Analysis of an Indirect Freeze Desalination System” [35]. By analyzing numerical models developed in [35], the design team determined that a total cycle for the system would take one hour. This was assigned the highest rank on the scale, as a component failure within a single cycle is the worst-case scenario. The rest of the table was scaled down to the smallest case which is less than 1 failures per 10^4 hours of operation. This last rate is labeled as "eliminated through preventive control". The scaling of the table ratings was done along with the committee members. Table 9 shows part of the FMEA after completing steps 6 and 7.

Table 9: Part of the FMEA table after completing steps 6 & 7

Item/ Function	Potential Failure Mode	Potential Effect(s) of Failure	**SEV**	Potential Cause(s) of Failure	**OCC**	Design Control (Detection)	**DET**	**RPN**
Compressor / Refrigerant compression in refrigeration-compression cycle	Fail to start on demand	Complete inability to cool refrigerant	**8**	Dirty condenser coils, clogged lines, undesired amount of refrigerant, improper lubricant, undesired voltage, contaminants in the system, suction line size	**5**			
		Delayed start on refrigerant cooling	**6**		**2**			
	High output	Unexpected fluid properties	**5**		**2**			

3.3.8 FMEA Steps 8 & 9: Control Systems and Detection (DET)

The eighth and ninth steps in the FMEA are to designate control systems and develop a table for their corresponding detection rankings. The control systems determine the way failure modes will be detected in the system. The control systems are listed in the detection scale seen in Table 10, along with their corresponding ranks. These ranks were determined by how quickly a failure mode can be detected with the designated method.

Table 10: Detection scale

Likelihood of detection	**Criteria: Likelihood of Detection by Design Control**	**Rank**
Absolute Uncertainty	Cannot be detected	5
Remote	Corrective maintenance	4
Moderate	Preventive maintenance	3
High	Inspection/audible	2
Almost certain	Designated sensor in component	1

The lowest ranking on the scale is assigned to failures detected by the sensors assigned to each component in the system. The sensors provide an immediate reading on flow properties, and failure modes can be immediately detected. The second ranking was given to failure modes that can be detected by simple inspection or that are audible to the operator. The second ranking includes false readings by the sensors and strong component vibrations. The next ranks on the scale are given to preventive and corrective maintenance. Preventive maintenance is a scheduled maintenance with the purpose of testing components and preventing failure, while corrective maintenance is done when a failure has already occurred and requires maintenance [36]. The highest score on the table is given to a failure mode that cannot be detected. Table 11 shows part of the FMEA after steps 8 and 9 have been completed.

Table 11: Part of the FMEA table after completing steps 8 & 9

Item/ Function	Potential Failure Mode	Potential Effect(s) of Failure	SEV	Potential Cause(s) of Failure	OCC	Design Control (Detection)	DET	RPN
Compressor / Refrigerant compression in refrigeration-compression cycle	Fail to start on demand	Complete inability to cool refrigerant	**8**	Dirty condenser coils, clogged lines, undesired amount of refrigerant, improper lubricant, undesired voltage, contaminants in the system, suction line size	**5**	Temperature sensor	**1**	
		Delayed start on refrigerant cooling	**6**		**2**	Temperature sensor	**1**	
	High output	Unexpected fluid properties	**5**		**2**	Temperature sensor	**1**	

3.3.9 FMEA Step 10: Risk Priority Number (RPN)

The RPN of each failure mode effect is calculated by multiplying the Severity (SEV), Occurrence (OCC), and Detectability (DET) scores assigned.

$$RPN = SEV \times OCC \times DET$$

It is important to know that while this number can give a good assessment on the criticality of a component in the analyzed system, it is also limited to the developed severity, occurrence, and detectability scales and the judgment of the team that developed the FMEA [23]. The FMEA can be seen in Table 12 after step 10 is completed.

Table 12: FMEA after completing step 10

Item/ Function	Potential Failure Mode	Potential Effect(s) of Failure	SEV	Potential Cause(s) of Failure	OCC	Design Control (Detection)	DET	RPN
Compressor / Refrigerant compression in refrigeration-compression cycle	Fail to start on demand	Complete inability to cool refrigerant	**8**	Dirty condenser coils, clogged lines, undesired amount of refrigerant, improper lubricant, undesired voltage, contaminants in the system, suction line size	**5**	Temperature sensor	**1**	**40**
		Delayed start on refrigerant cooling	**6**		**2**	Temperature sensor	**1**	**12**
	High output	Unexpected fluid properties	**5**		**2**	Temperature sensor	**1**	**10**

A reference RPN was also calculated to determine a threshold of what calculated values would be considered critical to the system. This number was calculated by assessing which number on each scale would represent a significant failure to the system. The severity value for the threshold was determined to be 4, as any failure that affected system efficiency could compromise the production of water. The Occurrence value selected was 3, this was because any component with a moderate chance of failure could hinder the operation of the desalination system. Lastly, the Detectability value selected was 3. If any failure had to be detected by any method that was not planned or scheduled, it would represent a component that requires close attention. These selected values yield a threshold RPN of 36.

3.3.10 FMEA Step 11: Recommended Actions

The final step of the FMEA is to recommend possible changes or actions to reduce or eliminate the risk associated with the analyzed failure modes [23]. This step will be covered in the results and discussion section of this thesis. These recommendations take the severity, detectability, and occurrence score into consideration and propose solutions to improve the system.

4. Results & Discussion

4.1 Results

The complete FMEA table can be seen in Appendix A – FMEA table. Table 13 presents all the failure modes with RPN values higher than the established criticality threshold.

Table 13: Failure modes with RPN values above criticality threshold

Item/ Function	Potential Failure Mode	Potential Effect(s) of Failure	**SEV**	Potential Cause(s) of Failure	**OCC**	Design Control (Detection)	**DET**	**RPN**
Pump/ generate fluid flow	External leakage	Corrosion	**3**	*See Appendix A for potential causes of failure*	**4**	Preventive maintenance	**3**	**36**
	Internal leakage	Corrosion	**5**		**2**	Corrective maintenance	**4**	**40**
	Vibrations	Loss of energy efficiency	**5**		**3**	Preventive maintenance	**3**	**45**
Heat Exchanger / Energy transfer from salt water to refrigerant, leading to water phase change (liquid to solid)	Abnormal instrument reading	Inaccurate reading of water level in the system	**7**		**3**	Inspection	**2**	**42**
Valves /flow restriction	External leakage	Corrosion/affecting other components	**5**		**2**	Corrective maintenance	**4**	**40**
Vessels / Storage of clean water, salt water, refrigerant, residues	Abnormal instrument reading	False reading of the amount of fluid in system	**7**		**2**	Corrective maintenance	**4**	**56**
Compressor / Refrigerant compression in refrigeration-compression cycle	Fail to start on demand	Complete inability to cool refrigerant	**8**		**5**	Temperature sensor	**1**	**40**
	Spurious stop	Lack of refrigeration in system	**8**		**5**	Temperature sensor	**1**	**40**
	Abnormal instrument reading	Unknown system state/improper refrigeration	**7**		**5**	Inspection	**2**	**70**

4.2 Discussion

From the resulting Table 13 it can be noted that each component in the system, except for the pipes and connectors due to their lack of failure modes in the OREDA handbook [21], has at least one critical failure mode. The results confirm that the system is reliant on proper functionality of each of its components in order to operate successfully.

From all the components, the compressor and the pumps are the ones that had the most critical failure modes. This was due to their higher failure occurrence due to both being mechanical components with moving parts, and higher detectability scores due to the difficulty in detecting corrosion from small leaks, and small vibrations. It was expected that these components hold the most critical states as their functionality in fluid flow and refrigerant cooling is vital to the functionality of the system.

Abnormal instrument reading is another failure mode with several appearances in the table. While improper sensor behavior can be easily detected, they can heavily affect the performance of the system if the sensors send a false-positive reading. In this scenario, the system would be working under undesired conditions until cycle completion, and the desired output will not be generated.

The recommended actions and modifications to this design in order to prevent failure are the following:

- Implementation of bypass valves and pumps in parallel to the existing ones in the design in order to mitigate the damage caused by the failure of one of these components.
- Proper material and component selection to prevent corrosion and leaking due to extended contact with salt water, or refrigerant.
- Careful assembly to avoid pipe and connector failure.
- Regular scheduling for preventive maintenance to avoid necessity of corrective maintenance and ensure proper system functionality.
- Continuously update FMEA with system data through development, testing, and usage to provide a more accurate representation of the system behavior.

5. Conclusions & Recommendations

With the use of literature and a relevant component data it was possible to perform an FMEA in the early stages of the design process of an indirect freeze desalination. From the FMEA, it was possible to determine appropriate recommended actions to improve system reliability and performance. The FMEA will work as groundwork for later stages of the design process of the freeze desalination system, and aid design engineers with decision making.

Even though it was possible to successfully develop an FMEA of the freeze desalination system at the early design stages, there exists considerable room for improvement in the analysis. As expected, there were difficulties encountered during the development of the FMEA due to lack of expertise with the desalination system. This made difficult the component selection, and the assessment of severity and detectability scores. It is recommended to collaborate with a bigger FMEA team in order to avoid any possible bias in the development of the severity, occurrence, and detectability scales.

The freeze desalination system being in such early stages of development also was an obstacle. As none of the components in the system other than the chiller had been specified, assumptions had to be made to choose components to analyze. While the results generated from the chosen components provide valuable insight into the expected behavior and general criticality of the component, these results could be improved by doing further research in component selection.

It is recommended that the FMEA and scales are updated once components are selected and working with the suppliers of the selected components to get up-to-date data on the components. In the meantime, it could be beneficial to perform the FMEA with the different available component reliability data to validate the results obtained from this study. This would provide a more accurate representation of the system as it is developed.

The other mentioned reliability methods could also be performed on the detected failure modes with RPN values higher than the established threshold. This would produce a more in-depth representation of what is causing these critical failure modes and provide additional guidelines on how to improve the system design.

Finally, combine results from this thesis with that of the parallel studies being done on the mobile freeze desalination system in order to finalize a design and continue development and testing of the system.

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APPENDICES

APPENDIX A – FMEA TABLE

Item/ Function	Potential Failure Mode	Potential Effect(s) of Failure	**SEV**	Potential Cause(s) of Failure	**OCC**	Design Control (Detection)	**DET**	**RPN**
Pump / generate fluid flow	Breakdown	Lack of pump functionality in system	8	Flow conditions outside of pump specifications, weep hole leakage, leaking from mounting surface, rust and corrosion, deposit buildup, cavitation, damaged bearing, damaged shaft	2	Pressure sensor	1	16
	External leakage	Major loss of fluid & properties	7		2	Pressure sensors	1	14
		Slight loss of fluid & properties	5		3	Pressure sensors	1	15
		Minor loss of fluid & properties	2		2	Preventive maintenance	3	12
		Damage on system components	7		2	Pressure sensor	1	14
		Corrosion	3		4	Preventive maintenance	3	36
	Fail to start on demand	Lack of desired fluid in the system	8		3	Pressure sensor	1	24
	Fail to stop on demand	Overflow of desired fluid in the system	8		1	Pressure sensor	1	8
		Time delay for flow to stop	7		2	Pressure sensor	1	14
	High output	Structural damage on component	7		2	Pressure sensor	1	14
		Slight change in fluid properties	4		1	Pressure sensor	1	4
	Internal leakage	Critical internal damage	8		2	Pressure sensor	1	16
		Corrosion	5		2	Corrective maintenance	4	40
	Low output	Insufficient fluid displacement	7		2	Pressure sensor	1	14
		Slight fluid property loss	5		3	Pressure sensor	1	15
	Overheating	Loss of pump functionality	8		2	Pressure sensor	1	16
		Degraded functionality	5		2	Pressure sensor	1	10
	Spurious Stop	Loss of pump functionality	8		3	Pressure sensor	1	24
	Structural deficiency	Component failure due to corrosion/inappropriate conditions	8		2	Pressure sensor	1	16
		Slight effect on functionality due to conditions	5		2	Pressure sensor	1	10
	Vibration	Loss of pump functionality	8		2	Audible	2	32
		Loss of energy/efficiency	5		3	Preventive maintenance	3	45
	Abnormal instrument reading	False reading on pump functionality	7		2	Inspection	2	28

Continued on next page

Item/ Function	Potential Failure Mode	Potential Effect(s) of Failure	**SEV**	Potential Cause(s) of Failure	**OCC**	Design Control (Detection)	**DET**	**RPN**
Heat Exchanger / Energy transfer from salt water to refrigerant, leading to water phase change (liquid to solid)	External leakage	Major loss of water & properties	8	Fluid properties outside of system specifications, corrosion, overcapacity, wear, material incompatibility	2	Volume sensor	1	16
		Moderate loss of water & properties	7		2	Volume sensor	1	14
		Minor loss of water & properties	5		2	Volume sensor	1	10
		Corrosion/affecting other components	4		2	Preventive maintenance	3	24
	Structural Deficiency	Structural failure	8		2	Volume sensor	1	16
		Slight deformations	3		2	Preventive maintenance	3	18
	Abnormal instrument reading	Inaccurate reading of water levels in the system	7		3	Inspection	2	42
	Plugged/Choked	Obstruction of flow affecting flow properties	4		2	Pressure sensor	1	8
Valves /flow restriction	Fail to close on demand	Overflow of desired fluid in the system	8	Fluid properties outside of operating parameters, wear on elastomers and seals, abrasive debris, material incompatibility	1	Pressure sensor	1	8
	Fail to open on demand	Lack of desired fluid in the system	8		2	Pressure sensor	1	16
	Delayed operation	Process is briefly delayed	5		2	Pressure sensor	1	10
	External leakage	Corrosion/affecting other components	5		2	Corrective maintenance	4	40
	Internal leakage	Component corrosion/damage	4		1	Preventive maintenance	3	12
	Fluid leakage while in closed setting	Flow of undesired fluid	5		1	Pressure sensor	1	5
	Abnormal instrument reading	False reading on valve functionality	7		2	Inspection	2	28
Vessels / Storage of clean water, salt water, refrigerant, residues	Abnormal instrument reading	False reading of the amount of fluid in system	7	Maintenance/hot work, operational error, equipment failure	2	Corrective maintenance	4	56
		Slight variation of fluid volume in system	6		3	Volume sensor	1	18
	Structural deficiency	Corroded vessel	3		2	Preventive maintenance	3	18
		Deformation of vessel	2		3	Preventive maintenance	3	18
	External leakage	Slight loss of fluid	2		2	Volume sensor	3	12

Continued on next page

Item/ Function	Potential Failure Mode	Potential Effect(s) of Failure	**SEV**	Potential Cause(s) of Failure	**OCC**	Design Control (Detection)	**DET**	**RPN**
Compressor / Refrigerant compression in refrigeration-compression cycle	Fail to start on demand	Complete inability to cool refrigerant	8	Dirty condenser coils, clogged lines, undesired amount of refrigerant, improper lubricant, undesired voltage, contaminants in the system, suction line size	5	Temperature sensor	1	40
		Delayed start on refrigerant cooling	6		2	Temperature sensor	1	12
	High output	Unexpected fluid properties	5		2	Temperature sensor	1	10
	Overheating	Component failure	8		2	Temperature sensor	1	16
	Spurious stop	Lack of refrigeration in system	8		5	Temperature sensor	1	40
	External leakage	Loss of refrigerant	5		3	Pressure sensor	1	15
		Corrosion/affect other components	3		4	Inspection	2	24
	Internal leakage	Corrosion/damage to compressor	3		3	Preventive maintenance	3	27
	Abnormal instrument reading	Unknown system state/improper refrigeration	7		5	Inspection	2	70
	Structural deficiency	Operation deficiency	5		3	Temperature sensor	1	15
Piping / Fluid Transportation	Leaking	Corrosion/high pressure	8	Corrosion, fluid pressure, flow speed, poor installation	1	Preventive maintenance	3	24
Connectors / Piping and component connection	Leaking	Corrosion/high pressure	8	Fatigue, vibrations, stress corrosion, wear, load capacity	1	Preventive maintenance	3	24