# COSMIC ICE

Night-Sky Radiative Refrigerator for the Ni-Vanuatu

INFINITE LIMIT TEAM:

# Executive Summary


Keeping things cool is a tough task in any tropical climate, but it is especially difficult in a nation where over 75% of the population do not have regular access to electricity. In Vanuatu, the lack of refrigeration has resulted in a population that is heavily reliant on imported canned foods, despite the vast prominence of fishing activity in the nation. Unreliable yield from subsistence farming activity also means less food security for families throughout the year, as a consequence of the unfavourable weather conditions that characterise the nation's climate.

This report details our solution to this problem for communities in Espiritu Santo and beyond. Presenting a detailed appraisal of various other issues affecting local communities, this report initially seeks to assert the importance of introducing refrigeration in Vanuatu, despite the subject's limited attention thus far in the nation. Then, potential design options are weighed against a carefully constructed project criteria which seeks to maximise the device's functionality, practicality and feasibility within the context of the communities we are working with. A final product, along with a detailed description of an initial prototype will close out the design section of this report.

No successful project can be undertaken without a sustainable implementation plan, and so this report will seek to present a comprehensive action plan that not only details how we will introduce the product into the community, but also how we will go about presenting a framework from which locals can continue to achieve their own development goals in the future.

Ultimately, the scope of our project is not limited to merely providing a solution to a single problem in Espiritu Santo, but providing an impetus that stimulates the sustainable growth and development of remote communities long after our initial intervention.

# Table of Contents

# 1. Introduction

# 1.1 Vanuatu

The Republic of Vanuatu, located 1750 km northeast of northern Australia, is one of the twelve Pacific Islands in the South Pacific Ocean. Vanuatu consists of about 82 relatively small islands and Espiritu Santo is the largest of all. Vanuatu was first inhabited by Melanesian people and later colonized by the United Kingdom and France. Independence movement arose and the Ni-Vanuatu (Indigenous Vanuatu population)  gained freedom from the United Kingdom and France in 1980.

Vanuatu has a tropical climate, with daily temperatures ranging from 20 to 32 degrees, the year consisting of about nine months of warm weather and three cooler months. The rainy season begins in December and ends in April, with significant amount of rainfall almost everyday, and the driest months coming in June through to November. Tropical cyclones often occur in the rainy season, often damaging crops and even causing deaths.

The economy of Vanuatu is based on their agriculture products such as copra, cocoa, kava and other fruits, that provides living for approximately two-thirds of the population. The fish industry is another major sector of Vanuatu's economy, as over 77% of households are involved in the production of fish. The agriculture, forestry and fishing sector has accounted for 15% of Vanuatu's GDP and for almost all of the export products[1].

Espiritu Santo, one of the constituent islands of Vanuatu

# 1.2 Current Challenges

The Ni-Vanuatu community is currently facing many challenges, these areas include limited water supply, sanitation, agriculture and food production, transport and energy supply.

The Vanuatuans have limited access to water during dry seasons as the availability of water highly depends on the season. Water is used sparingly during dry seasons, and in most communities, everyone saves the higher quality water for drinking and cooking. The pollution in the water is the driving factor of waterborne diseases such as Malaria, scabies and skin diseases are the most common health issues of the country. The poor sanitation and waste management provide waterways that is the best for mosquito breeding[1].

Since the Ni-Vanuatu primarily lives off of subsistence agriculture, damages to the agriculture is detrimental to their lives as well as to their income. Furthermore, Vanuatu's increasing population is burdening the resources for farming, hunting and fishing.

Transportation is another issue in Vanuatu as the road systems on the island are rather basic. Many of the roads in Vanuatu remain unpaved, and after intense rainfall, the roads turn into uneven muddy tracks. This is often a big challenge for pregnant women, children and people who are ill as they have to walk for several kilometres to have access to trucks that will take them to their destinations.

Only two electricity grids are on Espiritu Santo, one in Luganville and the other in Port Orly. The communities on the east coast do not receive grid electricity as the two electricity grids do not extend much beyond the two towns. Furthermore, due to the dispersed nature of the islands the implementation costs for renewable energies are high. Electricity is an important for hospitals as vaccines are required to store in cool temperatures, for rural regions of Vanuatu, many people must travel to Espiritu Santo or Sola for immunisation. [3]

# 1.3 Case Study: Hope for Haiti

From evaluating the implementation of programs into developing countries, our team will be able to learn from their shortcomings in order to create a better program for the Vanuatu community.

Hope for Haiti is an American based, non-for-profit organisation which was founded upon a vision for building a sustainable society through education. Hope for Haiti targets five key areas: education, healthcare and nutrition, clean water, infrastructure and economy. With their goal of building sustainable communities, the company directs 95% of its income at benefitting the Haitian community.

Although the work that Hope for Haiti has done demonstrated a positive impact within several Haitian communities, the sustainability of its work can be questionable. Hope for Haiti's clean water program, for example, limits the potential to sustain outcomes for a long period of time. By employing an in-house technician that visits the target community on a monthly basis, the project leaves the community in reliance of the organisation for clean water. As engineers, the sustainability of a project is substantial to its impacts for the target society. Hence, one of our goals for this project can be to make the Vanuatu community in control of the idea that is presented. It is necessary however to work closely with the government and the local community to generate a larger impact on the entire population even if the organisation were to leave the country.

Moreover, as traditional methods of technical assistance has been found to be ineffective at yielding long term results due to its frequent incompatibility with capabilities of the target population. Therefore, our team should take the local custom and resources into considerations and thus the probability of our project continuing to be adopted beyond our initial intervention will be maximised. We should seek to undertake local methods of consultation and encourage the Vanuatuans to participate into all levels of refining and planning process of our proposed idea.

Ultimately, the example of Hope for Haiti's work informs it is necessary for a program not just to provide an immediate solution, but to develop the capacity of locals to tackle other issues which may arise in the future.

## 2. Engineer’s Role in Global Society - Our Mission

Tasked with the crucial responsibility of devising and implementing solutions to some of the most pressing global issues, engineers naturally assume a leadership role within the communities that they work with. At Infinite Limit however, it is our belief that leadership goes beyond merely just creating and acting on an engineering vision, but rather empowering local institutions to take ownership over their own future development. We achieve this by building and proposing frameworks, as opposed to finished products, that seek to develop a community’s capacity to autonomously achieve their own development objectives over time. It is our belief, that it is an engineer’s responsibility, to motivate and inspire benefitting communities to engage with their own vision, providing only necessary technical support and guidance to help communities turn these into a reality.

At Infinite Limit, we acknowledge that the only people who can ultimately bring about lasting change in a community are the members of the community themselves. It is a culture that is profoundly rooted in all of our initiatives - from the ground up. Our solutions are deeply informed by the ultimate goal of making our initiatives *theirs* and not *ours*, so as to foster a lasting, intrinsic sense of motivation to grow amongst these communities. Driven by their own self-determination, our projects are designed to evolve with the communities, and adapt to changing local landscapes; creating a sustained positive impact long after our initial intervention.

To do so, Infinite Limit is committed to always engaging in an open dialogue with the communities that we work with, as well as their associated local institutions and governments. Doing so enables all stakeholders and parties involved to remain equally driven and focused on bringing about real, impactful change that will be holistically appreciated by the benefitting community. We adopt local channels of communication in order to better integrate our involvement into the existing norms of local life, creating an organic, rather than burdensome path towards growth and development.

This is what we believe to be the role of an engineer within global society - a quality leader that nurtures a local vision and provides mentorship to help communities achieve their own development goals. This report will detail just one implementation of our vision in a developing community.

# 3. Initial Project Ideas

# 3.1 Proposal 1: No Energy Refrigeration

## Why it Matters

Though grid electricity can be accessed in the urban centres of Luganville and Port Vila, about 75% of Vanuatu lives without access to electricity.[4] The logistical difficulties associated with distributing energy over 64 inhabited islands means that many communities, especially rural, either cannot source electricity, or rely on small (but expensive) solar kits to generate energy for their homes.[5] As a consequence, access to refrigeration on Espiritu Santo is also limited to large urban establishments like Luganville.

Refrigeration is not necessarily an expressed desire of the ni-Vanuatu. As the diet of communities in Espiritu Santo is derived primarily from subsistence farming, food is most commonly consumed fresh, trivialising the need for refrigeration.[6] However, such a mechanism leaves families vulnerable to unexpected seasonal or weather influences that affects the yield from community farms and gardens.[7] By extension, the nation's susceptibility to devastating natural disasters such as droughts and cyclones also affect the availability of food for extended periods of time. Refrigeration would provide an opportunity for communities to therefore mitigate the effect of these events by enabling them to save their excess yield for periods where access to fresh food is limited. For example, much of Vanuatu's ability to maintain a balanced diet is limited by their inability to preserve meat, which can only be consumed in instances where it is freshly available.[8] A study by the National Institute of Health concluded that many communities "became sick by repeatedly eating the same food".[8] To combat this, the nation has begun to rely on large quantities of tinned food imports, which are unfortunately rich in saturated fats and unhealthy chemicals.[8]

Furthermore, one of the biggest impediment to the development of rural fishing industry is the inability to preserve fish so that it can be sold to urban or even overseas markets.[9] Greater rural consumption of domestic fish (as well as meat in general) would result in better nutrition by reducing consumption of low quality and less nutritious imported tinned products.[10] Access to refrigeration would enable communities to preserve fish before distributing them to village or urban markets. As over 75% of households are involved in fishing,[9] this could potentially have a very substantial impact on the nation's economy, as the nation's current fishing resources are being taken advantage of by foreign corporations.

Finally, medical supplies to remote communities can be unreliable as they are often inaccessible after frequent rain. Delivery of medical supplies to some secluded villages requires personnel to work for several days, which can provide challenges to the reliable and safe delivery of temperature sensitive medications and vaccines.[10] Therefore, refrigeration provides an opportunity for remote rural community to maintain reliable access to necessary pharmaceuticals without travelling to distant medical centres, or waiting for deliveries to arrive.

## Our Proposal

We propose the implementation of a refrigeration system that does not require any access to electricity; operating purely off of mechanical cooling processes. Such a system would be able to keep perishable foodstuffs and medical supplies at a temperature low enough to extend their lifetimes by at least 500%; even in the warmer tropical climate associated with Vanuatu's geography. This will provide enough buffer time for remote communities to sustain themselves until yield returns back to adequate levels. It will also serve to keep food away from potential pests such as snails, and will be compact enough to be either located inside or within a close vicinity of family homes. Finally, it will be durable enough to maintain a lifetime of over 10 years, and be relatively simple to keep clean and maintain.

## How it Will Work

There are a variety of different mechanisms that could be employed to provide refrigeration to communities with no access to electricity. The following options will need to be evaluated against criteria including feasibility in the climate of Vanuatu, inexpensive and simple to operate, as well as safe to handle.

1. Evaporative cooling (limitations in the humid Vanuatu climate however)
2. Night Sky Radiant cooling
3. Thermoelectric cooling (will require a battery)

Furthermore, the system should have mechanisms in place so that it can be carried as a self-contained object. Made of insulating material, it should be able to keep food cool for a short period of time even if the cooling cannot be undertaken. This could be particularly useful in a natural disaster situation, where families can store food to sustain themselves until aid arrives.

# 3.2 Proposal 2: Portable Water Filtration

## Why does it matter?

Water is the drink of life. For the local communities on East Santo, it is scarce in the dry season, yet it is needed for drinking, washing, agriculture and well-being.[11] Imagine having fresh, clean water anywhere and anytime. A portable water filtration device is the solution to produce potable water from the rainwater tanks, open-air wells, springs, rivers or beaches in the East Santo communities. Storing a large amount, it can be transported from the source to homes and provide days of fresh drinking water for families.

Currently in the East Santo region, the dry season lasts three to four months, with sea water being used to bathe and wash clothes while clean, quality water is conserved.[11] With solar-powered filtration, energy from the sun is captured to produce a constant supply of water for crops, drinking, cooking and cleaning. This would simultaneously improve the health of the population, improve sanitation and prevent transmission of waterborne diseases. If families have no time to journey to the water source, filtration can be used domestically to recycle dirty water and provide a reliable source of fresh, clean hydration. This would save the time-consumption associated with 2 hour walks in the dry season.[11]

## Our Proposal

A portable, solar-powered water filtration device that produces potable water from any water source, including drains, rivers, beaches and groundwater. With a capacity to store 30 to 40 litres, it is capable of providing quality water to any household. It can desalinate, kill pathogens and remove macromolecules.

## How Will it Work?

The compact device utilises standard filtration, reverse osmosis and boiling, to decontaminate used or salt water. Ions, fungi and bacteria are removed to produce fresh water that can be taken anywhere and anytime. The device is also environmentally efficient; with the sun's radiation fuelling the incorporated pump and heater. An extendable handle and wheels make it easy for consumers to transport water.

As proposed materials, filtration membranes can be derived from the abundant crops of coconut in the East Santo region. Aluminium is a viable choice for the external capsule of the device; possessing lightweight and strong properties. In terms of its general design, the capsule incorporates an entry pipe for water, and external tap for output. It compacts the water filtration apparatus into a bucket-sized system.

# 3.3 Smoke-Free Cooking Stove

## Why does it matter?

Alarmingly, fumes from traditional wood cooking kill more people globally than Malaria and Tuberculosis.[12] Smoke particles diminish the function of cells that are responsible for the natural defences of the lungs, increasing the risk of chronic illnesses and infections such as pneumonia - a leading cause of death in children across the developing world.[13]

Food preparation in East Santo predominantly necessitates the use of open fires, with firewood being the most commonly used combustible fuel.[11] Burning wood however leads to the emission of large quantities of carbon monoxide (CO), a colourless, odourless smoke that is toxic in high concentrations.[14] Unsurprisingly, community members in Espiritu Santo have shared that smoke from cooking has caused coughing and irritated eyes, precursors to more severe physical ailments.

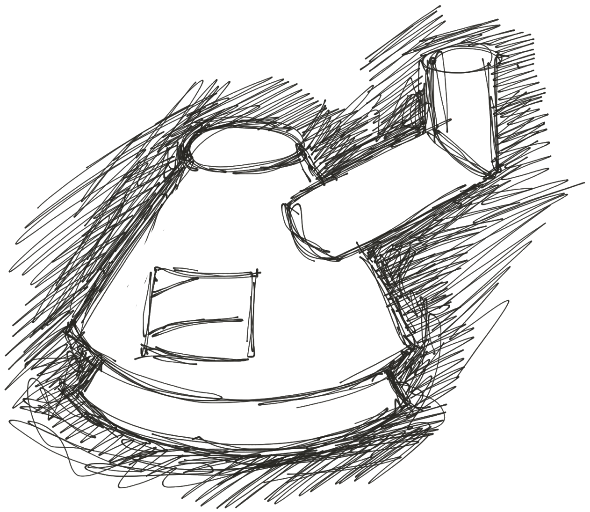
Along with the degradation of local air quality, wood burning can also have detrimental consequences on the environment, with nitrous oxides (a product of open fires) contributing to instances of acid rain. Acidic pollutants can have a severe impact on the health of vegetation, which is particularly problematic for the agriculture-reliant communities of East Santo.[15]

## What is it?

Smoke is a result of the incomplete combustion of fuels, which occurs when there is an insufficient supply of oxygen for the fuels to react with. We propose a new cooking stove for communities of Espiritu Santo, which still operates off of the abundant firewood resources, but stimulates complete combustion in order to minimise smoke production. The stove will be compact - knee high in a conical shape, so that its operation is viable in existing enclosed kitchen spaces. Such a shape will also facilitate the convenient execution of traditional cooking methods involving flat pans and lap lap.

## How Will it Work?

The stove will actively seek to ventilate the fire via numerous perforations on its surface as well as supplementary air duct. These structures serve to actively expel the combustion products from the combustion chamber and create a negative pressure within the stove that drives in fresh air from the external surroundings.[16] As a consequence, this increase in the concentration of combustion reactants like oxygen drive the complete combustion of the hydrocarbons in the trees, minimising smoke production.[16]



*A model of a smoke-free cooking stove devised by engineers at MIT.*

# 4. Project Criteria

The process by which we decided between the proposals.

**Underpinning** the holistic fulfilment of our mission is the pursuit of an initiative that has the potential to yield the greatest possible impact on the communities of Espiritu Santo. Concurrently, the solution must be one that can seamlessly coexist with local customs and lifestyles. Doing so will enable the people to autonomously sustain the project, and take it beyond our initial, envisioned scope.

To critically evaluate the fitness of the proposed ideas for the fulfilment of our mission, as well assess their feasibility as a real engineering solution, we have identified five key needs that will govern our final initiative:

## 1 Tackle Multiple Local Issues

As detailed in our introduction, Vanuatu (specifically Espiritu Santo) is faced with a variety of development issues with respect to water supply, sanitation, farming and food production as well as shelter. Thus, an ideal final project would be one that, whilst still maintaining the integrity of its primary purpose, can also help provide solutions to other related issues. This is about maximising the impact of our initiative to place Espiritu Santo in good stead to undergo broad sustainable development into the future.

## 2 Opportunity for Future Development

Being a developing nation, the landscape of Vanuatu and its communities is subject to continual change during and beyond our initial intervention. Consequently, an effective engineering solution would be one that can easily be adapted to complement new opportunities and challenges that may arise throughout the initiative's lifetime. This is about ensuring the sustainability of our initiative, and its ability to cause a prolonged impact on benefitting communities.

## 3 Self-Sustainable

In accordance with our mission, our initiative will be one that we will no longer have to have a direct involvement with beyond the initial intervention. This is about developing the local communities' capacity to achieve their own development objectives, and minimising their reliance on external support to consolidate themselves as a self-sustaining society.

## 4 Low Environmental Impact

Being a society that is reliant on agriculture and fresh produce, the environment is one of Vanuatu's most valuable assets. Therefore, any initiative aimed at benefitting local communities must always be informed by an ongoing awareness of its potential detriments to the natural landscapes of Espiritu Santo. This is about appropriately positioning our project within the context of the grander realities that define life in Vanuatu - making sure that it does degrade what they consider their homes and sources of livelihood.

## 5 Simple to Adopt

In order for our initiative to be accepted and integrated into daily living, it must be something that can easily coexist with established local lifestyles and customs. For our initiative to be self-sustainable, locals must never consider our solution to be incongruous, as this limits its potential for it to be maintained into the future. Concurrently, our initiative should be something that locals themselves can adapt or transform to better suit their changing needs over time. This is about making our project *theirs* instead of *ours*.

**Along** with these identified needs, we have also devised two supplementary “wants” for our final project in Espiritu Santo:

## *1 Innovative Concept*

Our initiative should be something that is not being currently done by somebody else. Whilst we can draw inspiration or build on ideas that have been successfully employed in the past, merely repurposing an existing concept or design for communities in Espiritu Santo is unlikely to holistically target their specific needs.

## *2 Interesting*

A comprehensive and successful initiative requires passionate and interested participants throughout the duration of the project. To maintain levels of morale and commitment during the arduous times that will inevitably arise, having a concept that is interesting will be of great value.

# 4.1 Evaluation of Proposed Ideas: The Kepner-Tregoe Table

In order to systematically evaluate the proposed ideas against the established criteria, a Kepner-Tregoe Table was employed as a means of deciding on the optimal concept to pursue as our final project.

| **Proposal** | *Refrigeration* | | | *Water Purification* | | | *Smokeless Cooking* | | |
|---|---|---|---|---|---|---|---|---|---|
| **Criterion** | Weighting (/10) | Rating (/10) | Score (/100) | Weighting (/10) | Rating (/10) | Score (/100) | Weighting (/10) | Rating (/10) | Score (/100) |
| **Need** | | | | | | | | | |
| Address multiple issues | 8 | 9 | 72 | 8 | 8 | 64 | 8 | 6 | 48 |
| Future development opportunities | 8 | 9 | 72 | 8 | 6 | 48 | 8 | 7 | 56 |
| Self-sustainable | 9 | 9 | 81 | 9 | 6 | 54 | 9 | 8 | 72 |
| Low environmental impact | 9 | 9 | 81 | 9 | 7 | 63 | 9 | 7 | 63 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Simple to adopt | 10 | 8 | 80 | 10 | 6 | 60 | 10 | 7 | 70 |
| **Want** | | | | | | | | | |
| Original concept | 7 | 8 | 56 | 7 | 8 | 56 | 7 | 5 | 35 |
| Interesting | 6 | 7 | 42 | 6 | 8 | 48 | 6 | 5 | 30 |
| **Total** | | | 484 | | | 393 | | | 374 |

# 4.2 Qualitative Analysis of Proposals Against Criteria

## 4.2.1 Refrigeration

Address Multiple Issues

With over 75% of Vanuatu living without access to electricity, refrigeration will enable many remote Espiritu Santo communities to preserve food for a longer duration of time, helping them get through periods of poor yield from their subsistence farms. Currently, their livelihoods are greatly influenced by uncontrollable climate influences and so, such a device will reduce communities' vulnerability to unforeseen circumstances that affect their food sources.Additionally, the increased lifetime of perishable foods will make it more feasible for remote communities to consume meat (especially fish) on a frequent basis, reducing their reliance on imported, packaged goods. Reduction in food wastage will also come as a benefit to the implementation of such a system, resulting in the achievement of greater economic efficiencies with regards to the domestic product. Refrigeration can also be utilised to store temperature sensitive medical supplies and vaccines, addressing the current issue of unreliable deliveries of medical goods following periods of adverse weather conditions.

Future Development Opportunities

With schemes being implemented involving the gradual rollout of small solar panels to remote communities, the cooling capacity of this refrigeration system can potentially be improved by implementing low power thermoelectric coolers. Furthermore, better access to higher quality materials over time could potentially improve the portability of this system. Subsequently, the design has the potential to be adapted so that it can be used to transport temperature sensitive vaccinations into dense, remote regions of the island.

Self-Sustainable

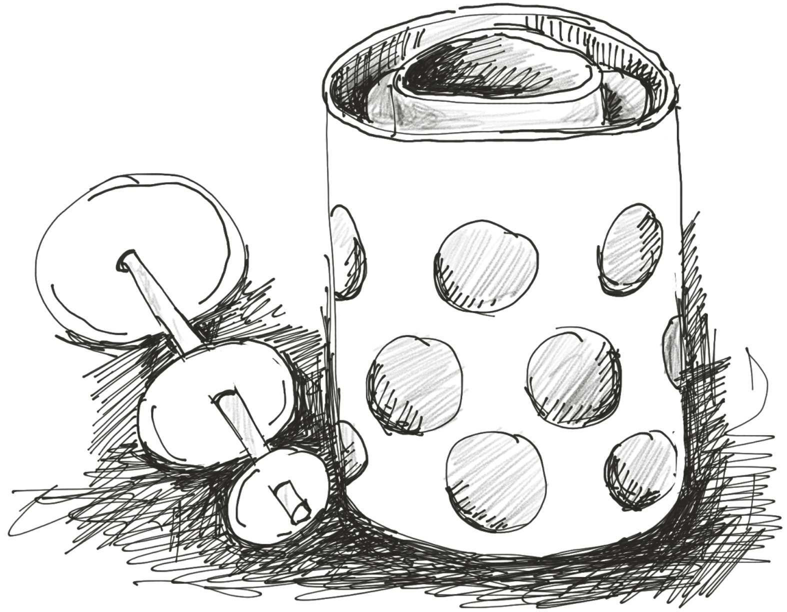
A simple design that can operate purely off of abundant local resources, very little external intervention will be required to sustain this concept. Relying on a purely natural physical process, the absence of mechanical or moving components further guarantees the longevity of this device.

Low-Environmental Impact

Operating off a natural physical process, the device is unreliant on chemical refrigerants or electricity and thus there are no harmful emissions or pollutants that could detriment the environment. Furthermore, the thermal mass (water) utilised to initiate the cooling process can be recycled and reused, eliminating the potential for thermal pollution when discarding elements of the device.

## Simple to Adopt

The refrigeration mechanism is very easy to actuate and aligns with existing agricultural practices involving water - there are no new technologies or techniques that the locals need to be trained for. With a minimal footprint and friendly looking exterior (looks like a pot), the device can also seamlessly integrate into existing households without appearing incongruous or foreign.



No-energy refrigeration model designed by Emily Cummins in 2008. It operates off of a process known as evaporative cooling and was designed to be used in Africa.

## 4.2.2 Water Purification

### Address Multiple Issues

Addresses a very important issue in securing fresh water during the frequent dry spells characteristic of the Vanuatu climate. Along with a positive impact on the physical wellbeing of communities, this device would have a beneficial effect on agriculture as well as the quality of local sanitation.

### Future Development Opportunities

Potential to alter the composition of the device in response to access to more affordable, durable resources in Vanuatu. The potential for this device to adapted for other purposes is limited however, due to the rigidity of its function and scope of design.

### Self-Sustainable

Somewhat self-sustainable due to its simple operation, however the presence of electrical components (which could be difficult to source in remote regions) means that external intervention is likely inevitable in the case of malfunction or faulty design. Furthermore, lack of local expertise in fields related to electronics may also hinder the initiative's potential to evolve autonomously.

### Low-Environmental Impact

Solar power is a very clean source of energy for this device, however the electrical components and circuitry may be difficult to dispose safely without polluting the environment. Furthermore, the hot byproducts of osmosis and boiling can lead to the thermal pollution of the ocean and other bodies of water, which can have a detrimental impact on local ecosystems and promote algal blooms.

### Simple to Adopt

Though relatively simple in function, the device may not necessarily be the most simple to adopt as it involves the execution of techniques and mechanisms that are foreign to locals. Furthermore, psychologically, its unique aesthetic appearance may come across as intimidating and complex to locals, who may consequently be tentative to adopt it.

## 4.2.3 Smokeless Cooking

### Address Multiple Issues
The reduction of smoke emissions can improve the general wellbeing of locals by reducing the risk of contracting harmful diseases such as pneumonia as a consequence of smoke inhalation. Furthermore, the reduction in carbon monoxide emissions can have a positive effect on the local air quality of communities and bring down instances of acid rain. However, ultimately, the project is relatively limited in its scope with regards to providing a holistic benefit to communities of Espiritu Santo.

### Future Development Opportunities
Improvements in the functional design of the device, particularly with regards to the efficiency of heat energy transfer, can be implemented upon further investment into the research and development of the idea. Furthermore, the longevity of the system can be prolonged through improved access to more durable materials.

### Self Sustainable
Very simple in functional design and construction, the smokeless cookstove has the potential to be a sustainable initiative. The lack of mechanical/moving components means that the majority of potential breakdowns in the structure will be easy to mend by locals, using locally available materials and tools.

### Low Environmental Impact
The construction of the device itself will have minimal impact, as it is likely to be made of mud brick (which is particularly resistant to high temperatures). However, the nature of burning firewood is inherently detrimental to the environment, even when minimising smoke, as the byproducts of the combustion reaction still need to be disposed of safely.

### Simple to Adopt
The cooking stove is merely a small adaptation that complements existing cooking methods over open fires. Consequently, the implementation of this project will not disturb any local customs and practices, rendering it relatively easy to be adopted by the locals.

# 4.3 Final Verdict

It is clearly evident from both the quantitative results of the Kepner-Tregoe table, as well as a qualitative appraisal of each of the project proposals against the devised criteria, that the **no-energy refrigeration** initiative is the project that our team should take forward. Complementary to both our mission as well as the defined needs of the communities of Espiritu Santo, such an initiative has the potential to create a sustained positive impact on the island nation, with plenty of opportunities to grow and evolve in the future.

# 5. Problem Definition

## Food wastage

Agriculture plays an important role in the Ni-Vanuatu's life. Without a refrigerating system, food losses are common in places like Vanuatu where the food becomes spoilt and wasted due to the high humidity on the island, leaving detrimental impacts on the incomes of families. Produce is often wasted when it is in season. For example, when yams are in season, the market is flooded with yams, the price of yams drops. However, without the presence of refrigerating systems and other effective storage methods, the yams have to been consumed quickly, and as a result, no yams can be found a few months later, as much of the produce is wasted.

## Unreliable Yield

Climate change is affecting the harvest of produce, causing concerns for food security within communities which rely heavily on subsistence farming. For example, the intense rainfall caused by the two La Nina events have adversely impacted the yield of mangoes as the extreme weather conditions can cause the trees to fruit early, late or not fruit at all.[17] Furthermore, it requires a lot of time and effort to repair the fields that were destroyed by cyclones productive. Therefore, it is essential to preserve food for cyclone seasons. Many Vanuatuans do not prepare for disasters as they do not know how. This highlights the need for the communities to have protocols that reduces the impact of a disaster. A possible strategy to overcome the critical weather conditions is to develop ways to store and preserve excess food produce for the cyclone season when the yield of crops is limited.

## Restrictions in the diet

Although 75% of the households in Vanuatu is involved in the fishing industry, Vanuatu has the lowest per capita fish consumption in the South Pacific region. Due to the underdeveloped transportation system, and lack of refrigeration, the fish prices increase and thus, only 27% of the protein is obtained from fish and shellfish for regional Vanuatuans.[20] Fish contains approximately 17 - 20% of protein and is a source of important minerals and vitamins.[20] However, the Ni-Vanuatu consumes imported chicken or canned food as their source of protein due to the competitive pricing between imported food and locally produced fish.

Furthermore, the absence of a refrigeration system means that the diet of the Ni-Vanuatu is often limited. As food must always be consumed fresh, perishable food like meat do not form a part of their diets, as they cannot be stored. This increases the community's reliance on unhealthy canned food imports, which has adverse effects on the wellbeing of the people. These tinned imports are characteristically high in preservatives and saturated fats.

## Storage temperature for medicines

There is currently only one hospital in Espiritu Santo which is located in Luganville, with only a few aid posts and dispensaries scattered across the rest of the region. With less than 25% of roads paved in Vanuatu, only one two-lane main road has been paved that runs from Luganville to Port Olry. The quality of the paving in other connecting roads is inconsistent. .

This means that when a prescribed temperature sensitive medicine is taken home, the patient is required to walk a few kilometres to the main road to wait for a truck to be sent home. However, there is no way for the patient to store the medicine at home. Even with most other types of medications, the best temperature for storage is below 25℃, and since the temperature in Espiritu Santo is relatively warm, the medication may lose its effectiveness prior to the expiring date.[18]

Deliveries by health institutions to regional dispensaries are also made difficult following periods of heavy rain, where much of the villages become inaccessible.

Northern District Hospital located in Luganville, Vanuatu. (Source: The Electives Network)

# 5.1 Current Methods of Food Preservation

The current food preservation methods in Vanuatu are designed for the maintenance of staple food crops like breadfruit, yam, sweet potatoes and cassava - foods that constitute the Ni-Vanuatu's day to day diet.

## Using Sea water

The traditional method of storing breadfruit involves the use of salt water, where the prepared breadfruit is placed into a salt water pool lined with coconut and clean banana leaves. The breadfruit is then covered with more banana leaves and coconut leaves and the pit is sealed with rocks. Another way of using salt water to preserve food is to place the fruits in a banana lined woven coconut baskets. After the fruit becomes soft, the pulp is placed in another basket. These are then placed in a 'V' shaped pit lined with more banana and coconut leaves. Sea water is sprinkled over the food and finally the pit is sealed with rocks. The pit is then left for 1 year.[19]

## Drying

The breadfruit can also be preserved by using a method of drying. The stem and soft core is removed and slowly dried over hot embers[19].

These traditional methods of using salt water and drying is still practiced today, however, this method relies heavily on labour, as seawater has to be accessed and only the elders of the community know the methods of storing food as the younger generation are reluctant to receive these conventional skills.[19] By implementing a refrigerating system, the amount of workload for food preservation will be reduced significantly. The perishable food can remain its original texture and also be safe to eat for weeks. Furthermore, refrigeration would enable for a greater variety of foods to be preserved for consumption.

# 5.2 Case Studies

Examples of passive refrigeration methods are taken into consideration when generating our ideas for a no-energy refrigeration system. These designs have been evaluated and served as a source of inspiration from which we can devise our own design criteria and requirements.

## 5.2.1 Case 1: The Coca Cola Bio Cooler

The Coca Cola company designed The Coca Cola Bio Cooler in Colombia for the community to enjoy iced coke. The bio cooler employs an evaporative cooling mechanism by watering the plant that is on the top of the Bio Cooler and as the water evaporates, it causes the chamber to cool down.[21] Not only so, a mirror is incorporated in the chamber which captures the heat from the sun. As a result, proprietary gases in the chamber condense into liquid, thus creating a cooling effect.[21] The Bio Cooler is said to cool the temperature inside the chamber more effectively in hotter conditions.[21] Like Colombia, Vanuatu is warm throughout the year. A similar refrigeration method that uses this evaporative method could potentially be employed into our design of the no-energy refrigerator. However, measures must be put in place to reduce the relative humidity of the surrounding environment for evaporation to occur.

*Coca Cola Bio Cooler*
*Source: News Atlas*

## 5.2.2 Case 2: The Persian Ice House

Yakhchal, the Persian ice house is a building which allowed the Persians to make ice in winter and store it throughout the summer in the desert. Water is led into the Yakhchal from the *qanat*, a underground water delivery channel that transports the water to the surface of the ground.[22] The water freezes in winter when it is at rest on the ground.

The building allows cold air to enter through the entries at the base of the structure and which eventually descends to the lowest part of the building.[23] Not only so, the conical shape of Yakhchal along with the opening at the top of the structure allows hot air to be guided upwards and out.  The building itself has thick walls and tare built from a water resistant mixture made of sand, clay, egg whites, lime, goat hair, and ash in certain proportions.[23] This allows the Yakhchal to be an effective insulation throughout the year as it is heat resistant and impenetrable by water.

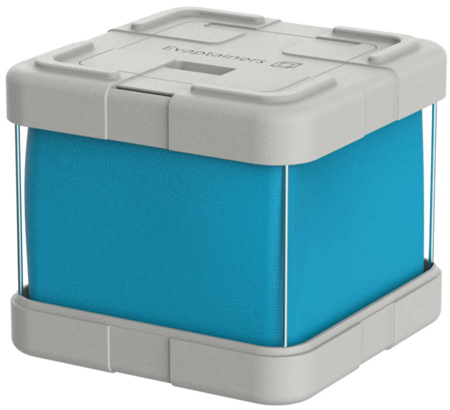
A well insulated chamber is the key to this design, similar designs can be applied to our project since the insulation can refrain hot air from getting into the chamber and the cold air escaping out. The mechanism by which this structure creates ice may potentially be adapted to be able to cool a smaller insulated chamber, containing food.

*The Yakhchal*
*Source: Misfits' Architecture*

## 5.2.3 Case 3: EV-8 Evaptainers

The EV-8 is a product designed by a US organisation Evaptainers. It is a portable, lightweight refrigerator that stores approximately 60L of perishable goods. PhaseTek is the patented technology of the Evaptainers that activates in EV-8 once water is poured into the internal tank.[24] Heat is then drawn out from the interior by the walls via evaporative refrigeration. The EV-8 does not require any energy to operate, and does not emit any greenhouse gases, thus it is environmental friendly. The interior of EV-8 can cool down 15 to 20 degrees from ambient temperatures,  and it works best at dry and arid conditions.

This design has qualities such as portable, lightweight and environmentally friendly that our team can adopt into our planning phase for the requirement of our fridge. Qualities like portability and lightness is advantageous during natural disasters as the users can store a week's worth of food. This can enable families to sustain themselves whilst they rebuild, or whilst they wait for aid to arrive.



The compact EV-8, which operates off of evaporative refrigeration. (Source: Evaptainers)

# 6. Design Criteria

**Upon** conducting a detailed appraisal of the current physical and social landscape of Espiritu Santo, we arrived at the following criteria for our refrigeration system:

## 1 Refrigerate down to 4 degrees Celsius

The average monthly temperature in Espiritu Santo stays steady at about 25.5 degrees Celsius throughout the year.[25] With relative humidity levels reaching up to 90% during the summer, these conditions make it an almost impossible task for families to keep their root crops fresh for more than a couple of days upon ripening, or implement any high quality protein sources into their diet.

A temperature of 4 degrees celsius makes it possible for communities in Espiritu Santo to store fresh fish for up to 2 days, and cooked fish for 4 days. Fresh beef can be stored safely for up to 5 days. Currently, the lack of a means for preserving their abundant fresh produce has resulted in locals relying on imported tinned meats as their primary source of protein.

Furthermore, a temperature of 4 degrees celsius prolongs the lifetime of ripened root crops, which may otherwise go to waste in the humidity. A means of further preserving the yield from subsistence farms means communities are less vulnerable to unexpected climatic conditions which may otherwise affect the volume of their produce. It also opens up the opportunity for excess produce to be preserved longer for resale at roadside village markets - a practice that is commonplace in Espiritu Santo, but has not quite reached its full economic potential due to technical barriers.

## 2 Protect food from pests

Currently, produce in Espiritu Santo is susceptible to being damaged by pests including the Common Mynah, Giant African Land Snail and Pacific Rat. Therefore, creating a sturdy structure that can isolate foodstuffs from both pests and climatic conditions will go a long way in further securing the livelihoods of communities from damage.

## 3 Portable

Our ideal product will be dynamic in the sense that it can be moved to better adapt to changing climate conditions, as well as the changing physical landscapes of the benefitting communities. Furthermore, portability opens up the opportunity to be able to transport fresh food to places in need, or maintain a supply of crucial foodstuffs during periods of frequent natural disasters. It will provide communities with a means of sustaining themselves in crisis situations, until aid arrives.

## 4 Construct locally using readily available materials

Much of the developing communities on the island are incredibly remote, and are particularly difficult to access following period of rainfall. Consequently, it can often be an unviable task to transport goods from the main city Luganville, to villages in need.

Therefore, in order to streamline the implementation process of the device, as well as encourage adaptations that better suit the needs of individual communities, our product should ideally be constructed using known local manufacturing techniques, as well as readily available materials. Minimising the need for external intervention will go a long way in ensuring the sustainability of this project long after our initial involvement.

## *4 Be simple in design and construction*

Manufacturing technologies and techniques are quite limited, particularly in the remote regions of Espiritu Santo. There is little to no access to machine tools and much of the utensils and upholstery are constructed by hand. Therefore, in order to encourage local manufacture, as well as simplify the resolution of any faults or breakdowns in the structure of the device, the final design should be relatively simple in nature. Again, this is about minimising the need for external involvement in the implementation process of this device, and making the product feel more like ***theirs*** as opposed to ***ours****.*

## *5 Simple to operate and maintain*

No new solution or product will be adopted by any community if it is cumbersome or creates inconvenience. Therefore, we are committed to coming up with a final design that minimises any physical involvement with respect to the operation of the device, so as to reduce our interference with established community practises and customs. In particular, time taken to maintain and operate this refrigerator should not take away from valuable time required by locals on farms or their involvement in religious or cultural rituals.

# 7. Refining the Design - Part 1: The Refrigeration Mechanism

# 7.1 Design Parameters

The refrigeration mechanism is arguably the most crucial aspect of our final design, as it will be responsible for bringing the temperature of the food down to an ideal level. There are a number of different potential proven processes that we may employ into our final design, and each of these are described below. The optimal mechanism for our particular design however will be assessed and ranked against these following categories:

## 1 Cooling potential

How low can the temperature go inside a refrigerating chamber, given the inherent climate conditions of Espiritu Santo?

## 2 Cost

What is the financial burden of implementing such a mechanism into our final design?

## 3 Reliability

Is there any potential for this mechanism to fail, even if the climate conditions are optimal?

## 4 Ease of Use

Is there much user involvement required to achieve the cooling effect?

# 7.2 Option 1: Evaporative Refrigeration

Evaporative refrigeration is a commonly employed refrigeration mechanism that takes advantage of a purely physical process in order to reduce the temperature of an insulated chamber, often containing food or water. The well-known *Zeer Pot* for example is created by placing one earthenware pot inside another, filling the space between them with sand (or an alternative substance that can be soaked), and then wetting it.[26] Food is then stored inside the chamber of the inner pot, and then covered by a wet towel or lid to isolate the contents from the external environment.

The evaporation of the water from the sand draws heat away from the inner pot, cooling the chamber and its contents. The main advantage of this refrigeration system is that it works in harsh climates that may not otherwise have a means of keeping food cool without access to electricity. Furthermore, the water used for evaporation does not need to be clean, meaning that this kind of technology can even be suitable in remote or developing communities with little access to clean drinking water.

## The Physics Behind the Process

The physical principles by which evaporation stimulates cooling can be seen in our very own bodies - sweating enables us to regulate our body temperature. Temperature, by definition, is a measure of the average kinetic energy contained by the molecules in a substance.[26] In certain conditions however, the molecules near the surface of the liquid collide with one another with enough force to overcome the intermolecular forces in the liquid, causing it to escape (evaporate).[26] Oftentimes, the stimulus for this kind of process is the increased energy content of the molecules due to heat.

As more and more of these high kinetic energy molecules escape, or evaporate, the remaining molecules have lower kinetic energy on average.[26] This happens to be the very definition of cooling - to lower the average kinetic energy content of the particles contained within a structure.[26]

The Zeer Pot involves soaking Sand with water in order to encourage evaporative cooling

## *Limit to the Cooling*

The extent to which evaporative cooling can lower the temperature of a space is dictated by a quantity known as the wet bulb temperature. Regardless of how much liquid evaporates, or the rate at which it evaporates, the minimum temperature that can be reached solely through direct evaporation is the wet bulb temperature [26]. Common means to increase the cooling effect of the evaporation process involve feeding the evaporative cooler with air that has already been chilled by another cooler - creating a chain of evaporative coolers in an effort to overcome the barrier of the wet bulb temperature.[26] Such a device is often very complex however, requiring many mechanical components which are prone to failure and can significantly reduce the mean time between failures.

Minimum temperature possible due to evaporation

| *Relative Humidity %* | Ambient Temperature in Celsius | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **18.3** | **21.1** | **23.9** | **26.7** | **29.4** | **32.2** | **35.0** | **37.8** | **40.6** | **43.3** | **46.1** | **48.9** |
| **10** | 6.7 | 7.8 | 9.4 | 11.1 | 12.8 | 14.4 | 15.8 | 17.2 | 18.6 | 20.0 | 21.7 | 23.3 |
| **20** | 7.8 | 10.0 | 11.7 | 13.3 | 15.0 | 16.7 | 18.6 | 20.6 | 22.2 | 23.9 | 25.8 | 27.8 |
| **30** | 9.4 | 11.1 | 13.1 | 15.0 | 16.9 | 18.9 | 21.1 | 23.3 | 25.3 | 27.2 | | |
| **40** | 11.1 | 13.3 | 15.3 | 17.2 | 20.0 | 21.7 | 23.9 | 26.1 | 28.1 | 30.0 | | |
| **50** | 12.2 | 14.4 | 16.7 | 18.9 | 21.1 | 23.3 | 26.1 | 28.9 | | | | |
| **60** | 13.9 | 15.6 | 18.1 | 20.6 | 23.1 | 25.6 | | | | | | |
| **70** | 15.0 | 17.2 | 19.7 | 22.2 | 25.0 | 27.8 | | | | | | |
| **80** | 16.1 | 18.9 | 21.4 | 23.9 | 26.7 | | | | | | | |
| **90** | 17.8 | 20.6 | 22.8 | 25.0 | 28.3 | | | | | | | |
| **100** | 18.3 | 21.1 | 23.9 | 26.7 | 29.4 | | | | | | | |

*Source: Rebuilding Civilisation*

Consequently, as seen from the table above, locations characterised by high humidity will not be able to experience the full benefit or value of an evaporative refrigerator, due to their higher characteristic wet bulb temperatures. Espiritu Santo, for example, has an average wet bulb temperature in the mid 20's all throughout the year.

# The Structure of an Evaporative Refrigerator

## *The Liquid*

Water is the most practical evaporating agent for this kind of system as it is readily available in most locations; even if it is not in a potable state. Furthermore physically, water's high specific heat capacity means that it is capable of removing a large amount of heat per kilogram of evaporation, which accentuates the cooling effect.[26]

The material to hold the liquid should ideally be able to carry a large volume of water, whilst providing a large surface area for evaporation.[26] Possible materials include sponges or charcoal, however most commonly, sand is used do to its easy access and larger surface area.

## *Container*

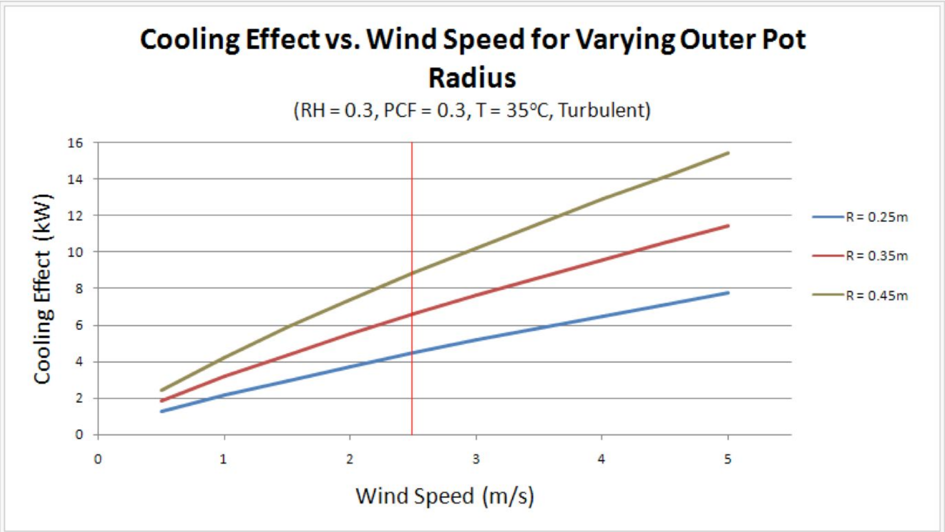
The structure of the chamber should ideally be made of any material that conducts heat. Conductive materials will better facilitate the transfer of heat away from the chamber's contents. In addition to this, maximising the surface area will also lead to increased rates of cooling as there is a greater interface for interaction between the system and the outside environment. A high surface area to volume ratio is ideal, meaning that a tetrahedron would be the optimal shape, however due to the logistical difficulties of constructing such a device, spheres are more commonly implemented.[26] This also means that it is generally better to have several small devices than one large device.[26] Ideally, to promote evaporation, the outer shell also needs to be porous.

## *Other Measures to Maximise Performance*

1. Place device in shade, ideally areas where there is a light breeze
2. Elevating the device will maximise the number of sides that can undergo evaporation.

*Source: Appropedia*

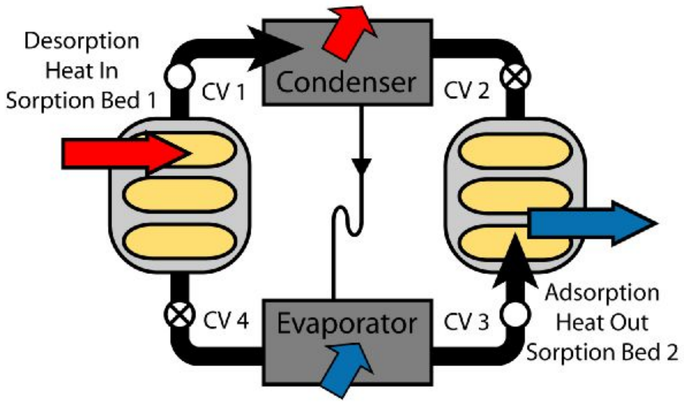
Notice that the larger the radius of the outer pot of a Zeer, the greater the cooling effect.



# 7.3 Option 2: Sorption Heat Driven Cooler

The term "sorption" refers to both liquid absorption and solid adsorption processes, both of which can be employed to generate a refrigerating effect.[27] It relies on a multistep heat-reliant chemical process that results in a pressure drop that cools down its surroundings.[28] The benefit of this kind of system is that it can harness the sun's radiation as the heat source that stimulates the chemical process.[27]

Such a mechanism has been rigorously studied and investigated as a potential viable solution to the problem of delivering no-energy refrigeration to developing nations. A potential product was introduced by Adam Grosser in 2007, but the fact that his (and others') mechanisms have not yet gained any traction lends credence to the idea that it is too complex of a mechanism to be implementable.




*Basic principles of a sorption heat driven cooler. (Source: Sustainable Thermal Systems Laboratory)*

## How it works

There are two main phases to the sorption cooling process: the heat and the refrigeration phase.

During the heat phase, high temperatures increases the pressure inside of a chamber, stimulating a refrigerant to free itself from its bonds with an absorbent material.[28] The now vaporised refrigerant is then driven into a separate, cooler chamber, where it begins to condensate.

During the refrigeration phase, the low pressure in the cooler chamber causes the refrigerant to evaporate – a process that draws in heat and cools its immediate surroundings.[27] The vapour then recombines with the absorbent material from the heat phase, which can be a solid (e.g charcoal, calcium) or a liquid (water).[27]

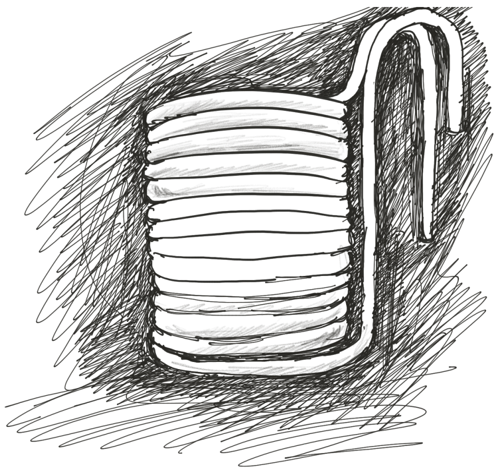
This specific example is that of an intermittent operating system, where heat is applied only once per day. Continuously operating systems also occur, but often necessitate the implementation of complex pumping systems.[28]

Sorption units are advantageous in theory because they can be designed to contain no moving parts (in an intermittent operating system), meaning that maintenance personnel are less likely to be necessary.[27] Furthermore, they can be implemented using locally available fuels such as biomass and solar energy.[27]

## Structure

### *Evaporator*

The evaporator is the component in the system that has the role of cooling the designated space. Shapes such as helices are often recommended as they effectively increase the surface area of the evaporator to maximise the rate of cooling.[29] Creating such a shape would necessitate the use of a malleable material such as copper, which also has very good heat transfer properties and is easy to work with.[29]



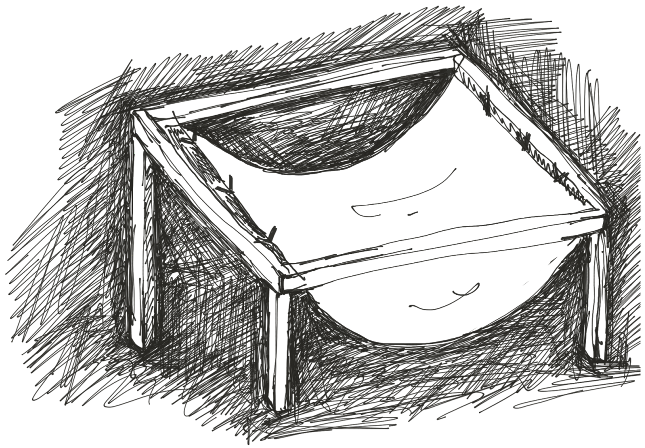
*Ideal evaporator model constructed out of copper.*

### *Condenser*

The condenser is responsible for the heat phase of the absorption cooling process. Its design should ideally be very similar to the evaporator coil design but at a larger gauge to promote easy transfer of liquid refrigerant.

### *Solar Collector*

If the heat is to be sourced from the sun's radiation, then a solar collector is necessary to concentrate enough heat to initiate the separation of the refrigerant from the absorbent material.

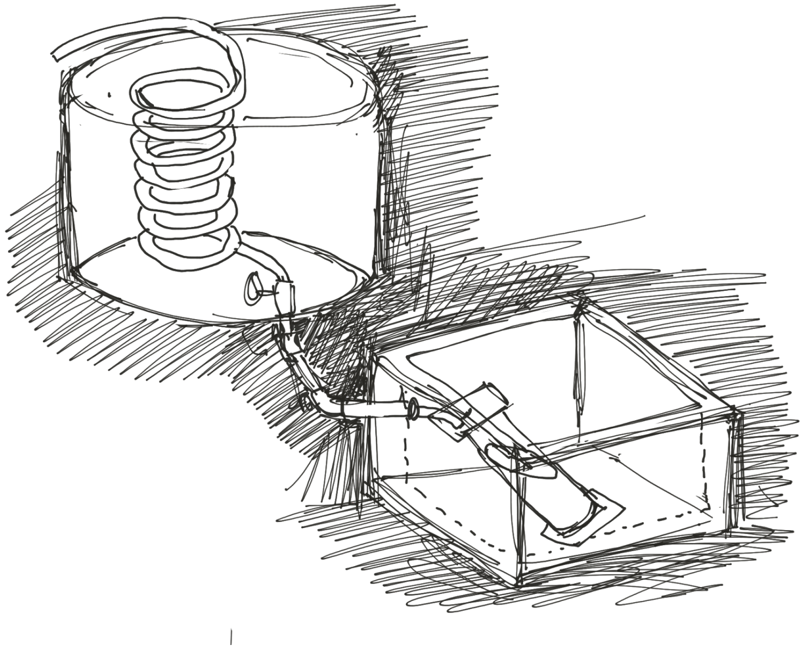


*Rough model of the solar collector for such a system.*

## *Absorbent and Refrigerant*

An absorbent/adsorbent and refrigerant are necessary to actually facilitate the cooling process of this particular system. Some common pairs of substances include:

1. Zeolite and Water
2. Silica gel and Water
3. Activated Carbon and Methanol
4. Activated Carbon and Ammonia
5. Activated Carbon and Ethanol



*Condenser coil and evaporator placed in the context of a potential final model.*

# 7.4 Option 3: Thermoelectric Cooling

Thermoelectric coolers are solid state heat pumps that are commonly employed for applications requiring temperature stabilisation or cooling below ambient temperatures. Thermoelectric cooling is often preferred over other traditional cooling methods due to its greater benefit to the environment, operating without a reliance on chlorofluorocarbon or refrigerant emissions.[30] They are also low in weight and size, and do not necessitate frequent maintenance, due to their lack of moving parts (has a mean time between failure of 100,000 hours). Current applications of thermoelectric cooling include Thermocyclers in aerospace and defence technologies (due to their resistance to extreme conditions), as well as in single-stage thermoelectric coolers for maintaining constant viscosity in ink jet printers.[30]

## How it works

Thermoelectric coolers operate on a process known as the Peltier Effect, which aims to create a temperature difference between two electrical junctions. A typical thermoelectric module consists of two thin ceramic wafers with a series of P and N doped semiconductor materials sandwiched between them.[31] When current flows through the junction between the two conductors, as a consequence of an applied voltage, heat is removed at one junction and cooling occurs.[30] This decrease in temperature at the “cold-side” of the junction results in the absorption of heat from the environment.

The Peltier heat absorption is given by W = PIt:

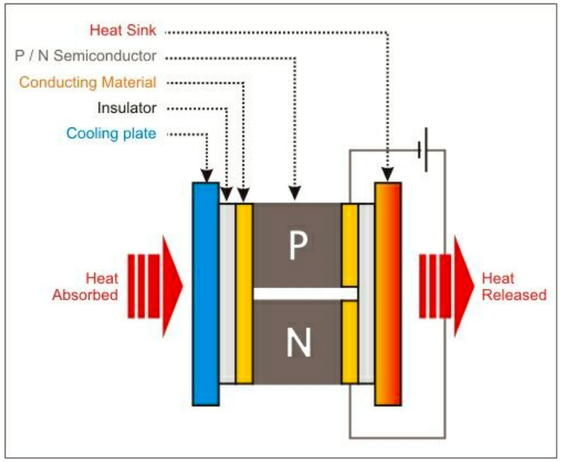
1. P = Peltier Coefficient
2. I = Current
3. t = time

A single stage thermoelectric cooler can produce a maximum temperature disparity between the two ends of the junctions of about 70C.[30] A beneficial side-effect of the Peltier effect is that it can be used to both heat and to cool, depending on the direction of the current.

## Structure

The material by which thermoelectric coolers are constructed require careful consideration. In order to promote adequate heat transfer, the heat sink and “cold-side” mounting surfaces require construction out of materials which have high thermal conductivity (e.g copper or aluminium).[31] Insulation hardware on the surface conversely require materials that have low thermal conductivity (e.g polyurethane or stainless steel) in order to reduce heat loss.[31] Typically, the effects of condensation and humidity are alleviated through the use of perimeter seals, which eliminate corrosion and thermal/electrical shorts which may damage the module.[31]

With respect to the junctions themselves, semiconductors are most typically the material of choice. The module is generally constructed using two contrasting types of semiconductor (N-type and P-type), as their different electron densities facilitates the actuation of the Peltier effect.[32]




*Source: Active Cool*

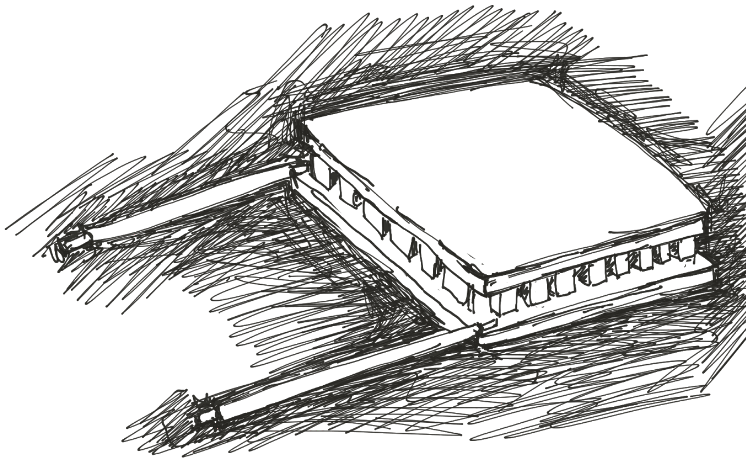
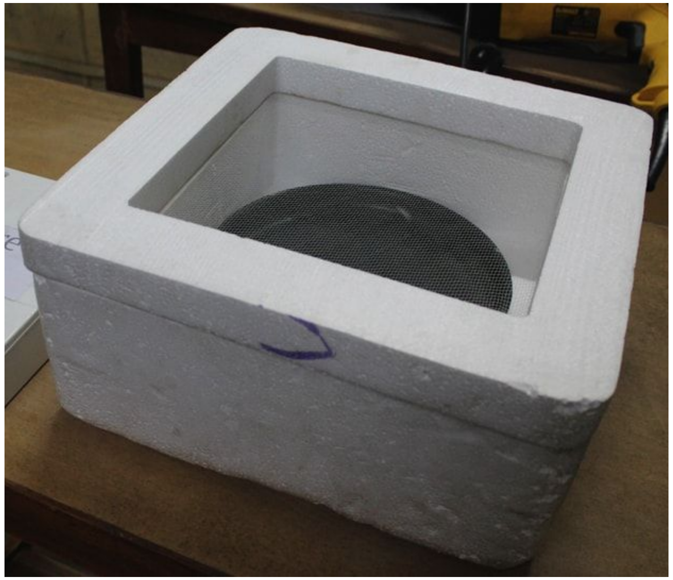


*Illustration of a typical Peltier Cooling module that operates on the process of thermoelectric cooling*

## 7.5 Option 4: Night Radiation Cooling

Night radiation cooling is another example of a purely physical process that has been employed throughout history as a means of providing cooling in remote and developing environments. During night sky radiative cooling, a thermal medium emits heat in the form of long-wave infrared radiation towards the sky, which acts as a low-temperature heat sink.[33] By morning, insulating panels are placed to isolate the cool water from solar radiation, and the "pond" is then situated on top of a chamber in order to cool the immediate space below.[34] The warm air of the chamber rises towards the cool ceiling, losing its heat immediately.

In antiquity, nocturnal radiative cooling was used by the ancient people of Iran to form ice in the desert, even during evenings where ambient temperatures were above freezing.[33] Such a mechanism has also been employed in the roofs of homes to provide supplementary, energy efficient cooling in warm climates.



*A primitive ice maker designed by Tata Technologies in India, operating off the principles of night radiation cooling. Source: Tata Centre for Technology and Design*

## How it Works

Radiation cooling to the night sky is based on the principle of long-wave radiation heat loss from one body to another at a lower temperature.[44] Heat from the earth is always radiating back to space in order for the surface to maintain thermal equilibrium with the sky - otherwise, the earth would continue to heat up to extreme temperatures. Evidence of this radiant heat leaving the earth's surface is visible on some mornings, where a layer of frost forms on rooftops and cars, even if ambient air temperatures were well above freezing.[44] Such frozen condensation is evident when surfaces lose heat energy to the night sky faster than the surrounding warmer air could replace it by natural convection.[44]

Roofs of buildings radiate heat day and night at an average rate of between 75-100 W/m$^2$.[37] Whilst during the day, this radiative heat loss is offset by solar radiation gains on the roof, at night, this process has the capacity to cool air or water down 6 to 22 degrees below ambient.[37] The radiation emitted by the earth's surface mostly passes through the atmosphere unabsorbed (wavelengths between 8 to 14 micrometers make up a continuum of scarcely absorbed radiations), and is emitted directly to space.[44]

The net cooling achieved by such a system is achieved as a result of both radiative cooling, as well as the convective heat exchange between the radiator and the air. The equations that govern these physical processes appear as follows:

*Stefan Boltzmann-Law*

$$R = \sigma \times e_r \times (T^4_r - e_s \times T^4_a)$$

- $R$ = *net radiative cooling (W/m^2)*
- $\sigma$ = *Stefan-Boltzmann constant*
- $e_r$ = *emissivity of the radiator*
- $T_r$ = *absolute temperature of the radiator (K)*
- $e_s$ = *emissivity of sky*
- $T_a$ = *absolute temperature of the air (K)*

*Convective Heat Exchange*

$$Q_c = h_c \times (T_r - T_a)$$

- $Q_c$ = *Convective heat exchange (W/m^2)*
- $h_c$ = *convective coefficient*
- $T_r$ = *absolute temperature of the radiator (K)*
- $T_a$ = *absolute temperature of the air (K)*

Both these equations illustrate the significance of often uncontrollable environmental conditions in bringing about effective cooling. Specifically, observed temperature drops on cloudy nights are generally more temperate as a result of the increased sky emissivity [40]. The outgoing radiation from the thermal mass is offset by the incoming radiation from clouds.

## Structure

Whilst active cooling systems can circulate a working fluid in order to accelerate the cooling effect, passive systems purely consist of containers filled with a thermal mass (generally water) to moderate diurnal temperature swings.[33]

*Shape*
The reported ideal shape for the container is a deep paraboloid with a broad flat radiating plate.[41] The parabolic shape helps to minimise the convective heating and wind losses that will hinder the cooling process. It also serves to maximise the surface area by which outgoing radiation can reflect towards the sky, as opposed to being trapped within the walls of the container. Coating the interior of the radiator with a reflective material (such as mylar) or white paint (which has an emissivity value of 0.9) can further augment this effect.[34] The white paint can also have the added benefit of reducing the daytime solar radiation gain.[38]

Finally, the base of the container (which will act as the ceiling to the refrigerated chamber) needs to be conducting so as to facilitate the smooth transfer of heat. Furthermore, it would be preferably constructed with ridges or corrugations to increase its interacting surface area with the chamber.[34]

*Protecting the Fluid*
In order to prevent risks such as the buildup of algae and other contaminants inside of the open water container, chemical biocides such as glutaraldehyde and sodium bromide are often placed into solution with the thermal mass.[33] However, these chemicals can be hazardous to work with due to their caustic nature. An alternative is to protect the water using a polyethylene film, which is almost transparent to infrared radiation (85% transmissivity) and can also isolate the fluid from external contaminants.[35]

*Insulating during the day*
In order to be able to maintain the low temperatures of the thermal mass during the day, a set of insulating panels is required to protect the water from heat losses.[34] A model created by Etzion and Errel in 1991 featured a lid constructed out of polystyrene (an insulating material) sandwiched between two thin slabs of plywood.[38]

# Final Decision

| | Evaporative | Sorption | Thermoelectric | Night Radiation |
|---|---|---|---|---|
| Cooling Potential | • Limited in Espiritu Santo where the wet bulb temperature is high.<br>• Temperature can theoretically only get as low as about 22C (average wet bulb temperature). | • Studies have shown that it can reach temperatures as low as 4C.<br>• Largely dependent on refrigerants used.<br>• Gets cold very quickly. | • Can reach sub-freezing temperatures.<br>• Fast cooling rate (can reach freezing within 2 minutes).<br>• Not energy efficient. | • On clear nights, with minimal wind, can get up to 20 degrees below ambient (so about 5C in Espiritu Santo).<br>• Slow process that works overnight. |
| Cost | • Cooling system itself has essentially no cost, as it can operate off dirty water.<br>• Sand is a free resource for the soaking material. | • Comparable models (like one created by Appropriate Technology Collaborative) cost $1,100<br>• Refrigerants are costly. | • A typical Peltier module can exceed $50 on its own.<br>• Ongoing cost of drawing electricity (unless powered by solar). | • Only cost is that of constructing the radiator.<br>• Thermal mass can be dirty water. |
| Reliability | • No mechanical or electrical components which can undergo failure | • High pressure required for mechanism to operate.<br>• Chamber must be in a vacuum state. | • Cannot operate when they are wet.<br>• Though durable, electronics components are prone to eventual failure. | • In optimal conditions, as long as it is placed beneath an open sky, will work.<br>• No mechanical moving parts that can fail. |
| Ease of Use | • Very easy to use.<br>• Only requires periodic "re-watering" of the sand to maintain cooling effect. | • No moving or electrical parts.<br>• Straightforward operations.<br>• Handling refrigerants can be cumbersome and inspections for dangerous leaks are required. | • Very little involvement required.<br>• Just plug it in and it will work its magic. | • Easy to use apart from the fact that users will have to wake up early to bring their radiator inside before experiencing sunlight. |
| Total | 15 | 11 | 17 | 18 |

| Optimal | | | | Unfavourable |
|---|---|---|---|---|
| 5 | 4 | 3 | 2 | 1 |

## *Evaluation*

Cooling mechanisms with any of aspects of criteria coloured in red were immediately ruled out as they were just too infeasible to justify implementing into our final design. For example, though evaporative refrigeration is very cost effective, reliable and easy to use, its ineffectiveness within the humid Vanuatu conditions makes it simply too difficult to propose as a viable solution. Sorption cooling as a whole was simply too complex to costly to manufacture, and so it had to be ruled out.

Thermoelectric and night radiation cooling both have their own strengths and downsides. Thermoelectric can quite easily achieve the desired 4C temperatures, and require very little user involvement to function. On the other hand, night radiation cooling is not reliant on electricity and can be manufactured locally using very simple construction techniques - as there are no mechanical or electrical components to its design.

Ultimately, thermoelectric was ruled out due to its reliance on electricity, something that drew away from the integrity of our initial proposal, which we introduced as being “no-energy refrigeration”. However, it still represents an opportunity for future advancements in our design, if more communities throughout Espiritu Santo gain access to solar panels. In doing so, the cooling capacity of our refrigerator would be such that it would be viable to store temperature sensitive medications and vaccines.

With night radiation cooling chose as our cooling mechanism, the next section of this report discusses the appropriate materials, shape, and dimensions of our refrigeration chamber - the structure in which the food will actually be stored.

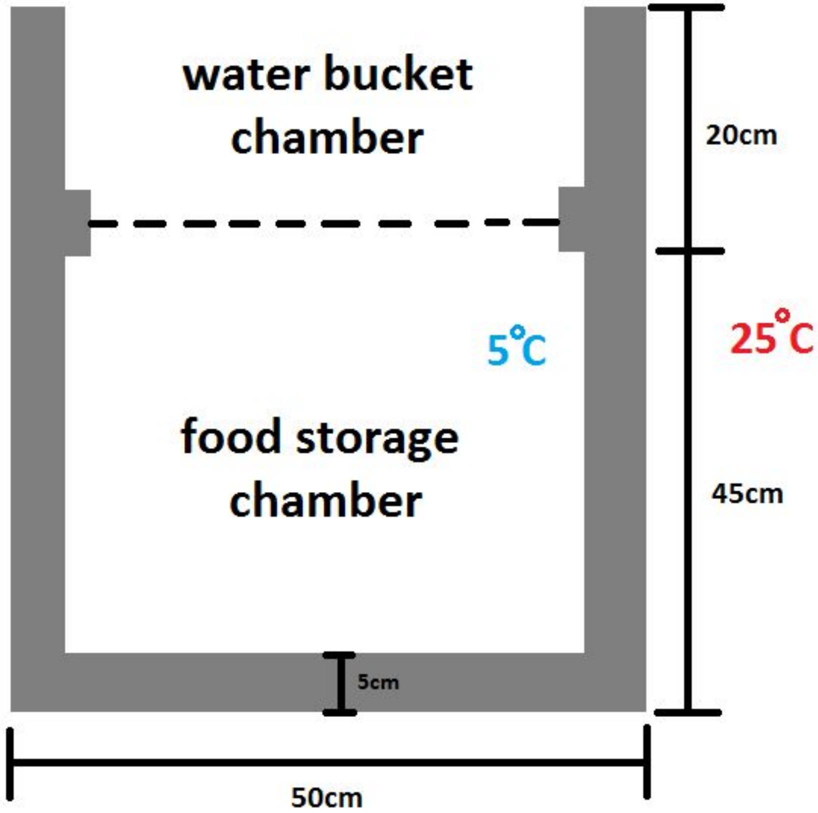
# 8. Refining the Design - Part 2: The Insulating Chamber

# 8.1 Shape and Dimensions

The fridge will have two distinct containers - the water container chamber and the storage chamber, with the water chamber sitting directly above the storage chamber.

First we need to consider the overall shape of the fridge. As investigated previously, greater surface areas conduct more heat, so therefore in order to be as insulating as possible, the walls of the fridge must have a minimised surface area. While technically we achieve this with a triangular prism shape, it greatly restricts the volume of food we can store, and is also difficult to mould or join. Therefore, we should construct the walls out of four flat walls creating a square prism. This also has the added benefit of being easy to join (with planks) or mould (with concrete) than a round barrel-like design, depending on the material we choose.

The dimensions of the fridge should be small enough that it is very easy to access the food storage chamber from the top of the fridge.  A storage area of 40x40x40cm measured between the inside surface of the concrete walls will be able to store 64L of contents, which is more than enough to store the produce for a family's meals for a few days. With 5cm thick walls and floor, and 20cm added height for the water bucket chamber, its overall dimensions become 50x50x65cm, which is small enough in size that it is easy to access even for children.




*The overall dimensions of the fridge*

# 8.2 Material Options

Following the design specifications, we can weigh up different options for the materials to make the walls of the fridge. We first must consider locally available materials in rural areas in order to minimise negative impacts of importing and transportation of materials. We must also only consider materials which are insulating. The 'Local Materials' slideshow shows that these materials are available:[45]

- Trees
  - Cannot be treated or shaped, not suitable for our project
- Bamboo
  - Can be woven into an airtight structure, suitable
- Rocks
  - Cannot be airtight without concrete support, unsuitable
- Coconut tree leaves
  - Can be woven, suitable

We can also consider importing goods from local shops in Luganville, which can be found in the 'example material costs' spreadsheet:[46]

- Treated wood planks
  - Can be joined together easily to form structure, suitable
- Concrete
  - Can be moulded into shape, suitable
- Bricks
  - Can be stacked and kept airtight, suitable

For each suitable material/property, we give a score out of 5, and all properties are weighted at equal importance.

| | Bamboo (woven) | Coconut tree leaves (woven) | Wood | Concrete | Bricks |
|---|---|---|---|---|---|
| **Insulation** | 1 | 1 | 4 | 5 | 4 |
| **Weather Resistance (Strength)** | 1 | 0 | 3 | 5 | 4 |
| **Portability** | 5 | 5 | 4 | 0 | 0 |
| **Life-span** | 1 | 1 | 3 | 5 | 4 |
| **Cost** | 5 | 5 | 3 | 2 | 3 |
| **Total** | **13** | **12** | **17** | **18** | **15** |

Here, wood and concrete are two very good options we can choose from, so we will take a closer analysis of both of these materials and how they meet the design criteria.

# 8.3 Concrete vs Wood

## Heat Flow

Heat flow through a wall is given by: [47]

$$H_t = U \times A \times dt$$

Where:

$$H_t = \text{Heat flow } (W)$$

$$U = \text{Heat transmission coefficient } (\frac{W}{m^2K})$$

$$A = \text{Wall Area } (m^2)$$

$$dt = \text{Temperature Difference } (K)$$

For four 40x40x5cm walls of wood and concrete, we can calculate the heat flow in Watts emitted by each material.

| | **Wood** | **Concrete** |
|---|---|---|
| Heat transfer coefficient ($W/m^2K$) | 2.6 | 1.7 |
| Wall Area ($m^2$) | 0.64 | 0.64 |
| Temperature difference (°K) | 20 | 20 |
| **Heat Flow (W)** | **33.28** | **21.76** |

Both materials result in an extremely small amount of heat loss (in comparison, domestic fridges can consume between 100 and 200W).[48]

## Portability

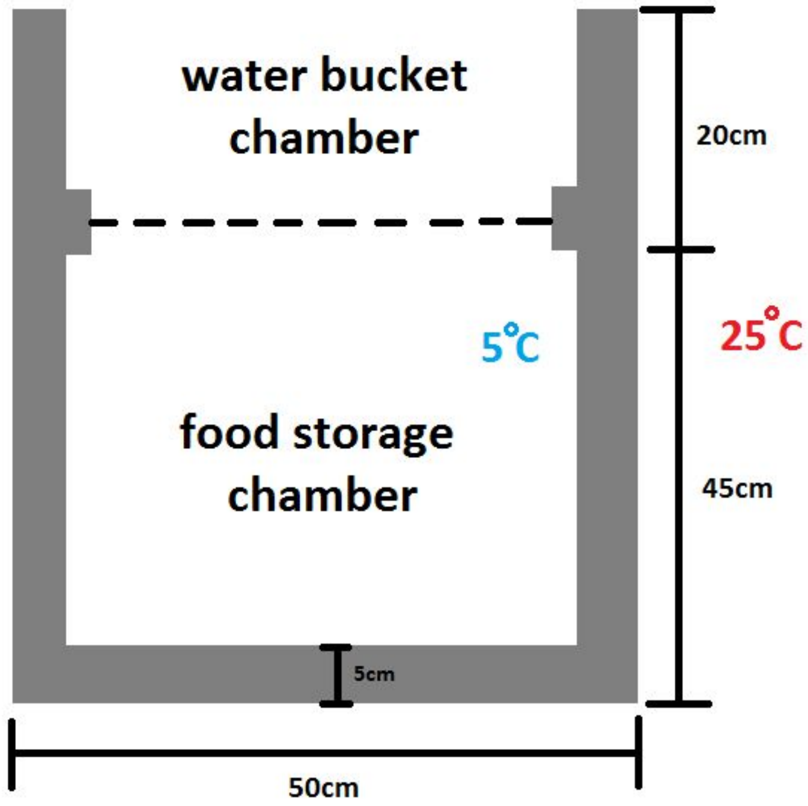
The volume of the fridge can be calculated:

$$0.65 \times 0.5 \times 0.05 \times 4 + 0.4 \times 0.4 \times 0.05$$
$$= 0.073m^3$$

Wood is a relatively light material, having an average density of approximately 700 kg/m$^3$.[49] So the fridge would weigh 700 x 0.073 = 51.1kg. Therefore, only 1-2 people are required to carry it, so it can be moved to wherever is most convenient at the time, significantly reducing the need to walk back and forth from the fridge. Also, in case of extreme weather conditions that requires villagers to move long distances, multiple fridges can be taken with them on a vehicle, allowing them to bring many food supplies with them.

Concrete however, has a density of 2400kg/m$^3$, resulting in a weight of 2400 x 0.073 = 175.2kg.[50] This would require many people to be able to lift it, and given its small size, would be extremely unfeasible. Therefore the residents would not see the convenience that comes with being able to move the fridge, that they would otherwise experience with a wooden structure. Though we note that in an emergency situation, the fridge could still be loaded onto a vehicle and driven to safety.

Therefore, the wooden structure is much more portable and convenient than concrete, though they both can be moved in case of an emergency.



## Weather Resistance

Vanuatu is prone to many extreme weather conditions, such as intense heat, winds, and rainfall. Therefore, the walls of the fridge must be weather resistant, as well as insulating.

Concrete as a building material is extremely weather resistant. It's weight makes it difficult to tip over due to strong winds, and it being a ceramic makes it extremely heat and water resistant. Over time, concrete does not wear out, and does not rot. However, it is difficult to repair if it were to get damaged, and would most likely result in having to build a completely new one.
The lifespan of structural concrete is around 50-100 years in unideal conditions, which is more than enough for our needs.[51]

Wood is also structurally very strong, but is more prone to weather conditions. While it won't tip over, it is also not heavy enough to completely resist the effects of strong winds. It also is extremely susceptible to rot due to rain, as well as moisture in the air, which is always at a >90% humidity. Furthermore, wood is susceptible to bugs and pests eating it, and getting inside the storage chamber. However, educating the residents on good maintenance practices will minimise this risk, and wood is very good at repairing any damage that may be caused. If a piece of wood gets damaged, it is easy to remove and replace.
The lifespan of timber in our context can be compared to the lifespan of a wooden deck, as they have similarly high usage and exposure to the environment.[52] Therefore we can expect the fridge to have a lifespan of 10-15 years.

Therefore, concrete can survive in the Vanuatu environment and has a longer lifespan than wood, and thus requires less maintenance However it must be noted that wood is much easier to repair than concrete, if the structure were to get damaged.

Residents use timber and concrete as structure for their houses and rainwater wells
Source: EWB Australia

## Cost, material availability, and education

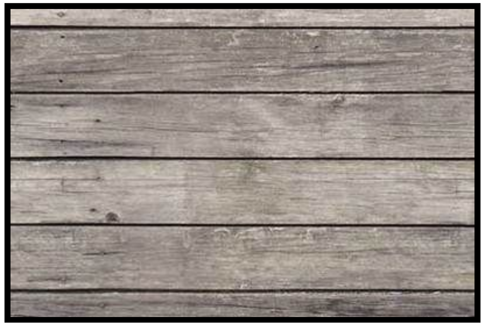
Neither wood nor concrete can be found readily available to use in rural areas. Therefore we must consider importing from shops in Luganville, and accept the negative impacts that come with transporting these goods to these areas.

Wood can be bought easily at a local hardware shop. It comes in dimensions 100x50mm for 2020Vatu ($23.50AUD) at a length of 5.4m.[46] We can cut this into 10 500mm long pieces, with a 400x100x50mm piece left over which can be used to make the lip and any joining braces required. Stacking 6 500x100x50mm pieces lengthways on top of each other gives us one wall, so we will need 24 of these pieces to make all 4 walls. The floor will require another 5 of these 500x100x50mm piece, so 29 pieces in total. Therefore we require 3 units of this length of wood at a cost of 6060Vatu ($47AUD). Also, residents will not have to be educated much, only on how to use basic hand tools, since constructing things out of wood is very simple. Therefore there will be little wastage.

Concrete cannot be bought as easily as wood. Note that in the 'example materials costs' spreadsheet, it is claimed that cement mix can be bought in units of 1m$^3$ (2400kg) for 3200Vatu ($37AUD).[46] This is extremely unreasonable and most likely a mistake. It is actually very difficult to find pre-mixed concrete, especially in rural areas, so the only option for residents is to make their own. Most will have to be taught optimal mix ratios. Cement can be bought in 40kg bags for 1000Vatu ($12AUD).[46] Sand and aggregate can be found for free in the environment. Water, being a somewhat scarce resource, will be very expensive to use in concrete mix, and takes it away from a more necessary usage such as cleaning or drinking. However, it is clear to see the process of obtaining concrete is extremely complex and unfeasible for many communities, especially in rural areas. Also, if residents are not educated on how to mix, there is a high chance that a lot of material will be wasted which further adds onto the cost.

Another way to obtain concrete is to go through concrete companies in Vanuatu, however the monetary costs and the environmental impact of transporting cement trucks across the island makes this option unfeasible.

Therefore, wood is a much better choice here, being readily available and much cheaper than concrete mix. Residents also will not have to be educated much, and added material costs due to making mistakes will be minimised.



Wood planks can be stacked on top of each other to make a wall
Source: textures.com

## Decision

| Design Requirement | Wood | Concrete |
|---|---|---|
| Refrigerate down to 4 degrees celcius | Loses a negligible amount of heat (less power consumption than a regular fridge), and can therefore insulate food for a long time (>24 hrs) | Loses a negligible amount of heat (less power consumption than a regular fridge), and can therefore insulate food for a long time (>24 hrs) |
| Protect food from pests | Is susceptible to wood-eating pests like termites | Completely impenetrable by pests |
| Portable | Can be lifted to and from different places in the village<br><br>Can be transported to safety in an emergency | Unfeasible to move it often, must stay in the same spot<br><br>Can be transported to safety in an emergency |
| Construct locally using readily available materials | Treated wood can be purchased directly from a local shop in Luganville | Residents must make their own cement mix, as it is not readily purchasable from a shop, or they must go through a cement company |
| Be simple in design and construction | It is very easy to join planks of wood to form the rectangular-prism shape of the fridge | Moulding cement mix by hand is quite difficult, and requires complex tools and techniques |
| Simple to operate and maintain | The structure is made of many pieces, so if a piece sustains damage it can be easily removed and replaced<br><br>Cleaning wood is somewhat difficult, as too much moisture can damage its structure | Any damage to the concrete will be difficult to repair, and will most likely result in having to build an entirely new structure<br><br>Cleaning concrete is easy, since it is water resistant and won't get damaged by moisture |
| Lifespan of 10 years | Has a servicable lifespan (10-15 years) | Has an extremely long lifespan (50-100 years in unideal conditions) |

To make a decision, we need to compare the properties of each material and weigh them against our original design requirements.

In this case, we have decided to make the structure out of treated wood planks. While concrete has slightly better insulation and strength, the difference is negligible and the wooden structure will still service our needs. Concrete not being easily accessible for rural communities is a severe detriment to our project's vision, and it severely outweighs any small benefits concrete has over wood.

# 9. Final Design: Cosmic Ice

# Overall Structure

The fridge's walls will be made of treated wood planks which we can source from a local hardware shop in Luganville. The planks can be cut up in such a way that we can stack them up on top of each other, joining them with nails to create a wall. We can fashion 4 insulating walls and a floor in this way.

The structure is split up into two compartments - a smaller water radiator on top of a larger food storage chamber. Separating the two is a small lip, shaped such that a water bucket can sit on top of it. The water bucket has cold water in it, and draws heat from the food below it. Ideally, this is the only way heat leaves the chamber, as we want to preserve the "coldness" for as long as possible.

*How much heat is lost through the walls?*
Much like a house, we can assume the storage chamber will only radiate heat through the walls. We calculate the heat loss to be 33.28W. For reference, a standard fridge requires 100 to 200W.[48] Therefore in an ideal situation, the fridge will stay insulating for a long time.

*How well is the food protected?*
Pests like the tuber-eating beetle are known to damage crops and food supplies in Vanuatu. Also, the timber is prone to wood-eating bugs like termites. Therefore we need to take extra measures to make sure the contents of the fridge are well protected.

One way of protecting the inside is to line the inside of the fridge with woven bamboo.[53] This acts in a similar way to a plastic bag in a rubbish bin, whereby the food sits inside the woven bamboo which sits inside the wooden structure. While this does not protect the fridge itself, if pests do manage to get inside the fridge, there will be added protection through the strong bamboo. As an added benefit, bamboo is also a very good insulator.

*How will it be cleaned and maintained?*
Wood is relatively easy to clean with just water and elbow grease, however excess moisture can cause it to rot. Unfortunately, there is no reliable way of protecting the wooden walls themselves. It will have to be maintained regularly, and any visual inspection should reveal structural damage easily. We can educate the residents if needed on what damage to look for and how to repair it when necessary. UV cured lacquers could be a potential advancement in the design, if such resources become available.

# Night Radiator

Given the parameters described in the previous section, the ideal shape of a radiator to be utilised as a part of our refrigeration system would look like this:

The radiator would be parabolic so as to minimise convective heating and wind losses, as well as maximise the surface area by which outgoing radiation can reflect towards the sky. The base of the container would be flat, so that it can sit steadily, yet corrugated in order to increase its interacting surface area with the chamber. An outer lip would also be constructed so that the radiator can sit comfortably on top of the refrigeration chamber, once it has been cooled down. Ideally, this kind of structure would largely be constructed out of galvanised steel, which has been utilised to great effect in similar night radiation systems. Galvanised steel is resistant to corrosion and a poor conductor of heat and therefore, is optimal for this purpose, as the thermal mass would not gain any heat from its surroundings via the structure. Coating the insides of the radiator with materials such as Mylar and white paint can also serve to increase the emissivity of the radiator, increasing the efficiency of the cooling system.

The base on the other hand needs to conductive, so that heat can be transferred from the chamber into the radiator whilst food is being cooled. Therefore, an optimal design would involve a corrugated base being constructed separately out of a material such as aluminium, which is also resistant to corrosion and is a fairly good conductor of heat.

The water can also be protected from contaminants by covering the radiator’s opening with a polyethylene sheet. Polyethylene is infrared transparent, meaning heat can still very easily transmit through its surface.

## *How cold can it get?*

The radiative heat energy loss on a night radiation cooling system can be modelled by the following equation, which is a slight modification of Stefan-Boltzmann Law that is better tailored to modelling this specific phenomenon:

$$R = e_r\,(\sigma T^4_{water} - S)$$ [54]

- *$R$ = radiative cooling $W/m^2$*
- *$e_r$ = roof emissivity*
- *$T_{water}$ = water temperature*
- *$S$ = global thermal radiance*
- *$\sigma$ = Stefan - Boltzmann constant*

The temperature that the water can then be deduced by observing the solution for $T_{water}$ becomes 0 - that is, the water is at thermal equilibrium with the sky and its surroundings and thus, cannot radiate any more heat.

The global thermal radiance $S$ can be deduced using the following formula:

$$S = e_s \sigma T^4$$ [54]

- $T$ = ambient temperature
- $e_s$ = the emissivity of the sky

The emissivity of the sky can be deduced approximately using the following equation:

$$e_s = 0.741 + 0.0062T_{dew}$$ [55]

- $T_{dew}$ = dew point temperature

Therefore, utilising these models, the approximate theoretical temperature that the radiator can achieve throughout the year, as a result of this process, is presented on the next page.

It must be noted however that these are the temperatures that the radiator can achieve via radiative cooling with the sky alone. It does not take into account the potential heat energy gains as a result of convection from the surrounding environment. Furthermore, it does not take into account the heat gained by the radiator as a result of the radiation experienced by surrounding objects and the ground.

The model for convective heat exchange is described in a previous section, however it is too complex to be applied in this report. Nevertheless, the radiator has been designed such that the temperature gains as a result of convection is minimised.

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average Ambient Temperature (C) | 27 | 27 | 27 | 27 | 26 | 25 | 25 | 25 | 25 | 26 | 26 | 27 |
| Average Relative Humidity (%) | 84 | 85 | 86 | 86 | 82 | 83 | 81 | 80 | 80 | 80 | 81 | 82 |
| Dew Point Temperature (C) | 24 | 24 | 24 | 24 | 23 | 23 | 22 | 22 | 22 | 22 | 23 | 24 |
| Emissivity of the Sky | 0.8898 | 0.8898 | 0.8898 | 0.8898 | 0.8836 | 0.8836 | 0.8774 | 0.8774 | 0.8774 | 0.8774 | 0.8774 | 0.8836 |
| **Temperature of the radiator water (C)** | **0.4047** | **0.4047** | **0.4047** | **0.4047** | **0.3897** | **0.3740** | **0.3740** | **0.3734** | **0.3734** | **0.3734** | **0.3883** | **0.3890** |

*Climate data sourced from timeanddate.com*

## *Final Radiator Design*

Unfortunately, the ideal radiator described above is not feasible given the limited physical resources and manufacturing expertise available in Vanuatu. Therefore, the following modifications have been made to materials that will compose the final radiator of our device:

| Ideal Material | Alternative | Description | Source |
|---|---|---|---|
| Stainless Steel | Treated Wood | Stainless steel was part of the ideal design due to its durability and insulating properties. Unfortunately, stainless steel can be difficult to source Espiritu Santo, even in the island's commercial hubs such as Luganville. Furthermore, it can be very difficult to shape stainless steel into the desired parabolic shape. Therefore, treated wood was chosen as an alternative. Wood is relatively easy to work with and is still a relatively good insulator of heat, which is necessary to minimise the convective heating of the water whilst it is cooling. As described earlier, wood also has adequate durability for the purposes of this refrigeration system. | Treated woods are not available within remote villages, but can be sourced from stores located in Luganville. Due to the durability of treated woods, sourcing this material from Luganville is still viable as frequent trips are not necessary to construct and maintain this device. Delivery is possible via vans, which is the current mechanism by which medications are transported from the city centre to remote village communities. If necessary, the delivery of woods and other materials can be coordinated with these regular deliveries of health supplies. |
| Aluminium | Flat Iron | Aluminium was deemed to be ideal for the purposes of creating the base of the radiator, as it is a conductive material. This is important so that heat can be transferred from the refrigeration chamber to the cold radiator water to keep temperatures low. Like stainless steel however, aluminium is not readily available in Espiritu Santo. Furthermore, it is not entirely feasible, given the existing manufacturing infrastructures, to create corrugations onto the metal. Therefore, flat iron, which is another conductive metal, has been deemed to be an adequate substitute. | Like the treated wood, flat iron can be sourced from stores located in Luganville. Due to its durability, it is also unlikely that iron has to be purchased again after the initial construction. The iron is also likely capable of being reused in newer systems when design modifications or repairs occur. |
| Mylar | Flat Iron | Mylar is not readily available all throughout Vanuatu. However, a reflective surface is still optimal for the efficient radiation of heat from the water into the sky. Therefore, flat iron, which is reflective with an acceptable emissivity value of 0.9, has been deemed to be an adequate substitute. | As above. |

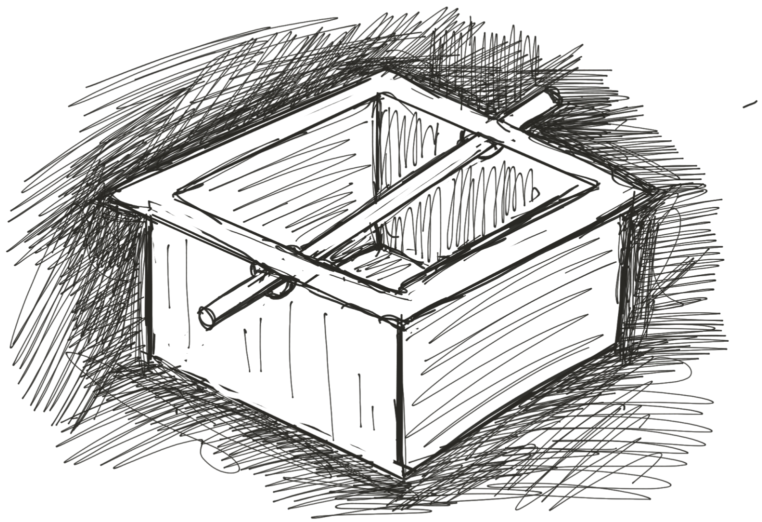
Our final radiator design will have a rectangular, as opposed to circular cross-sectional shape. This decision was made in accordance to the restrictions placed on locals with regards to available materials and construction tools. Wood and iron are sold as planks and sheets respectively, and so the construction of a rectangular "box" as opposed to a parabolic dish is a much more feasible reality.

The main chassis of the radiator will be constructed out of wooden planks of approximately 5cm thickness (which is what is available in stores at Luganville). These will be the same planks as the ones used to construct the storage chassis. The dimensions of this chassis will be 40 x 40 x 20 cm, so that it can fit snugly inside of the chamber structure. Such a depth was chosen so as to further isolate the water from external convective heating.

The inside of this chassis will be lined with sheets of flat iron, which will serve to improve the emissivity of the radiator, as well as create a "waterproof" structure in which the fluid can rest. Likewise, the base will also be constructed of flat iron, mated with the other iron sheets with silicone sealant (also available in Luganville) or construction adhesive. A lip may also be constructed out of flat iron, as illustrated, which will make it easier to situate the radiator on top of the chamber.

If available, protection against algae and other contaminants can be achieved by covering the opening of the radiator with a polyethylene sheet. However, the availability of such a material is difficult to confirm and so, if inaccessible, the water will just have to be replaced once it appears contaminated to the naked eye (e.g clear algae growth)

Finally, holes may be drilled into the sides of the radiator (if possible), in order to thread a dowel rod through it. In doing so, a handle can be created, rendering this entire structure more ergonomic to manage on a day to day basis. The handle can also be removed so as to minimise interference with the night radiation effect.



*Model illustration of final radiator*

# 9.1 Weight of the Radiator

If the water level reaches a height of 1cm, the water bucket would contain approximately 40x40x1 = 1.6L of water.
0.8mm thick iron sheets weigh 10kg/$m^2$.[56] So metal radiator would weigh (0.3*0.2*4+0.3*0.3)*10 = 3.3kg without the water.
The wooden insulation, at a density of 700kg/$m^3$, would weigh (0.4*0.2*0.025*4)*700 = 5.6kg.[49]
Therefore we should expect the functioning weight to be about 10kg.

This is relatively heavy, however it is something that cannot be helped without sacrificing the effectiveness of the refrigeration.

# 9.2 Lid

The lid of the entire structure must also insulate the water during the day, and must be easily removable in order to expose it during the night. It must also be water resistant to repel rain. Bamboo is an extremely abundant material that can be woven into a light, airtight, and insulating structure which we can use as a lid for the drum. This is the same technique residents use currently to build the walls of their houses, so using bamboo in this way is not a foreign concept.

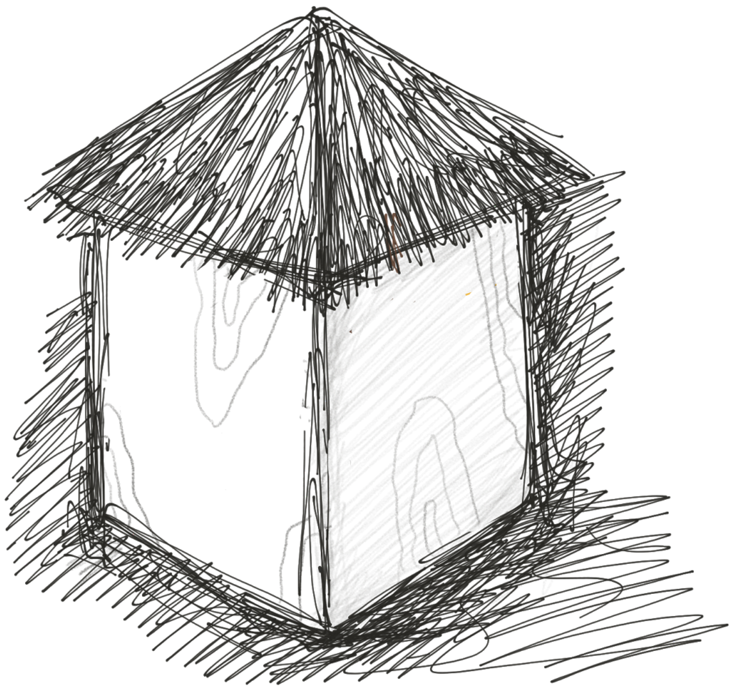


*Illustration of "Cosmic Ice"*

# 9.3 Construction

Wood can be bought easily at a local hardware shop. It comes in dimensions 100x50mm for 2020Vatu at a length of 5.4m, which can be cut into smaller lengths.[46] We can stack these smaller lengths in heights of multiples of 10cm, which allows us to form the walls and floor of the fridge (60cm and 50cm respectively), as well as the insulation chassis of the water drum. They can be joined together with nails and wood adhesive, which can also be supplied by the hardware shop. The walls of the fridge itself require 3 lengths of wood, while the walls of the bucket insulation will require 1 length of wood.

The water chamber itself is made of iron sheets, which can be supplied and cut to size by the hardware supplier. They come in dimensions 900x1000mm at 740Vatu per unit, so we only require one sheet to make the bucket.[46] The sheets are then held together by either construction adhesive or silicone sealant.

If availability of power tools allows, 2 holes can be drilled near the top of the chassis on opposite walls, in order to thread a dowel through to form a handle. The dowel does not need to meet any structural requirements and can therefore be fashioned out of a long tree branch for free. This process should also be repeated for the wooden insulation of the chassis. The chamber can then be glued to the wooden chassis.

# 9.4 Risk Assessment of Construction and Operation

| Hazard | Who is at risk? | Existing control measures | Risk rating (low, med, high) | Preventative measures |
|---|---|---|---|---|
| Cutting wood with machines | Machine operator | PPE, formal training | med | Only let professionals handle heavy machinery |
| Cutting wood with hand tools | Tool operator | --- | low | Teaching locals how to use tools safely, introducing PPE |
| Cuts from the edges of the aluminium sheet | Anyone who uses the fridge | --- | med | Make the sheet slightly bigger than needed, hammer in the sharp edges to make a blunt corner |
| Hammering nails | Tool operator | --- | low | --- |
| Dropping the radiator | Anyone who uses the fridge | --- | low | --- |
| Dropping the entire fridge when transporting it | Person carrying the fridge | --- | low | Have multiple people carry the fridge |

# 9.5 Cost Analysis

Our total cost of 9020Vatu becomes $105AUD. This final cost is unfeasible in the context of developing communities. Therefore we decided to alter the thickness of the walls of the structure and water radiator insulation to 25mm instead of 50mm. The hardware shop supplies 150x25mm planks at a length of 5.4m, at a cost of 1606Vatu per unit.[46] This allows us to construct the fridge walls with 2 lengths of wood rather than 3, lowering the cost of materials without significantly affecting the insulation and strength of the fridge.

Our final cost becomes 5758Vatu ($67AUD) which is much more feasible.

Though it may seem unreasonable, we see this cost to be an investment that will be able to pay for itself in the future, given its many benefits (as will be described in Section 11).

| | Units | Price per Unit (Vatu) | Cost (Vatu) |
|---|---|---|---|
| Treated wood planks (100x50mm), 5.4m length | 4 | 2020 | 8080 |
| Flat iron sheet (900x1000mm) | 1 | 740 | 740 |
| Miscellaneous (nails, adhesive, etc) | -- | 200 (Estimation) | 200 |
| | | **Total Cost** | 9020 |

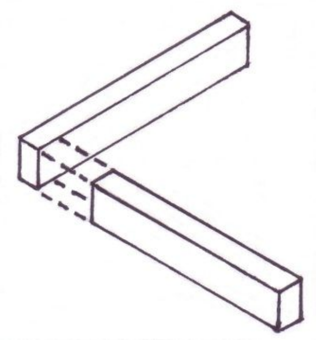
| | Units | Price per Unit (Vatu) | Cost (Vatu) |
|---|---|---|---|
| Treated wood planks (100x50mm), 5.4m length | 3 | 1606 | 4818 |
| Flat iron sheet (900x1000mm) | 1 | 740 | 740 |
| Miscellaneous (nails, adhesive, etc) | -- | 200 (Estimation) | 200 |
| | | **Total Cost** | 5758 |

# 10. Prototype

## 10.1 Overview

The design of our prototype was made to be as close as possible to our actual product, in order to closely test the physics behind its operation. From Bunnings, we sourced sheets of wood particle board with a white paint veneer, with dimensions 2400x600x16mm for the chamber, and sheets with dimensions 1800x450x16 for the radiator. The white paint, with its high emissivity value, mirrored the enhanced cooling effects of the reflective insides of the actual design of our radiator. We also sourced a thin sheet of aluminium which was cut down to 420x420mm, for the base of our radiator.

We decided to join the sheets of wood together with butt joints, held together by PVA glue and nails. While crude, this technique significantly reduces construction time as there is no need to cut out any joints in the wood. The slight reduction in dimensional accuracy is negligible, as this is only our first prototype and does not need to be very efficient.



*Butt Joint*
*Source: woodworkbasics.com*

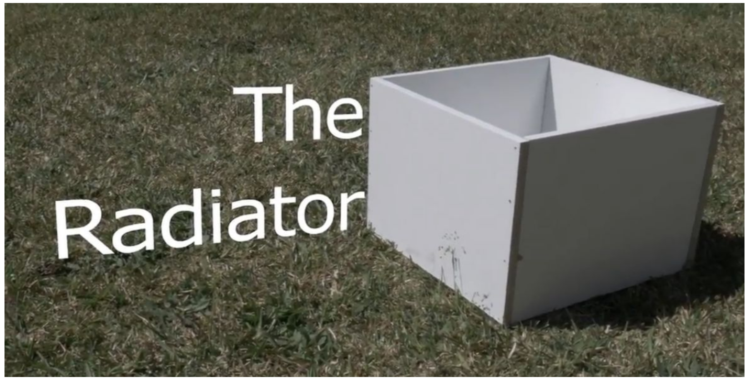
## 10.2 Chamber

The walls of the chamber should have dimensions of 450x600x16mm. In order to meet this requirement, we cut 2 lengths of 450mm from our 2400mm long sheet, and 2 lengths of 450-16-16 = 418mm to account for the extra thickness due to butt joining. The floor of the chamber should be 450x450mm, and nailed and glued directly to the bottom of the walls.


*Source: Infinite Limit*

## 10.3 Radiator

The walls of the radiator should fit as snugly as possible inside the chamber. Therefore, applying the same logic as before, we should cut 2 lengths of 418mm from the 1800mm long sheet, and 2 lengths of 418-16-16 = 386mm. The floor of the radiator is made out of a thin aluminium sheet, which should have dimensions slightly bigger than the radiator (approx 420x420mm), and joined in the same way as the floor of the chamber. The excess aluminium protruding from the 4 sides should be hammered into the walls of the radiator so it wraps "up and around" the walls, creating a blunt edge where the wood meets the aluminium. If the sheet is cut exactly to the dimensions of the walls, it creates a sharp edge which is a safety hazard.




*Source: Infinite Limit*

## 10.4 Supports + Lid

There should be at least 2 excess lengths of wood, which can be stood up at a shorter height than the chamber. These should be cut to the same length, as they act as the supports for our radiator to sit on top of. The supports can simply be glued and nailed into the sides of the walls.

For the lid of our radiator, we simply used a towel in place of a woven bamboo lid, as they achieve the same thing of insulating the cold water from the sun during the day.


# 11. Impacts

## 11.1 General overview

Cosmic Ice is a refrigeration system that operates without utilising electricity; instead being run on a process known as night radiative cooling. The incentive behind this design stems from the fact that resources and food supplies in Espiritu Santo are extensive, yet most of it is lost to spoilage or is wasted due to a lack of proper storage. Access to a design such as Cosmic Ice will undoubtedly have a major impact on numerous aspects; namely diet, health, economy and environment among others. In addition to raising the overall standard of living, it will also play a role in shaping and enhancing the way of life among the communities in Vanuatu.

## 11.2 Impact on General Diet

At present, the diet in Vanuatu consists of the consumption of fresh foods such as fish, vegetables and fruits.[57] Fishing is extremely commonplace, with statistics in 2010 dictating that 79% of households in Vanuatu involved in some capacity.[60] With access to one of the world's largest fishing industries, yet without an efficient way to store it, an alarming amount of food is wasted every year. As known, the humidity in Vanuatu is extremely high and fish is notoriously prone to spoilage; these two factors combine to result in tonnes of wasted fish every year. In terms of impact, it will be profound and widespread. For the community, it will mean that food will be able to be stored efficiently and without concern about immediate spoilage, allowing people to savour and enjoy their food better. More importantly, the impact on preservation is considerable. With access to Cosmic Ice, people can preserve their food and have options with regards to usage and consumption, resulting in a general broadening of the average individual's diet.

The impact of our design on the diet in rural regions will be even more considerable. This is because of the fact food shortages are common in rural areas, owing to the large distances and difficult journey required to acquire food from the mainland. Thus, the detrimental effect of the lack of refrigeration is felt more by rural communities, which means that culinary variety is severely limited as there is even less time to consume the food before spoilage. Hence, the positive impact that Cosmic Ice will have on diet in rural communities is profound, enabling a significant shift in the consumption and cooking methods that are currently in place.

With most of food consumed in Vanuatu being fresh food, proper preservation will result in avoidance on consuming food quickly and better savouring of the food itself. The argument can be made that since most of the food consumed in Vanuatu is indeed fresh food, there is really no need for refrigeration. But this argument is flawed in that it relies on simply accepting a consequence that is because of a hugely limiting occurrence; the lack of refrigeration. By introducing a refrigerator that does not consume energy, it opens a world of opportunity to experiment with different culinary methods that will play a pivotal role in shaping and perhaps even revolutionising Vanuatu's diet. With the abundance of food supplies available, coupled with the fact that most are extremely limited with regards to the variety of their usage, Cosmic Ice has the potential to propel Vanuatu into a strong culinary nation.

Dishes such as these are generally only found in the resorts of Port Vila and Luganville (Source: SBS)

## 11.3 Impact on Health: Eating Habits

The people in Vanuatu enjoy a wide access to fresh foods, driven largely by the importance and emphasis placed on the agricultural sector. Subsistence farming coupled with the fact that nearly four fifths of the population engage in some sort of agricultural work means that the production and access to food supplies is extensive.[64] However, it is known that an alarming proportion (over 30% and growing) consume much of their daily intake in the form of processed foods, largely from importation.[74] Processed foods are unnaturally high in chemicals and preservatives, and play a part in increasing likelihood of conditions such as obesity, Type 1 diabetes and heart disease. Furthermore, processed foods are a prime example of "empty calories"; which refers to foods that are very high in calories yet do not satisfy hunger. More importantly, such foods are notoriously low in nutrients which compounds the detrimental impact on the body.

A deficiency with regards to refrigeration; or more broadly a lack of food security coupled with inadequate storage plays a pivotal role in the population consuming increasing amounts of processed foods. A serious lack of nutrition education as well as general health awareness in Vanuatu is resulting in an exponentially increasing prevalence in the consumption of imported meats and fish, while disregarding traditional foods. The impact and influence of processed foods obtained through importation is on the incline due to 3 main reasons.[65] Firstly, a general shift towards urbanisation directly correlates to a shift from predominantly subsistence farming to an economy more reliant on money transfer. Migration from rural regions also means that there is reduced opportunity for people to cultivate their own food and crops, as transport of the supplies as well as general access to them becomes an issue.[65] Thirdly, because of the fact that fresh foods have a very short time before being lost to spoilage, the variety of consumption is limited and predictable which leaves people prone to the yearning for the better tasting processed foods.

Another factor that influences the preference of processed foods is that the price of fresh foods has been steeply increasingly in recent years. The overall impact of the harmful nature of processed foods can be summarised by the following statistic; in 2013, 73.4% of women in suburban regions were classified as overweight/obese whereas that number drops to 25.9% in rural areas.[75] This statistic is not merely a coincidence as it is well known that the consumption of fresh foods in rural regions far outstrips that of urban areas. The discrepancy shown above is damning and it puts a spotlight on the consequences of the gradual neglect of health shown by the people of Vanuatu through their preference of processed foods. Other ill effects include an alarming number of cases of nutrition deficiency, such as iron, Vitamin A and iodine among others. It can be gathered clearly that although Vanuatu is home to a myriad of food resources and supplies, the lack of storage and efficiency with respect to usage is causing profound issues with implications both now and well into the future.

Having analysed few of many potential threats posed by the continued use of processed foods, it can be predicted that Cosmic Ice can have a massive impact in alleviating some of the risks. By gaining access to a refrigeration system that can effectively store and preserve food, it gives the general population many more options with regards to cooking and preparing their food. This broadening of the diet and incorporation of new flavours will play a pivotal role in the consumption and preference of fresh foods among the people in Vanuatu. Consequently, the need and dependence on processed will be limited which results in an overall increase in the health and well-being of the general population.

Public health surveillance in Vanuatu is limited.

*Source: Vanuatu Independent*

## 11.4 Impact on Health: Prevention of particular diseases

The humidity in Vanuatu as well as most of the food consumed being fresh means that the food has an extremely limited lifespan before it is lost to spoilage. Unfortunately, and this is further accentuated in rural regions, many people consume the food regardless. Whether this is due to a lack of knowledge or a lack of options, diseases and illnesses due to food spoilage are widespread and have a hugely detrimental impact on the health and well-being of the community.

Owing to the fact that fish is one of the most common foods consumed in Vanuatu, the likelihood of food poisoning from consuming spoilt fish is considerably high. There are two main types of poisoning from fish; scombroid and ciguatera. Both have substantial negative impacts on the body and can have short term to long lasting impacts. Of the two, scombroid poisoning is more common as it is specifically caused by consuming fish that is not refrigerated properly.[66] Concerningly, there is no way to detect it either through smell or taste, which makes it exponentially more detrimental. Symptoms include painful rashes, sweating, diarrhoea and vomiting among others. More severe cases can include panic attacks, allergic reactions and difficulty breathing. However, the period of illness is quite short and only lasts between 8 and 12 hours.  Scombroid is one of the most common day-to-day illnesses in Espiritu Santo and owing to its' largely unavoidable nature, the vast majority of the population have been affected by it at some point.

Through the use of our design, substantial steps can be taken in reducing and gradually eradicating outbreaks of Scombroid poisoning in Vanuatu. By having access to a reliable refrigeration system, one of the staples of diet in the region can be consumed safely and the prevalence of Scombroid will be greatly reduced, playing a pivotal role in maintaining and enhancing the general health of the population.

The other main form of food poisoning with regards to fish is "Ciguatera poisoning".[67] This is caused by algae growing on the fish and most of the types of fish consumed in Vanuatu are prone. This type of poisoning occurs mainly in transport of the fish, usually in the transport of fish from urban to rural areas. Transport of fish is very much limited and there are concerns over safety and efficiency, especially considering the harsh weather and the manual labour required. Consequently, an estimated 43% of all fish transported are vulnerable to spoilage/have already been spoilt; with Ciguatera poisoning being among the main culprits. In rural regions, the prevalence of Ciguatera is exponentially higher than that of suburban areas, with an alarming number of fish contaminated in the transport process. Quite like scombroid poisoning, there is no prevention for Ciguatera with the exception of protecting the fish from spoilage in the first place. But unlike scombroid, the period of illness can last up to 6 months, constituting an extended negative effect on health. A curious statistic indicates that tourists are almost 30% more likely to contract Ciguatera than civilians, with the illness among the most common illness in Vanuatu due to most people consuming fresh foods. Symptoms include dizziness, headaches, low blood pressure and nausea.

The implementation of Cosmic Ice in various regions of Vanuatu will undoubtedly play a crucial role in minimizing the detrimental impact of Ciguatera poisoning. The growth of algae is optimized in conditions that are humid and/or when the fish is exposed to the environment for extended periods. Transport of fish and food in general is an area which requires considerable investment in time and resources to improve the quality of supplies for the people of Vanuatu. The flexible and somewhat portable nature of our design will greatly enhance the transport process as food can be stored safely inside and with a shelf-life of roughly 24 hours before replenishment, the design will be able to preserve the food with commendable efficiency. Subsequently, the detrimental influence of Ciguatera will be lowered. In short, it is evident that using Cosmic Ice in Vanuatu will greatly minimize the prevalence of two of the most common illnesses associated with one of the staples of the diet in fish, a result that could potentially result in an overwhelming increase in the general health and well-being of the population.

Other illness that originate from contaminated food/water include Hepatitis A and typhoid.[77] Broadly speaking, a lack of reliable refrigeration is one of the root causes of most food poisoning occurrences and implementation of our conveniently sized design will definitely reduce the prevalence and impact of illnesses and diseases that accompany spoilage and contamination

## 11.5 Economic Impact: Dependence on importation

The implementation and use of Cosmic Ice in Vanuatu could potentially play a massive role in reengineering its' importation methods and placing the economy in a much more financially viable position. At present, Vanuatu is the 180th largest export economy in the world, with importation costs totalling $328M in 2015. In the same year, the exportation value only hit a maximum of $133M, resulting in a net negative trade off.[70] For a country with such a wide and extensive access to natural resources and supplies, the surprisingly large dependence on importation places unnecessary stress on Vanuatu's economic and financial position; and a disproportionately large share of imports are of food supplies in the form of processed foods.

Although the main source of export was Non-filleted frozen fish (accounting for a net value of $73.4M), the mishandling and spoilage of a large amount of the food supplies means that Vanuatu spends millions of dollars each year importing processed foods such as fish, biscuits, rice and instant noodles.[70] Particularly in suburban areas, the increase in importation has resulted in people growing a strong affinity for the food; resulting in an even greater need for process food that demands further importing. This chain reaction has resulted in a rapid growth in the importation of processed foods, with its' impact so wide ranging that leaders in Vanuatu are attempting to ban the influx of processed foods in favour of traditional and far healthier foods.[62] Undoubtedly a major driver for this phenomenon is the lack of variety of traditional foods restricted by their short shelf-life, thus requiring them to be consumed quicker and with less culinary expertise.

Considering the above issue, Cosmic Ice will allow for foods to be preserved longer and hence used better and more efficiently. Consequently, the increasing dependence on importation will be alleviated gradually and the positive impact it will have on the financial status of Vanuatu cannot be understated. The capital saved through less importation could be used to address more pressing issues such as sanitation, nutrition and various other aspects which will lead to an overall increase in the evolution of Vanuatu as a developing nation

## 11.6 Impact on Economy: Manufacture and Distribution

With the preservation, storage and distribution of food requiring substantial aid in both suburban and rural regions, the implementation of Cosmic Ice will be a potential goldmine of opportunity for businesses across Vanuatu to tap into.

Conveniently sized and constructed entirely out of materials readily available in the region, the manufacturing of our design should be cost-effective and swift, with absolutely no disadvantage to rural regions whatsoever. This gives both small businesses as well as larger corporations a chance to take advantage of the situation and potentially produce the product in bulk; thereby making it more accessible to the community in terms of affordability. Demand of the product will always be significant so the market for the product should be financially viable for a long period of time; meaning that the profit and net capital of several companies in the Vanuatu region has the potential to grow exponentially.

As the consumers (general population) use the product and inevitably provide feedback, there is great potential to alter and enhance the product such that it remains relevant and socially feasible to fulfil the needs of an ever changing population. For example; the current proposed size of our design is roughly the size of an esky, but with community feedback and associated research, the product is open to changes and alterations. Coupled with the constant demand that the product will have, newer and/or modified versions could add another dimension to the market appeal of the product.

Distribution of the product should also be efficient and quite easy. The convenient size and dimensions means that much like manufacture, it can be distributed in bulk and to both suburban and rural parts of Vanuatu by various companies. The majority of purchases made by people from rural regions are time-consuming as they have to often make the long journey from their homes, but with our product the aim is to distribute the product so that access in rural regions is extensive.

All in all, the positive economic impact that Cosmic Ice will have on Vanuatu is significant. Through the introduction of a product that has widespread market demand and a tremendous amount of appeal, it provides businesses with a golden opportunity to exponentially increase their revenue flow and net capital by manufacturing and distributing the design to areas both rural and suburban.

## 11.7 Environmental Impact

One of the key aspects that exponentially increases the product's feasibility as well as marketability is the fact that it has virtually no detrimental impact on the environment. Conveniently sized and made entirely out of natural and renewable materials, manufacturing and usage of the product is completely natural and relies on a physical process. To quickly recap, the design utilises aspects of night radiative cooling which relies on the process of thermal equilibrium; which essentially refers to the process of the stored food trying to reach the same temperature as the environment.[73] Furthermore, an insulating mechanism will be used to preserve temperature, which is also constructed from natural materials. As evident from the description and design brief, there is no significant detrimental impact on any aspect of the environment from our prototype itself. There are no chemical processes or reactions involved in any capacity, eradicating the risk of harmful chemical pollution and/or emissions. Such a benefit will be absolutely critical in raising the appeal and overall marketability of the product. In addition to avoidance of further pollution in suburban areas, the positive impact on rural communities will be profound, providing a mechanism that fulfils a crucial need while simultaneously protecting the quality of life. The importance of such an occurrence cannot be understated; largely since most negative impacts are felt to a much greater extent in rural regions than suburban.

Another vitally important aspect to consider in our design is the fact that although there is a risk of thermal pollution, our product is constructed strategically in such a way as to avoid that very risk. Thermal pollution is defined as any occurrence where the temperature of natural sources of water are altered by chemical or industrial processes.[75] It is common in most situations where an artificial change in temperature of water is involved. That very process is indeed involved in Cosmic Ice, however all excess water will be reused as opposed to discarded into the environment. In the event that a discharge of water is required, we plan to use a natural coolant of some sort (perhaps a secondary insulation chamber) to cool the water to an appropriate, safe temperature before discharge. One of our major design aims at the start of this project was to construct an innovative product that not only enhanced the quality of life in Vanuatu but also minimized the detrimental impact on the environment as much as possible. With Cosmic Ice, the virtually non-existent negative impact on the environment means that it has the potential to make an immense impact upon the lives of thousands of people across different regions.

# 12. Implementation

# 12.1 Sustainable Implementation

As the primary objective of our project, we will build a sustainable implementation plan using schemes that are "home-grown, long-term, and generated and managed collectively by those who stand to benefit".[79] Generally, many previous charity and aid organizations which rely on a project-based approach in their intervention have become limited in their capacity to motivate a prolonged impact on their target population. Rather, they commit to providing ongoing support as continual external intervention which limits the potential for developing communities to sustain outcomes over an extended period of time. If our project is to meet the objective of sustainability, we must address its definition of improving the present while allowing 'future generations to meet their own needs'. Instead of operating as an external team who sources our product to current communities, we will pass-on the idea of our technology, so it integrates into their way of life. Via this strategy, knowledge of building, operating and maintaining the product can be imparted to future generations.

The major proportion of integrating our product in the East Santo communities involves personal one-on-one or direct contact with the target communities. To allow outcomes for self-sustainability, we aim to provide them with a framework but allow the communities to construct, operate and maintain the product themselves. In order to decide which avenues are most suitable for connecting with the communities, it is necessary to assess the current social structure and demographics in Vanuatu.

One such avenue of connecting with the communities is approaching the Chief and community committee. Presently, chief's are elected leaders in East Santo who are assigned the responsibility of supporting development and guiding the community.[81] There are interlocking ties within each community which provide a network of communication, mutual support and cooperation.[82] The chief heads this interrelated group of households and represents their views. Thus, by suggesting our mechanism to the Chief in each community, we gain a representative insight into the degree of necessity for the device, or any modifications and considerations which must be undertaken. Traditional meetings which often take place daily, occur at the Chief's nakamal, and are an effective avenue for discussions. By highlighting the widespread benefits of the device, the chief, in their responsibility for social development, may seek the opinions of others before deciding on implementing the technology.

Being heavily influenced by missionaries from Western churches in the $19^{th}$ and early $20^{th}$ centuries, the majority of the Vanuatu population is Christian.[83] This suggests that churches and religious bodies are effective avenues for communication. Although Vanuatu practices freedom of religion, about 83% of its population is Christian and are thus likely to be gathered in local churches on Sundays. There are more than 6 churches on the island of East Santo which can be sites to engage and liaise with communities.

The Chief and church bodies are only two such avenues which allow external innovation to be integrated with local knowledge, structures and processes. These avenues allow local skills and knowledge of materials to be applied in the design and manufacturing of the product.

Local women weaving natural fibres into baskets and mats - a process that can be used to create the lids for our devices

# 12.2 Ethical Issues

It can be argued that introducing a foreign technology in communities with well-established cultural and social routines is morally false. It is furthermore inappropriate to forcefully or wrongfully impose the introduction of a product into private households. Considering this, the delivery of our ideas and product to the East Santo communities must be carefully thought out in order to avoid conflict. For peaceful negotiation, consultation and communication is key to convey the perspectives of both the community and the project team members. Their willingness or acceptance of our intervention must be ascertained before concentrating efforts on undertaking the project. If the necessity for refrigeration is not supported in a community, we must respect their opinions, even if they are contrary to our belief of the product's potential.

Re-evaluating our perspective deems appropriate to ensure our intentions and plans are ethical. As our project focuses on development through aid, we may be inclined to assume a higher rank or status than our target population. This results in our assumptions of reduced knowledge, skills and capabilities of the East Santo communities. In reality, this is certainly not the case; with all humans possessing the same potential. Although there is a cultural disparity between developed nations and the East Santo communities, patience, understanding and dignity must be practiced in order to allow the local population to be treated fairly.

To avoid negative ramifications of our project, we must also consider the inherent culture in Vanuatu and any potential for our intervention to disrupt it. 80% of the working age population in Vanuatu is involved in subsistence agriculture, which does not require refrigeration.[84] An impact of our device encompasses the reduction of such subsistence farming through the preservation of food. With a history and diet being centred on subsistence farming practices, there would be disruption to individual roles in households and the types of food available. Although being a simple device, foreign intervention projects alike ours may force cultures into a way of living which reflect that of the developed world. A general cost of populations forming developed living standards is the forfeit of individual and unique culture. To prevent such consequences, we work to develop a technology which can be well-integrated into the population to suit their needs, using local materials and skills. We seek to involve the East Santo communities as early as possible so they primarily own the product.

Our pathways of implementation also must be carefully considered to prevent actions of discrimination. We have established an effective method of outreach through churches but this avenue excludes populations practicing other religions in Vanuatu. To act on equity and impartiality, we must dedicate efforts to communicating with all categories of the population. Thus, churches will not be our sole contact for liaising with communities: we will employ alternative avenues to ensure all of the target population is included.

Our alternate avenue of communication through Chiefs may also be indirectly discriminatory. Although chiefs are traditionally elected fairly and act on the benefit of the community, their decisions may not be truly representative of community opinions. In Vanuatu, there are no formal procedures for challenging decisions of chiefs, allowing a means for contrary individual beliefs in the community to be suppressed.[82] Furthermore, customary laws by chiefs often discriminate women, which may be a result of their male-dominated society.[82] Though it is difficult to avoid all degrees of bias and inequality, our actions can certainly be rethought in order to allow the opinionative rights of all to be heard.

Nakamal - a traditional meeting place in Vanuatu and a potential avenue for us to share our initiative.

# 12.3 Project Implementation Plan

Aligning with our mission statement, the proposed implementation plan is built around providing a framework for the East Santo communities to integrate the product into their lifestyle. We view our intervention as an initial catalyst for the communities to build upon the product and utilize it in any way they see fit. The following scheme for implementation is an approach which we feel is suitable for the context and purpose of this project. However, it remains flexible to suit the needs and expectations of the East Santo communities. Majority of the plan will be negotiated with East Santo representatives to ensure a smooth and successful transition of the project.

The following table presents an overview of the process of implementation, which will involve both Infinite Limit and representatives of the East Santo communities. The plan involves proposing our final design to the Ni-Vanuatu, and negotiating any modifications that need to be met. Once the design is resolved, the project will transition into helping produce information for users, receiving feedback and offloading the operation to East-Santo communities for self-sustainability. Throughout the process, we will act as a support team for the communities, instead of a leading team, to eventually shift all operation responsibilities to them.

Proposed implementation plan for Cosmic Ice:

| STAGE | TITLE | DESCRIPTION |
|---|---|---|
| 1 | Proposing initial design and project to Ni-Vanuatu | This stage would encompass approaching community committees and chiefs in order propose the idea and discuss the prospect of implementing the device in their community. An initial prototype of our design would be presented to assist in explaining its mechanism and the local materials required. |
| 2 | Refining and finalizing design | After such negotiation with chiefs and committees, a cooperated refinement of the design would accommodate for changing needs or suggestions from the Ni-Vanuatu. This stage would involve the Ni-Vanuatu, for knowledge of local skills and materials, as well as design engineers who provide technical assistance. |
| 3 | Create a working model and determine method of construction | By utilizing the final design, a working model will be created by locals with the appropriate skills in each community. Assistance may to provided if necessary. During the process, sources of materials for each community will be determined. |
| 4 | Communicate and provide information to users | The method of communication will be primarily decided by Chiefs or acting bodies. The most likely method of informing the community is through the primary meeting place named the Chief’s nakamal. If appropriate, providing information near churches would be a suitable avenue to liaise with most members of the community. |

| | | |
|---|---|---|
| 5 | Transition of operation to Ni-Vanuatu | The final stage is critical in upholding the sustainability of the project. By ensuring each community is capable of constructing and operating the refrigeration device, external assistance can discontinue. |

*As part of Stage 1, we will present a suggested method for using the proposed device to communities. The procedure is outlined below:*

Each chamber will be paired with two identical radiators, so as to ensure that refrigeration occurs 24 hours a day. The process by which optimal levels of functionality can be experienced is described below:

1. Before sunset, observe the outside environment and gauge the potential for rain overnight. If it seems likely, refrain from leaving the radiator out overnight, as the cooling effect cannot take place in the rain.
2. Fill the radiator up with water (or any other available fluid) to approximately half way.
   a. If available, then cover the opening of the radiator with a polyethylene sheet, making sure to leave no openings from which air can enter the radiator.
3. Upon sunset, find an open space with a clear line of sight path between the ground and the sky, and place the radiator in the most elevated position available.
4. Retrieve the radiator just before sunrise, and sit it on top of the refrigeration chamber.
5. Replace the bamboo lid on top of the radiator, in order to insulate the coldness of the water from solar radiation.
6. The next evening, repeat steps 1 to 5 with the second radiator, replacing the first one that is currently situated on the chamber the very next morning.

### 12.3.1 Funding and Involving Others

An important component of project operation would involve onboarding staff to assist in working with the Ni-Vanuatu. Obtaining the interests of other organizations, including the Vanuatu government, can create opportunities for funding, sourcing of personnel and operational support.

The Vanuatu government recently released a National Sustainable Development Plan for 2016 to 2030 which encompasses goals under the society, environment and economy pillars. The outcomes of Cosmic Ice would assist in meeting objectives to 'reduce reliance on food imports' and 'improve access to appropriate technology, knowledge and skills in food production, preservation and storage'.[85] By outlining the widespread impacts of our project and its effects in sustainable development, we can involve the government and receive subsidies which would assist in project funding. The Vanuatu government also possesses the business networks and contextual understanding to provide resourceful assistance throughout the project.

To involve suitable personnel who are familiar with the Vanuatu lifestyle, social structure and culture, we seek to partner with non-government organizations (NGOs) who already provide focused aid to East Santo. One such organization is Save the Children Australia which has provided support in Vanuatu for more than 25 years and is the largest NGO in the country.[86] With one of their focus areas being in health, they successfully installed and supervised 75 Village Health Worker Aid Posts for healthcare and nutrition services.[87] Alongside this, they provided healthcare training to 4000 caregivers to develop capacities of communities to be self-sustainable.[87] Such NGOs which have already undertaken thorough sustainability projects in Vanuatu possess the experience and management models to effectively be involved in East Santo communities. Onboarding such support and guidance for undertaking the project would be highly beneficial.

# 12.4 Risk Assessment for after implementation

| Possible problems after Implementation | Who is at risk? | Risk Rating (low, med, high) | Solutions |
|---|---|---|---|
| **Maintenance problems** | | | |
| Wooden structure deteriorating from white-ants | Users | med | • Line the inside of the fridge with woven bamboo<br>• Control pest from invading the structure by having harmless<br>• Have inspections every time putting the food into and taking it out of the fridge |
| Excess moisture causing the wood to rot | Users | med | • Have inspections regularly<br>• Educate the Vanuatuans about how to repair the damages when necessary |
| Pests getting into the fridge for the food | Users | high | • Regular inspections<br>• Clean the fridge by using water and elbow grease every week |
| **Other problems** | | | |
| Natural disasters and extreme weather conditions | Users | med | • Always have food stored for extreme weather events<br>• Carry the entire fridge and the radiator inside the house |
| Chiefs do not think the fridge is necessary | -- | low | • Persuade the chiefs, for example by having trials |
| Performance may not be as well as tested in Sydney | Users | high | • Readjust the overall design for better performance |
| Vanuatu people find it not useful in practice | -- | low | • Readjust the overall design by consulting to the locals, have questionnaires for feedback |

# 12.5 Difficulties and Solutions

Every project may encounter unforeseen consequences or issues regarding the initial plan of development and implementation. This section aims to prepare us for such situations by identifying potential difficulties and outlining appropriate solutions.

A key element which underpins the operation of the project would be funding and business support. The potential shortage of these components would, in the worst case, render the project idle. In the initial stages, emphasis must be placed on compiling persuasive applications for subsidies from the Vanuatu government, as well as support from non-government organizations. The source of funding and staff support must be ascertained before further progression in order to maximize productivity.

Possessing a unique cultural history, Vanuatu has three official languages, English, French and Bislama, but more than 24 different languages are spoken across the largest island of East Santo[88]. It is most likely that each community locality possesses a unique set of languages; which our implementation plan will need to adapt to. An ideal scenario would involve a local translator from each community or area who could assist at the interface of communication. Further research or discussion with non-government organizations currently working in Vanuatu could provide insight into methods of effective communication and avenues for overcoming language barriers.

Currently, our implementation plan outlines a hopeful prospect towards completion but in reality, set-backs may be faced which prolong its completion or even terminate it. There is uncertainty about the time frame of each stage, and whether the assigned outcomes would be achieved with ease. The procedure of implementation will have to involve a larger team of staff, not just those in Infinite Limit, in order to effectively manage communication, logistics, documentation and efficiency. Such staff may be representatives from the Vanuatu government, ni-Vanuatu, or non-government organizations. Coordination and communication will be key in producing successful outcomes.

One such set-back during implementation may be the decline of the product by community Chiefs. It is possible that they do not require such refrigeration in the interest of their community diet and culture preservation. In such scenarios, perhaps a re-evaluation of Cosmic Ice in the community context needs to be undertaken, with the outline of local impact being reshaped. This reshaping may dissuade Chiefs from their initial views, and progress the implementation process. Alternatively, prototype trialing by community residents may act to highlight the benefits to local lifestyles. This action may also influence the views of the Chief. However, during the process, it is important to maintain awareness of the ethics of intervention. Forceful implementation or misleading persuasion may be detrimental to our reputation as well as the impact of the project.

In evaluating the current phase of the project, most of the information regarding Vanuatu and East Santo has been derived from secondary, online sources. This presents a possible underlying issue regarding disparity between our understanding of the context, and the reality of the situation. Unintended assumptions about Vanuatu culture and lifestyle may be the source of the potential ill-fitting of Cosmic Ice as well as the implementation plan. Although we have consulted an EWB representative, Alison Stoakley, who has spent considerable time in East Santo, there is still obscurity regarding the specific skills of each community and their capabilities of constructing the device. Furthermore, Cosmic Ice must be tested in East Santo to ensure it operates effectively, especially with the highly humid and varied climate. Most issues may be addressed by visiting the target population and gaining a deeper insight into their culture, needs, operation and how the device will be subsequently integrated.

# 13. Conclusion

The conceptualisation and outline for the potential implementation of Cosmic Ice was a process with many facets, as well as one that considered a myriad of requirements and contextual considerations. The Vanuatu community in its current state could be greatly enhanced by the presence of a refrigeration system that requires no grid electricity, a requirement fulfilled in detail in the aforementioned section of our report. Providing an efficient method in alleviating the substantial concerns regarding the usage and consumption of resources, Cosmic Ice is a prime example of the engineer's role in society in identifying vital needs and striving to provide the wider community with an effective and manageable solution.

Such a responsibility is one that must be shared and communicated effectively with the community, a notion that our product is both endorsing and positively participating in. Part of the feasibility and ultimately the effectiveness of our design stems from the use of local and natural materials in the product's construction, placing no additional financial or stress and allowing people to utilise the environment in a beneficial manner while simultaneously engaging in a design that will play a huge role in shaping Vanuatu's culinary methods.

A critical part of the product's feasibility and marketability is the fact that systems can be effortlessly put into place to educate the community in operating the design, as it operates on scientific principles that are easy to understand and implement. Due to the minimal risk as well as manageable cost involved, the community can come to appreciate a product that will greatly enhance their quality of life with minimal cost, both financially as well as in a more broadened sense.

The beneficial impact felt will be compounded exponentially due to the significant positive impacts Cosmic Ice will have on various other aspects; ranging from the increase in the general health of the population to strengthening and enforcing the nation's economic position within the region. Couple that with the virtually non-existent detrimental environmental impact and it is evident that Cosmic Ice is a product that has the potential to not only revolutionise the diet, but morph into one of the most effective necessities in many regions across Vanuatu.

To conclude, the aim of the conceptualisation of Cosmic Ice was carried out for a very specific reason; to create a design that would have a significant positive impact on many aspects of life while also boasting a detrimental impact among the most minimal of its' sort. With the presentation of this report, the product and ideas that we have designed has undoubtedly fulfilled these aims; providing the Vanuatu community with a product that has the potential to revolutionise the standard of life and lead to an increase in the overall standing of Vanuatu in the Asia Pacific region.

We are Infinite Limit and we present to you: Cosmic Ice.

# 14. Team Reflection

This was a highly rewarding project which developed our capabilities to work and adapt with individual personalities, work ethics and skills. Due to the diversity of gender, background, interests and educational history, initial stages of the project focused more on our objectives, methods of communication and our individual adaptations to work with contrasting personalities. Initially, there existed a distanced work environment and poor communication which hindered the progression and unified completion of early assessments. However, we recognised the problem and ignited motivation by agreeing upon our team objective to 'produce work we are genuinely proud of'. The team relationship then became a cooperative environment with open communication, clear goals and responsibilities. A key turning point which highly benefitted the team environment was in fact from individual realizations. After each member was clear about their importance in the team, the direction of team outcomes and how they will cooperate with other members, the crucial elements of communication and initiative were achieved with ease. Upon describing these initial but crucial stages, individual adaptation was certainly the most important acquirement which launched our team journey.

During the project which spanned ten weeks, it became apparent that motivation was drifting, especially with commitments to other subjects and extracurricular activities. A surprisingly effective method which restored energy levels in the team was the challenge of competition with other teams. The presence of contrary teams undertaking their projects created a closer relationship between us, as we were working towards our common product. However, in recognizing there were other teams, we also found a sense of unity and reinforced our difference from them by reiterating our goal to generate 'work we are proud of'. The unity and common goal then became our source of motivation for the final stages of the project.

We believe this source of motivation was the basis for everyone assuming their responsibilities and completing their components in a specified time frame. With such a large project, we found it particularly useful to designate 'areas of expertise' to individual members; with Calvin and David focusing on design and development, Rouyan focusing on context, Adi exploring the impacts and Jessica synthesizing the implementation plan. This designation of responsibilities to each member enhanced the productivity as well as engaged each member with their own role in the team. Together with our open communication, we as a team could agree upon our underlying mission and what we expected in each section to create a unified report.

A major disadvantage of separating parts of the project between the team was the loss of responsibility of the project as a whole. It was apparent that each member focused mainly on their components rather than working towards the completion of the report as an entity. Furthermore, each member was only informed about their area and did not understand developments on the rest of the project. It was particularly difficult to maintain motivation while compiling the report and editing it as an entire piece, due to its extensive length as well as unfamiliarity of parts different to our own. In the future, we believe setting aside time for everyone to edit, compile and polish the report would be highly beneficial in ensuring everyone is updated on project content and that the report is of highest quality.

Overall, this has indeed been a valuable journey for us in understanding how to effectively work with others as well as for personal development. As a team dynamic, we believe common motivation is essential to maintain dedication and initiative. We prize each individual to assume responsibility for the project as a totality to sustain unity and quality outcomes. Although this was a team project, we as individuals have now grown to become unique engineers who know our roles in relation to others and can adapt ourselves to different social environments.

Infinite Limit Team
From left to right:
Calvin Xiao, Aditya Ramaswamy, David Kim, Jessica Truong and Rouyan Chen

# 15. References

[1] Government of the Republic of Vanuatu, “Agriculture”, 2011. [Online]. Available: http://www.vanuatuhktc.org/?q=node/19 [Accessed 19-Sep 2017]

[2] Pacific Community, “SPC Water Sanitation and Hygiene: Vanuatu”, 2008. [Online]. Available: http://www.pacificwater.org/pages.cfm/country-information/vanuatu.html [Accessed 19-Sep 2017]

[3] A. Naemon, S. O’Connor, F. Bani, B. Kaurua, et al. “Net Effects: Social and Economic Impacts of Telecommunications and Internet in Vanuatu: Research Findings Report 2011-2012”, 2012. [Online]. Available: http://dfat.gov.au/about-us/publications/Documents/social-economic-impact-of-introducing-telecommunications-throughout-vanuatu-2011.pdf [Accessed 20-Sep 2017]

[4] The World Bank, “Vanuatu Rural Electrification Program benefits remote communities”, 2017. [Online]. Available: http://www.worldbank.org/en/news/feature/2017/05/22/vanuatu-rural-electrification-program-benefits-remote-communities [Accessed 19-Sep 2017]

[5] The World Bank, “Power to the People in Vanuatu”, 2015. [Online]. Available: http://www.worldbank.org/en/news/feature/2015/10/21/power-to-the-people-in-vanuatu [Accessed 20-Sep 2017]

[6] Engineers Without Borders, “Energy – Refrigeration”, 2017. [Online]. Available: http://www.ewbchallenge.org/live-learn-vanuatu/forum/energy-refrigeration [Accessed 18-Sep 2017]

[7] Lonely Planet, “Vanuatu & New Caledonia”, 2016. [Online]. Available: https://books.google.com.au/books?id=eXZmDQAAQBAJ&pg=PT267&lpg=PT267&dq=lonely+planet+vanuatu+diet+%22yield%22&source=bl&ots=4ciHhBLaF-&sig=8LiPBh4E_ijbYOmabLang0J0lNk&hl=en&sa=X&ved=0ahUKEwiwn8qu1-nVAhXlW7wKHQugC18Q6AEIKDAA#v=onepage&q=lonely%20planet%20vanuatu%20diet%20%22yield%22&f=false [Accessed 19-Sep 2017]

[8] S. Sheridan, C. Brolan, L Fitzgerald, et al. “Facilitating health and wellbeing is “everybody’s role”: youth perspectives from Vanuatu on health and the post-2015 sustainable development goal agenda”, 2014. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4192338 [Accessed 20-Sep 2017]

[9] T. Szabo, “Prospective Impacts of Improved Energy on Income Generating Activities in Rural Vanuatu”, 2010. [Online]. Available: http://prdrse4all.spc.int/system/files/vanuatu-energy-and-rural-economic-development-study-may-2010-tyler-szabo.pdf [Accessed 20-Sep 2017]

[10] A. Brown, B. Gilbert, “The Vanuatu medical supply system – documenting opportunities and challenges to meet the Millennium Development Goals”, 2012. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3471189 [Accessed 19-Sep 2017]

[11] Engineers Without Borders, “The Challenge: Innovation for sustainability, access and opportunity 2017 Design Brief”, 2017. [Online]. Available:

https://elearning.sydney.edu.au/bbcswebdav/pid-4788287-dt-content-rid-20417852_1/courses/2017_S2C_ENGG1061_ND/2017%20Challenge_Live%26Learn%20Vanuatu_Design%20Brief.pdf [Accessed 20-Sep 2017]
[12] Wired, "The $10 cooking stove that could save millions of lives", 2016. [Online]. Available: http://www.wired.co.uk/article/glatt-smoke-free-cooking-stove [Accessed 19-Sep 2017]
[13] BBC, "Do smoke-free stoves really save lives?", 2016. [Online]. Available: http://www.bbc.com/news/magazine-38160671 [Accessed 20-Sep 2017]
[14] Government of Canada, "Avoid wood smoke", 2012. [Online]. Available: https://www.canada.ca/en/health-canada/services/air-quality/indoor-air-contaminants/avoid-wood-smoke.html [Accessed 20-Sep 2017]
[15] National Geographic, "Acid Rain", 2009. [Online]. Available: http://www.nationalgeographic.com/environment/global-warming/acid-rain [Accessed 19-Sep 2017]
[16] Massachusetts Institute of Technology, "Smokeless Stove", 2011. [Online]. Available: http://web.mit.edu/adnane/www/adnan/portfolio/idd/stove.html [Accessed 20-Sep 2017]
[17] pacificdisaster.net, "Vanuatu climate change adaptation through fruit drying and food preservation", 2011. [Online]. Available: http://www.pacificdisaster.net/pdnadmin/data/original/VUT_2011_CCA_friut_drying.pdf [Accessed 19-Sep 2017]
[18] Care Inspectorate, "The temperature requirements for medicines storage", 2016. [Online]. Available: http://www.careinspectorate.com/images/documents/1915/Temperature%20Reqs%20for%20Medicine%20Storage_HCR0316099.pdf [Accessed 19-Sep 2017]
[19] S. Parkinson, "The Preservation and Preparation of Root Crops and Some Other Traditional Foods in the South Pacific", 1984. [Online]. Available: http://www.pacificdisaster.net/pdnadmin/data/original/JB_DM418_FAO_1984_Strengthening_plant_protection.pdf [Accessed 20-Sep 2017]
[20] Food and Agriculture Organization of the United Nations, "A Regional Survey of the Aquaculture Sector in the Pacific", 2001. [Online]. Available: http://www.fao.org/docrep/t5816e/t5816e03.htm [Accessed 20-Sep 2017]
[21] New Atlas, "Coca Cola uses the sun to cool drinks", 2014. [Online]. Available: http://newatlas.com/coca-cola-bio-cooler/32464 [Accessed 19-Sep 2017]
[22] Wikipedia, "Qanat", 2004. [Online]. Available: https://en.wikipedia.org/wiki/Qanat [Accessed 20-Sep 2017]
[23] Misfits' Architecture, "Persian ice houses", 2013. [Online]. Available: https://misfitsarchitecture.com/tag/persian-ice-houses [Accessed 18-Sep 2017]
[24] Evaptainers, "Introducing the EV-8", 2017. [Online]. Available: http://www.evaptainers.com/ev8 [Accessed 20-Sep 2017]
[25] ASHRAE, "PEKOA AIRPORT (SANTO), Vanuatu", 2013. [Online]. Available:

http://www.cibse.org/getmedia/a141a8ab-3602-4a45-b46a-72ca11870ff1/915540_s.pdf.aspx [Accessed 19-Sep 2017]

[26] Rebuilding Civilization, "Build an evaporative refrigerator – no moving parts, no electricity", 2012. [Online]. Available: http://rebuildingcivilization.com/content/build-evaporative-refrigerator-no-moving-parts-no-electricity [Accessed 20-Sep 2017]

[27] R. Holland, "Refrigeration in developing countries", 2003.[Online]. Available: https://answers.practicalaction.org/our-resources/item/refrigeration-in-developing-countries [Accessed 20-Sep 2017]

[28] M. Rasul, A. Murphy, "Solar Powered Intermittent Absorption Refrigeration Unit", 2006. [Online]. Available: https://www.researchgate.net/publication/238678133_Solar_Powered_Intermittent_Absorption_Refrigeration_Unit [Accessed 20-Sep 2017]

[29] The Appropriate Technology Collaborative, "Solar Vaccine Refrigerator Drawings and Specifications 2007-2009", 2015. [Online]. Available: http://apptechdesign.org/apptechdv2/wp-content/uploads/2015/07/ATC-MSU-Solar-Vaccine-Refrigerator.2015.e.pdf [Accessed 20-Sep 2017]

[30] II-VI Marlow, "How Do Thermoelectric Coolers Work? (TEC)", 2014. [Online]. Available: http://www.marlow.com/resources/general-faq/6-how-do-thermoelectric-coolers-tecs-work.html [Accessed 20-Sep 2017]

[31] S. Godfrey, "An introduction to thermoelectric coolers", 1996. [Online]. Available: https://www.electronics-cooling.com/1996/09/an-introduction-to-thermoelectric-coolers [Accessed 20-Sep 2017]

[32] ActiveCool, "Understanding Thermoelectric Cooling", 2003. [Online]. Available: https://www.activecool.com/technotes/thermoelectric.html [Accessed 20-Sep 2017]

[33] A. Enderlin, University of Arkansas, Fayetteville, "Radiative Cooling to the Night Sky", 2015. [Online]. Available: http://scholarworks.uark.edu/cgi/viewcontent.cgi?article=1061&context=cheguht [Accessed 20-Sep 2017]

[34] Natural Frequency, "Roof Pond", 2010. [Online]. Available: http://wiki.naturalfrequency.com/wiki/Roof_Pond [Accessed 19-Sep 2017]

[35] Provident-Living-Today, "Alternative Refrigeration – Three Methods of Passive Cooling", 2010. [Online]. Available: http://www.provident-living-today.com/Alternative-Refrigeration.html [Accessed 19-Sep 2017]

[36] A. Ali, "Dessicant enhanced nocturnal radiative cooling-solar collector system for air comfort application in hot arid areas", 2013. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S2213138813000088 [Accessed 20-Sep 2017]

[37] J. Hollick "Nocturnal Radiation Cooling Tests", 2012. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1876610212016219 [Accessed 20-Sep 2017]

[38] Y. Etzion, E. Erell, "Thermal Storage Mass in Radiative Cooling Systems", 1991. [Online]. Available: http://in.bgu.ac.il/en/bidr/SIDEER/MID/Erell/Documents/1991%20Therm

al%20storage%20mass%20in%20radiative%20cooling%20systems.pdf [Accessed 20-Sep 2017]
[39] D. Parker, J. Sherwin, A. Hermelink, Florida Solar Energy Center, "NightCool: A Nocturnal Radiation Cooling Concept", 2008. [Online]. Available: http://aceee.org/files/proceedings/2008/data/papers/1_21.pdf [Accessed 20-Sep 2017]
[40] M. Luciuk, "Night Radiative Cooling", 2010. [Online]. Available: http://www.asterism.org/tutorials/tut37%20Radiative%20Cooling.pdf [Accessed 20-Sep 2017]
[41] halfbakery, "Cosmic Background Refrigeration", 2006. [Online]. Available: http://www.halfbakery.com/idea/Cosmic_20Background_20Refrigeration [Accessed 19-Sep 2017]
[42] E. Erell, Y. Etzion, Ben-Gurion University, "A Radiative Cooling System Using Water as a Heat Exchange Medium", 1992. [Online]. Available: http://in.bgu.ac.il/en/bidr/SIDEER/MID/Erell/Documents/1992%20A%20radiative%20cooling%20system%20using%20water%20as%20a%20heat%20exchange%20medium.pdf [Accessed 19-Sep 2017]
[43] solar-tower.org.uk, "Novel strategies to slow climate change and fight global warming", 2013. [Online]. Available: http://publications.solar-tower.org.uk/New%20ideas%20(3)%20on%20how%20to%20cool%20the%20Planet%20by%20Radiative%20Cooling%20through%20the%20Atmospheric%20Window%20by%20ERM.pdf [Accessed 20-Sep 2017]
[44] ATOA Scientific Technologies, "LOW COST REFRIGERATION", 2016. [Online]. Available: http://ajf.atoa.com/project-reports/low-cost-refrigeration [Accessed 20-Sep 2017]
[45] Engineers Without Borders, "Slideshow: 'Local Materials'", 2017. [Online]. Available: http://www.ewbchallenge.org/challenge/1773/node/1805 [Accessed 20-Sep 2017]
[46] Engineers Without Borders, "Luganville materials prices (examples)", 2017. [Online]. Available: http://www.ewbchallenge.org/challenge/1773/node/1791 [Accessed 19-Sep 2017]
[47] The Engineering Toolbox, "Transmission Heat Loss through Building Elements", 2006. [Online]. Available: http://www.engineeringtoolbox.com/heat-loss-transmission-d_748.html [Accessed 20-Sep 2017]
[48] Reduction Revolution, "Fridge Power Consumption – Can the Star Rating be trusted?", 2015. [Online]. Available: https://reductionrevolution.com.au/blogs/news-reviews/57784517-fridge-power-consumption-can-the-star-rating-be-trusted [Accessed 20-Sep 2017]
[49] The Engineering Toolbox, "Densities of Wood Species", 2006. [Online]. Available: http://www.engineeringtoolbox.com/wood-density-d_40.html [Accessed 19-Sep 2017]
[50] The Engineering Toolbox, "Concrete – Properties", 2007. [Online]. Available:

http://www.engineeringtoolbox.com/concrete-properties-d_1223.html [Accessed 20-Sep 2017]
[51] The Conversation, "The problem with reinforced concrete", 2016. [Online]. Available: https://theconversation.com/the-problem-with-reinforced-concrete-56078 [Accessed 20-Sep 2017]
[52] mcgarryandmadsen.com, "What is the average lifespan of a wood deck?", 2015. [Online]. Available: http://www.mcgarryandmadsen.com/inspection/Blog/Entries/2015/5/22_What_is_the_average_lifespan_of_a_wood_deck.html [Accessed 19-Sep 2017]
[53] Design490, "Bamboo: The Next Big Thing in Architecture", 2011. [Online]. Available: http://design490.org/bamboo-the-new-building-material [Accessed 20-Sep 2017]
[54] R. Dobson, "Thermal modelling of a night sky radiation cooling system", 2005. [Online]. Available: http://www.erc.uct.ac.za/sites/default/files/image_tool/images/119/jesa/16-2jesa-dobson.pdf [Accessed 20-Sep 2017]
[55] B. Chen, J. Kasher, J. Maloney, et al. University of Nebraska, "Determination of the Clear Sky Emissivity for use in Cool Storage Roof and Roof Pond Applications". [Online]. Available: http://www.ceen.unomaha.edu/solar/documents/SOL_26.pdf [Accessed 20-Sep 2017]
[56] Spanman, "Weights of Building Materials", 2013. [Online]. Available: http://www.spanman.net/Members/Technical/Weight-Of-Building-Materials [Accessed 19-Sep 2017]
[57] Food and Agriculture Organization of the United Nations, "Vanuatu", 2012. [Online]. Available: http://www.fao.org/ag/agn/nutrition/vut_en.stm [Accessed 20-Sep 2017]
[58] Safari the Globe, "Food, Dining, & Drinks in Vanuatu", 2014. [Online]. Available: http://www.safaritheglobe.com/vanuatu/culture/food-drinks [Accessed 20-Sep 2017]
[59] Countries and their Cultures, "Vanuatu", 2005. [Online]. Available: http://www.everyculture.com/To-Z/Vanuatu.html [Accessed 20-Sep 2017]
[60] JourneyMart, "Food in Vanuatu", 2012. [Online]. Available: http://journeymart.com/de/vanuatu/food.aspx [Accessed 20-Sep 2017]
[61] Global Table Adventure, "About the Food of Vanuatu", 2013. [Online]. Available: http://globaltableadventure.com/2013/09/24/about-the-food-of-vanuatu [Accessed 19-Sep 2017]
[62] The Guardian, "South Pacific islands ban western junk food and go organic", 2017. [Online]. Available: https://www.theguardian.com/world/2017/feb/03/south-pacific-islands-vanuatu-torba-ban-western-junk-food-health-organic [Accessed 20-Sep 2017]
[63] ABC, "Vanuatu's Cyclone Pam diet: the building blocks to an unhealthy future", 2015. [Online]. Available:

http://www.abc.net.au/local/stories/2015/04/14/4216017.htm [Accessed 19-Sep 2017]
[64] Australia Plus, "How Vanuatu is taking a shot at a healthy future", 2016. [Online]. Available: http://www.australiaplus.com/international/style-and-wellbeing/how-vanuatu-is-taking-a-shot-at-a-healthy-future/7622018 [Accessed 20-Sep 2017]
[65] S. Welegtabit, "Food Security Strategies for Vanuatu", 2001. [Online]. Available: http://ageconsearch.umn.edu/bitstream/32666/1/wp58.pdf [Accessed 20-Sep 2017]
[66] emedicinehealth, "Scombroid Poisoning", 2006. [Online]. Available: http://www.emedicinehealth.com/wilderness_scombroid_poisoning/article_em.htm [Accessed 20-Sep 2017]
[67] MedicineNet, "Ciguatera Poisoning", 2013. [Online]. Available: http://www.medicinenet.com/ciguatera_poisoning/article.htm [Accessed 19-Sep 2017]
[68] Turtle Bay Beach House, "Why You Should Avoid Eating Reef Fish Vanuatu", 2017. [Online]. Available: https://www.turtlebaybeachhouse.com/eating-reef-fish-vanuatu [Accessed 20-Sep 2017]
[69] Centers for Disease Control and Prevention, "Health Information for Travelers to vanuatu Traveler View", 2013. [Online]. Available: https://wwwnc.cdc.gov/travel/destinations/traveler/none/vanuatu [Accessed 20-Sep 2017]
[70] The Commonwealth, "Vanuatu: Economy", 2014. [Online]. Available: http://thecommonwealth.org/our-member-countries/vanuatu/economy [Accessed 19-Sep 2017]
[71] Massachusetts Institute of Technology, "OEC – Vanuatu", 2015. [Online]. Available: http://atlas.media.mit.edu/en/profile/country/vut [Accessed 20-Sep 2017]
[72] Misfits' Architecture, "It's Not Rocket Science #5: Night Sky Radiant Cooling", 2013. [Online]. Available: https://misfitsarchitecture.com/2013/03/01/its-not-rocket-science-5-night-sky-radiant-cooling [Accessed 20-Sep 2017]
[73] Georgia State University, "Thermal Equilibrium", 1999. [Online]. Available: http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/thereq.html [Accessed 20-Sep 2017]
[74] M. Gour, "Environmental Studies – Thermal pollution – causes, effects and control measures of thermal pollution", 2016. [Online]. Available: http://mjcetenvsci.blogspot.com.au/2013/11/thermal-pollution-causes-effects-and.html [Accessed 19-Sep 2017]
[75] Vanuatu National Statistics Office, "Vanuatu National Statistics Office", 2017. [Online]. Available: https://vnso.gov.vu/index.php/component/tags/tag/19 [Accessed 20-Sep 2017]
[76] Queensland University of Technology, "Vanuatu (facts and figures)", 2017. [Online]. Available: http://libguides.library.qut.edu.au/vanuatu [Accessed 20-Sep 2017]
[78] Travel Doctor, "Diseases Transmitted Through Food & Water", 2012. [Online]. Available:

http://www.traveldoctor.com.au/Page/Knowledge-Hub/Travel-Health-Fact-Sheets/Diseases-transmitted-through-food-and-water [Accessed 20-Sep 2017]
[79] United Nations Development Programme, "Capacity Development: A UNDP Primer", 2016. [Online]. Available: http://www.undp.org/content/dam/aplaws/publication/en/publications/capacity-development/capacity-development-a-undp-primer/CDG_PrimerReport_final_web.pdf [Accessed 20-Sep 2017]
[80] F. Azmat, "Sustainable Development in Developing Countries: The Role of Social Entrepreneurs", 2013. [Online]. Available: http://www-tandfonline-com.ezproxy1.library.usyd.edu.au/doi/full/10.1080/01900692.2012.756891?scroll=top&needAccess=true [Accessed 20-Sep 2017]
[81] Engineers Without Borders, "About Vanuatu", 2017. [Online]. Available: http://www.ewbchallenge.org/about-vanuatu [Accessed 20-Sep 2017]
[82] S. Nazal, Asian Development Blog, "To mobilize communities in Vanuatu, talk to the chiefs", 2017. [Online]. Available: https://blogs.adb.org/blog/mobilize-communities-vanuatu-talk-chiefs [Accessed 20-Sep 2017]
[83] Wikipedia, "Religion in Vanuatu", 2008. [Online]. Available: https://en.wikipedia.org/wiki/Religion_in_Vanuatu [Accessed 20-Sep 2017]
[84] B. Mullen, "Vanuatu", 2002. [Online]. Available: http://www.fao.org/ag/agp/agpc/doc/counprof/southpacific/vanuatu.htm [Accessed 20-Sep 2017]
[85] Department of Strategic Policy, Planning and Aid Coordination, "Vanuatu 2030: The People's Plan", 2016. [Online] Available: https://www.cbd.int/doc/meetings/mar/soiws-2016-05/other/soiws-2016-05-vanuatu-05-en.pdf [Accessed 20-Sep 2017]

[86] Save the Children, "Improving lives in Vanuatu", 2013. [Online]. Available: http://www.savethechildren.org.au/our-work/where-we-work/pacific-islands/vanuatu [Accessed 20-Sep 2017]
[87] The Footprints Network, "Healthy babies, healthy teens, Vanuatu", 2014. [Online]. Available: https://www.footprintsnetwork.org/project/113/Healthy-babies-healthy-teens-Vanuatu.aspx [Accessed 20-Sep 2017]
[88] TravelOnline Australia, "Vanuatu Language", 2017. [Online]. Available: https://www.travelonline.com/vanuatu/language [Accessed 14-Oct-2017]