Technology Transfer

A guide for SolarChill

The Solar Direct Drive refrigerators for:

Vaccines & Fresh Food Storage

Prepared by HEAT May 2019

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Nomenclature

A	Area of the insulation panel [m^2]
AEO	Adaptive Energy Optimization
DC	Direct current
DTI	Danish Technological Institute
ECU	Electronic Control Unit
GEF	Global Environment Facility
GIZ	Deutsche Gesellschaft für InternationaleZusammenarbeit
HC	Hydrocarbon
IKI	Internationale Klima Initiative (international climate initiative)
k	Conductivity coefficient of insulation material in kW/(m ºC)
L_{PCM}	Fusion latent heat of the PCM [kJ/kg]
m_{PCM}	Quantity of PCM that needs to be frozen [kg]
PCM	Phase Changing Material
PUR	Rigid polyurethane
PV	Photovoltaic panels
Q_{dem}	Energy demand (for a certain period, not accounting with PCM) [kJ]
Q_{door}	Energy demand due to door opening [kJ]
Q_{prod}	Energy demand due to the cool product [kJ]
Q_{wall}	Energy losses through the wall [kJ]
$\dot{Q}_{wall}$	Power losses through the wall [kW]
s	Insulation thickness [m]
SDD	Solar Direct Drive
t_{ho}	Hold Over time
VIP	Vacuum Insulation Panel
WHO	World Health Organization
φ	Security factor when calculating the frozen mass of PCM
ΔT	Temperature difference between the frozen PCM and the ambient [ºC]

1 Introduction

Over 1 billion people live in regions without reliable electrical supply. In those regions maintaining a secure "cold chain" for preserving vaccines, medicines and food supplies is extremely challenging [1].

Until recently, the market for vaccine and fresh food refrigerators in remote areas without reliable electricity has been dominated by **kerosene, or gas operated units based on the absorption principle**. These refrigerators possess several **disadvantages related to operating costs, effectiveness in maintaining appropriate temperatures and environmental impact**. In remote areas, obtaining kerosene on a timely and consistent basis has proven to be challenging and expensive. In addition, fossil fuel (mostly kerosene but also propane gas or diesel) powered refrigerators result in **greenhouse gas emissions** through normal operation and **emit toxic fumes that are dangerous for humans when in enclosed spaces**. These refrigerators are also more susceptible to catch fire as compared to electric and solar refrigerators. Ordinary electrical refrigerators operated with a genset is a poor alternative due to inefficiency and constant noise.

Another **solution is to use solar panels** as energy source for the (DC) compressor, which overcomes some of the problems related to the fossil fuels. Nevertheless, many solar refrigerators that are currently available on the market rely on lead-acid batteries to store energy. These **batteries are typically the weakest link in solar systems in developing countries because they break down frequently**, especially in hot climates. Batteries are also vulnerable to theft and pose an environmental hazard upon disposal.

Therefore, a better solution needed to be found. In this regard, the **SolarChill project** had been initiated. The SolarChill project was launched in 2001 by a unique consortium of several major international organizations to develop and deliver **affordable, technically reliable, climate friendly, solar powered and lead acid battery free refrigeration to regions with insufficient electricity**. **This is the Solar Direct Drive (SDD) refrigerator with a thermal storage, the SolarChill[1].** The SolarChill partnership currently includes the following organizations, the Danish Technology Institute (DTI), GIZ GmbH, Greenpeace, SKAT, HEAT GmbH, path, UN Environment, UNICEF and WHO

Two main versions of the SolarChill are involved in the project:

1) **SolarChill A**: Medical application "Preserving vaccines"
2) **SolarChill B**: Household and commercial purpose "Preserving food"

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[1] www.solarchill.org (last login 28/05/2019)

Continuing with this work, the GEF SolarChill project started in October 2016 and is still running. The project targets the uniform field monitoring of SolarChill appliances both for commercial and medical purposes and the technology transfer for the dissemination of the technology and the local production in developing countries, particularly in the two project countries eSwatini and Colombia. The project engages with local manufacturers in both countries.

SDD vaccine coolers (**SolarChill A**) have been on the market for some years and most of them use low power DC compressors with electronic control for direct solar PV operation. Due to **high requirements from WHO to safely store the vaccines and the high cost of the refrigerator components**, the prices are much higher than an on-grid domestic refrigerator. The **price of about 100 liters SC-A refrigerator is around 2,000 to 9,000 USD**.

The **high prices have prevented the SDD technology to enter in the off-grid market for fresh food commercial and domestic refrigerators**. Furthermore, commercial refrigerators have usually larger volumes than medical equipment, and **refrigerator size is limited**[2] due to the cooling capacity of the used DC compressor for SDD. Nevertheless, **alternatives could be explored to increase the cooling capacity, and price could be reduced due to less stringent requirements and a higher potential market**[3].

The purpose of this guide is to give an insight to refrigerator manufacturers into the **SolarChill A and B** technology and help them to overcome and anticipate the difficulties that they might find during the design and manufacturing process. The guide provides an overview on key technology features for the SolarChill technology rather than being a step-by-step guide for the design and production of SolarChill technologies. In this way, this report facilitates the technology to be spread and manufactured in the regions where the refrigerators are going to be installed, reducing costs of shipment. Furthermore, by informing manufacturers, the production of SolarChill can be enhanced, increasing availability, promoting research and development for new applications, and reduce cost.

First, presented is the working principle of the SolarChill technology and the main test requirements for SolarChill A and B. The main part of the report describes the different components of the refrigerator and gives several recommendations in the design. The report focuses on the most commonly applied design features.

[2] Experience has shown that the maximum refrigerator size for the standard DC compressor is around 200 liters.

[3] A recent off-grid PV market analysis estimates that the annual market for refrigerators would be 1,081 million of USD http://globalleap.org/resources/ (last login 21/06/2019)

2 SolarChill technology

SolarChill is a technology and product-centered initiative with the mission to create a battery-free refrigerator design that efficiently uses solar energy and is free of substances and emissions that may threaten human health or the environment.

The SolarChill Partnership has set the following requirements for the SolarChill application:

- **Off-grid installation:** SolarChill units can be installed in off-grid regions as they receive their energy directly from the installed solar panels.
- **No batteries:** The unique feature of SolarChill is that the energy is stored with environmentally friendly phase changing materials (PCM), for instance water to ice, instead of in batteries. The stored thermal energy (ice) keeps the cabinet at desired temperatures during the night and days with poor solar irradiation.
- **High autonomy:** It maintains the required temperatures in the vaccine (2ºC to 8ºC) or food storage compartment for several days (2-4) with poor solar irradiation.
- **Environmentally friendly:** SolarChill incorporates environmentally friendly GreenFreeze refrigeration technology. It utilizes **hydrocarbons,** as natural refrigerant and foam blowing agent. Additionally, no other hazardous materials such as heavy metals are deployed within SolarChill units.
- **Affordability:** The SolarChill partnership seeks to spread the technology, get more producers interested on engaging in the manufacturing and marketing of medical and commercial SolarChill appliances.

Figure 1 shows the scheme of the SolarChill. The **sun's energy is captured by PV solar panels** to directly power a special type of DC compressor (SDD), which runs the refrigeration cycle. Even though there are several peculiarities that need to be technically addressed, the refrigerant cycle works as in a typical vapor compression refrigeration system. It is composed by the compressor, the condenser, the evaporator, and the expansion device.

The biggest challenge comes from the discontinuity in the energy supply. There are periods when the refrigerator is not running, such as during the night or at heavy cloudy days. Hence, the energy captured by the solar panels must be sufficient to maintain the target temperatures, not only when the unit is running, but also when the solar panels are not supplying electricity. Since there are no batteries to store this energy, another way of energy storage must be used.

In this case, a phase change material **PCM (thermal storage)** is frozen during the day when there is power supply from the PV panels. The required cooling during night or hours with poor solar irradiance is provided by the PCM, which remains at a constant temperature while it is melting. The PCM material can be selected depending on the phase change temperature (freezing point), which will determine the temperature inside the refrigerator. **Water is usually used as a PCM**.

One should notice that the SolarChill could come with a refrigerator and a freezer compartment, which requires a more sophisticated temperature control in the appliance, see figure 2.

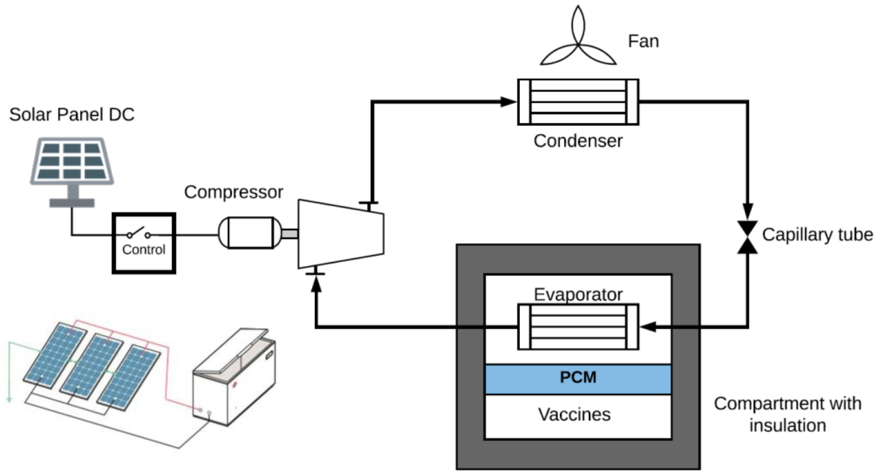

Figure 1. SolarChill scheme with one compartment

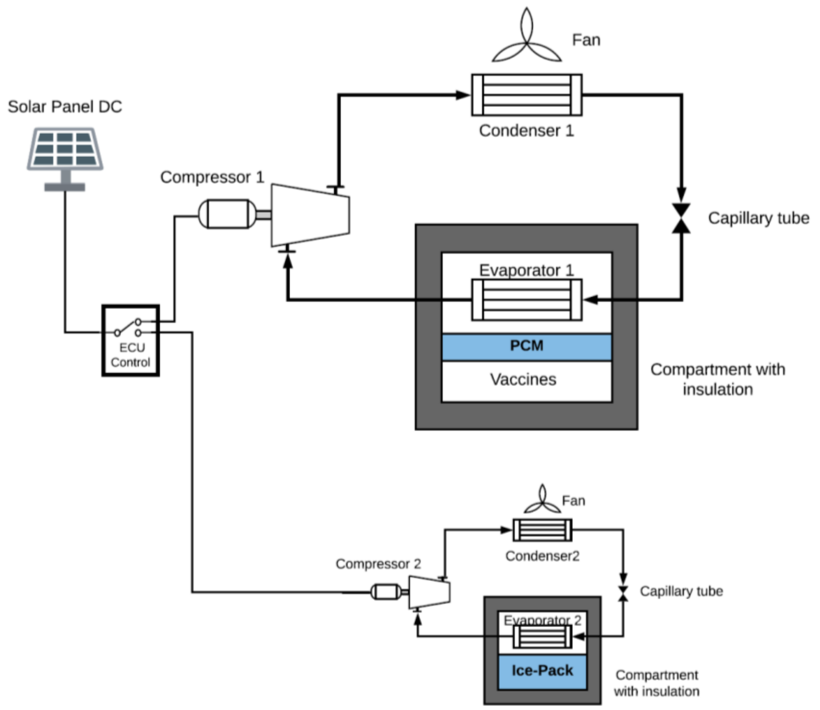

Figure 2. SolarChill scheme two compartments. Alternative solutions can be applied.

3 Test requirements

This section briefly describes the operational and manufacturing requirements of SolarChill A and B and the main manufacturing requirements due to the use of hydrocarbons (HC).

SolarChill A (vaccine) needs to be PQS qualified by WHO in order to be eligible by most of the organizations that usually purchase these refrigerators in remote areas. It is recommended to follow the WHO standards[4] during the design process to fulfill with all requirements (WHO standards for SDD refrigerators: [2] and [3]). This section just presents the main requirements that will be useful during the rest of the document. A more detailed requirements checklist can be found in Annex A.

SolarChill B (domestic/commercial) can be used for different applications, which might require different test methods. At the time of writing this guide, there are so far no international performance standards available for this product type. Therefore, in order to reach a good level of quality and performance, it is recommended to follow the test protocol elaborated by the SolarChill partnership for the GEF project "SolarChill B: DTI Labtest method and criteria." The test protocol applies to SolarChill B units dedicated to preserve fresh food. This section briefly describes the requirements of this protocol, for further information see the full protocol in annex B.

3.1 SolarChill A operational test requirements

The main characteristics of the SolarChill A refrigerator are:

- **Operating temperature: 2ºC to 8ºC**
- The unit must be able **to work inside the operating temperature at ambient temperatures between 10ºC and 43ºC**. The manufacturer can claim to work correctly at temperatures lower than 10ºC
- **Minimum autonomy time: 72 hours** (see test 6 in [3])
- **Minimum freezing capacity (if present): 1.6 kg of ice, or 2.4 kg per 50 liters of freezer gross volume**
- Most WHO certified units in the market have a **Grade A for freeze protection (user independent**, see annex A clause 4.2.4)
- **Solar module voltage: Maximum 45 V**

[4] To download the documents and for other information access: http://apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/categorypage.aspx?id_cat=17 (last login 20/06/2019)

- The unit should work normally in a partly cloudy day. The daily energy during laboratory test is: **3.5 kWh/m² per day**

[2] establishes the requirements for the SolarChill A. In annex A can be found a checklist of these requirements.

At the WHO website[4], an application guideline for manufacturers can be found to obtain the WHO PQS certification [4]. The different steps are summarized below:

1. Design and produce a SolarChill A refrigerator that fulfill all WHO requirements.
2. A preliminary application with a brief presentation of the product is sent to WHO
3. Once the model is pre-accepted by WHO, it needs to be tested in an independent WHO accredited laboratory. A list of the accredited laboratories can be found at the WHO website[4].
4. If the model passes the test, a detailed dossier according to [2] clause 7 will be sent to WHO for approval

The following test will be done according to [3]:

- ✓ **Test 1:** Type examination
- ✓ **Test 2:** Cool-down, initial stabilization and power consumption
- ✓ **Test 3:** Stable running and power consumption (with simulated pre-conditioned vaccines)
- ✓ **Test 4:** Water-pack freezing capacity, water-pack storage compartment capacity and power consumption (only refrigerators with freezers)
- ✓ **Test 5:** Day/night, frozen water-pack storage and power consumption
- ✓ **Test 6:** Autonomy and power consumption (minimum autonomy 72 hours)
- ✓ **Test 7:** Freeze-protection classification test
- ✓ **Test 8:** Door opening test (also to determine the Freeze-protection grade)
- ✓ **Test 9:** Minimum rated ambient temperature:

3.2 SolarChill B operational test requirements

The main characteristics of the SolarChill B refrigerator could vary depending on the application: fresh food storage, selling cold beverages, cold chain of milking process, etc. In this section are summarized the test conditions in the DTI test protocol (see annex B):

- **Operating temperature: 1ºC to 9ºC (thermostat targeting 4ºC)**
- The **ambient temperature** will depend on the classification of the refrigerator: **temperate zone → 32ºC; or hot zone → 43ºC**
- **Minimum autonomy time: 48 hours** (temperatures in the refrigeration compartment <12ºC)
- Cooling capacity: **Maximum 12 h to reach 10ºC with a light load of M-packages[5] (4.5 kg per 100 liters of volume)**
- **Solar module voltage: Maximum 60 V** (it has to be compatible with the rest of the components)
- Unit should work normally in a partly cloudy day. The daily energy during laboratory test is: **3.5 kWh/m² per day**

The following test will be done (see annex B):

- ✓ **Test 1:** Type examination
- ✓ **Test 2:** Stable running with constant power
- ✓ **Test 3:** Cooling capacity running with constant power
- ✓ **Test 4:** Autonomy time (heavily clouded condition)

Using the SolarChill test protocol developed by DTI for commercial appliances is highly recommended to guarantee a minimum of quality to the customers. The tests should be carried out by an independent ISO 17025 testing laboratory. One sample of the appliance is required for testing.

Section 4 will give more details on the designing process in order to fulfill the requirements presented for SolarChill A and B.

3.3 Manufacturers requirements

Using natural refrigerants for the refrigerant and the blowing agent is one of the requirements of SolarChill. Therefore, those manufacturers that are considering producing SolarChill refrigerators must also consider changing their production line to HC, if they have not done this yet.

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[5] M-Packages are standard "meat" packages with a thermocouple. It weighs 500 g and measures 100x100x50 mm (composition defined in [4])

Normally, cyclopentane is used as a blowing agent for the insulation foam[6] and isobutene or propane for the refrigerant cycle.

The introduction of HC as refrigerant and foam blowing agents also requires modification and replacement of major production equipment. For a detailed **guide of production line conversion** take a look to the "Production conversion of domestic refrigerators from halogenated to hydrocarbon refrigerants", **a guide produced by GIZ [5]**.

The main product security standards and norms that the manufacturer needs to fulfill depending on the type of refrigerator are:

- Household: **IEC 60335-2-24:2010/AMD2:2017**: Household and similar electrical appliances - Safety - Part 2-24: Particular requirements for refrigerating appliances, ice-cream appliances and ice makers
- Commercial: **IEC 60335-2-89**: Household and similar electrical appliances - Safety - Part 2-89: Particular requirements for commercial refrigerating appliances with an incorporated or remote refrigerant unit or compressor

The standard IEC 60335-2-24:2010 limits the refrigerant charge to 150 g for HC. For commercial refrigerators, the updated standard IEC 60335-2-89 since 2019 allows an increased charge from 150 to approximately 500 g of HC. For higher charges appliances can be designed and assessed under the **standard EN 378** "Refrigerating systems and heat pumps – Safety and environmental requirements", Parts 1 and 2.

Regarding to the **manufacture plant**, in **Europe** there are two **directives**[7] that specify the means of handling situations where there is a possibility of hazardous or potentially explosive atmospheres. These are:

- **99/92/EU** that sets the standards for the protection of the workers, and
- **2014/34/EU** that sets the standards for the materials and equipment designed for use in potentially explosive areas.

Furthermore, **if the manufacturer has a laboratory, it must be certified with the standard IEC 17025.**

[6] For insulation, other HFC-free foam alternatives can be used. For instance, vacuum panels.

[7] For other applicable regulations, laws and standards refer to [5]

4 Recommendations

In this section the different technical details of the SolarChill technology are introduced and discussed in order to help the manufacturers to overcome the difficulties of producing this new technological concept. This document does not pretend to be a manual to produce SolarChill, since there are many ways to overcome the different technical barriers. But, it aims to bring this technology closer to the new SolarChill manufacturers and help to improve those who are already manufacturing them.

One should notice that the working of SolarChill A (Vaccines) and SolarChill B (domestic/commercial) is basically the same. Nevertheless, the different requirements commented in section 3 will result in different design solutions (e.g. wall thickness, thermal storage, etc.).

4.1 Cabinet

4.1.1 Wall insulation

As commented before, the main challenge of the SolarChill refrigerator is to maintain the temperatures inside the permissible range even with periods with no, or poor, energy supply. 48 hours below 12ºC of all M-packages for SolarChill B and 72 hours below 8ºC inside the vaccine compartment for SolarChill A.

The parts of the system that most influence the autonomy of the appliance are:

- Insulation
- Thermal storage (PCM)

Therefore, having good insulation in conventional refrigeration appliances is highly recommended, for the SolarChill technology it is mandatory. Since the autonomy depends mainly on these two variables, the better the insulation, the less "thermal storage" will be needed.

The **cabinet insulation panels** must have good thermal properties and the right thickness. **VIP panels (Vacuum Insulation Panels)** are a good option due to the low thermal conductivity (**around 0.012 W/mºC)** compared to the rigid polyurethane **(PUR) foam (around 0.024 W/mºC)** [6].

According to [7], the adoption of VIPs in cold chain market is increasing but its full potential has not been reached yet, mainly due to high cost[8] and lack of

[8] According to [7], the cost per m^2 for a 20mm VIP panel is around 46 €, and the payback time due to the energy safe compared to a refrigerator using rigid PU panels is around 9.7 years.

knowledge on handling VIPs in a more complicated manufacturing process compared to PUR insulations. Furthermore, the rigid PUR panels have a higher mechanical strength. Therefore, the selection between both technologies will depend on the application and the manufacturer experience. Rigid polyurethane (PUR) foam can be used with thicker walls. It is more important to focus on low conductivity for small cabinets than larger, where the ratio surface/volume is higher.

The thermal losses across each wall can be calculated according to equation 1. This must be repeated for every wall, including the door.

$$\dot{Q}_{wall} = \frac{k \cdot A \cdot \Delta T}{s} \qquad (1)$$

Where: $\dot{Q}_{wall}$ is the power per each single surface in W
s is the thickness of the wall in meters (m)
k is the conductivity coefficient of insulation material in W/(m ºC)
A is the surface of the wall in m^2
ΔT is the temperature difference between the two sides of the wall (ºC)

When calculating the losses across each wall, one should take into account that **the temperature outside might be different depending on the position of the wall.** For example, for the walls next to the compressor and the condenser, a higher temperature might be considered. The walls next to the heat sources can be designed thicker to avoid high thermal losses.

The **melting temperature of the PCM can be considered as the inner temperature for calculation losses** (e.g. 0ºC for water).

Figure 3 shows the heat loss per day through a 1 m^2 surface as a function of the wall thickness for the PUR and VIP panels. The selected wall thickness will be a compromise between heat loss reduction and panel price, taking also into account the compressor capacity, PV panel size and refrigerator requirements (SolarChill A and B). 1 m^2 corresponds to an approximate volume of 70 liters[9]. **250 Wh heat losses can be reduced per day if the wall thickness is increased from 50 mm to 100 mm in the PUR panel**. More detailed calculation can be done for each wall taking into account the real geometry and the external temperature of each wall (condenser, ambient, compressor, etc.) In general, **it is not recommended to use a wall thickness less than 80 mm with PUR foam**.

One should consider that **small refrigerators and refrigerators with slender geometries have a higher surface/volume ratio**.

[9] Useful volume is generally less than 100 l for vaccine refrigerators, but can be higher for SolarChill B

Figure 4 shows the heat loss per day as a function of the wall surface for three different PUR panel thicknesses.

Furthermore, the thermal bridges should be avoided or minimized as much as possible. Some of the common thermal bridges are [8]:

- Metal sheets or tubes that connect the outside with the inside.
- Badly sealed holes to pass cables, the evaporator tubes, the water drainage, etc…
- Bad sealing due to low door gasket quality

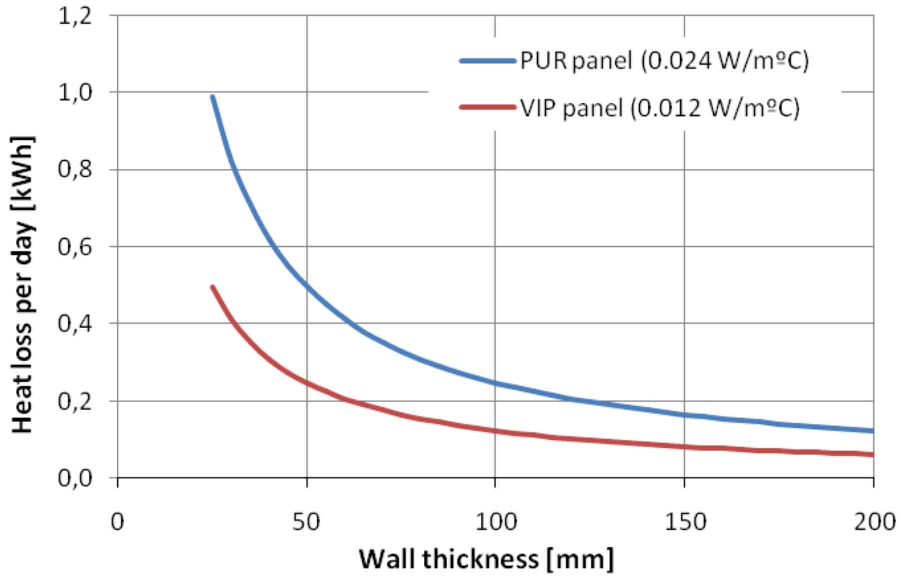


Figure 3. Heat loss per day as a function of the wall thickness for the PUR and VIP panels through a 1 m^2 surface with external temperature of 43ºC and internal temperature of 0ºC

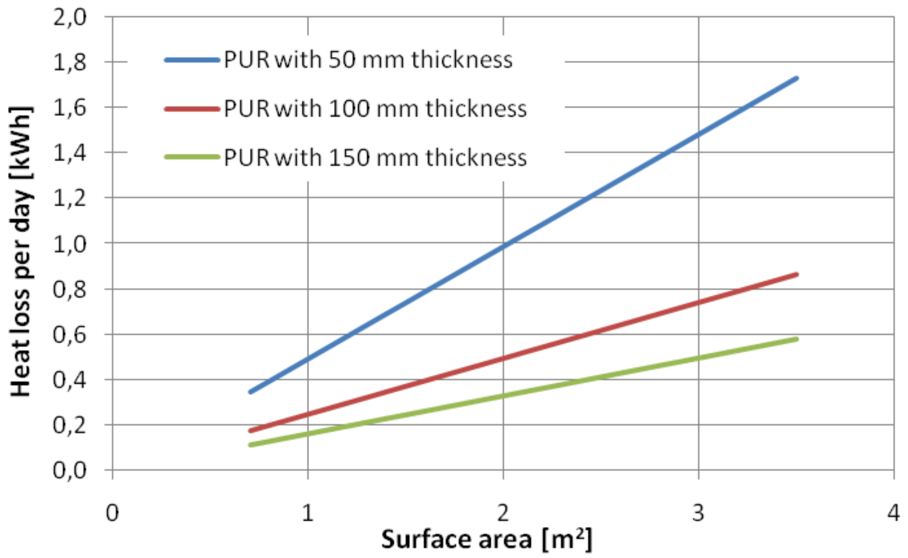


Figure 4. Heat loss per day as a function of wall surface for different PUR panel thickness (external temperature of 43ºC and internal temperature of 0ºC)

4.1.2 Gasket seal

The sealing between the cabinet and the door is one of the weakest points where a thermal bridge can occur. At this point, the outer high conductivity steel comes closer to the cold compartment, which is isolated by the door gasket. According to [9] the heat loses through the gasket are 0.08 W/mºC for refrigerators and 0.03 W/mºC for freezers in household refrigerators (heat loss due to conduction and air infiltration). For example, a typical **small refrigerator** with a 1.84 m of **seal gasket** amounts around 3 W **heat loss**, i.e. **72 Wh per day**.

Therefore, in order to decrease thermal losses, it is crucial to select a **good door gasket design with high quality**.

Gasket seals can lose tightness with time; therefore, it is important to provide the SolarChill units with quality sealing strips. Furthermore, it must be considered that these units might be installed in remote areas, so spare gaskets must be offered with the unit, and the replacement instructions must be included.

Since the wall thickness of the SolarChill refrigerator is usually thicker than the traditional ones, there might be sufficient space to mount two lines of seal gasket in the door to reduce heat losses through the door. Due to the high WHO requirements for vaccine refrigerators, special attention to heat losses must be taken in the SolarChill A refrigerator. Figure 5, shows the picture of a solar direct drive vaccine refrigerator with two door gaskets.

Figure 5: Picture of Solar Direct Drive refrigerator with two door gaskets (Credit: Dulas Ltd. Website https://www.dulassolar.org/solar-direct-drive-refrigerator-vc200sdd/)

4.1.3 Cabinet configuration

The thermal loss during the door opening must be added to the thermal loss through the wall and gasket when calculating the capacity of the refrigeration cycle and the capacity of the thermal storage. There are two main parameters that will affect the **thermal loss related to door opening: the number of times that the door is opened during the day and the type of refrigerator**.

The number of door openings will depend on the application, i.e. a commercial refrigerator might be open more times than a medical one. **[9] assumes that a domestic refrigerator is opened 20 times per day**.

When it comes to the door opening configuration, there are two main types:

- **Upright:** Front opening
- **Chest:** Top opening

On the one hand, upright refrigerators are more organized and easy to clean; on the other hand, **chest refrigerators lose less cold air when the door is opened. Cold air is heavier than hot air**; hence it falls out in vertical refrigerators when the door is opened, being replaced by hot air. Upright refrigerators might create more condensation inside the refrigerator due to higher amount of hot air entering in the compartment.

Therefore, in terms of energy losses, it is recommended to go for chest refrigerators. This will reduce costs, since the solar panels, the amount of PCM and the wall thickness can be reduced due to a lower cooling demand.

Nevertheless, the selection between chest and upright refrigerator will depend on the application and also on the thermal storage design.

Example of door-opening for an upright refrigerator:

Considering the worst-case scenario for an upright refrigerator where the air of the whole refrigerator volume is substituted by hot air each time the door is opened, the daily energy required to cool down the hot air will be: 20 times[10] x 70 liters x 1.1 J/lK (specific air heat capacity per liter & Kelvin) x 38 K (air temperature difference) → 58.52 kJ → ~**16 Wh per day for a 70 liters refrigerator.** This is small compared to the heat loss reduction accomplished by increasing the wall thickness from 50 mm to 100 mm (around 250 Wh per day in the PUR panels).

Refrigerator with freezer:

[10] Depending on the application the number of door openings can be different than 20.

The SolarChill refrigerator might come with a "freezer" compartment. One should notice that the freezer compartment can reach temperatures above 0ºC during night or periods with poor solar irradiation. Therefore, they cannot be used to store frozen perishable food, unless specific measures are taken, for instance, the use of low temperature PCM around the freezer compartment.

Some **SolarChill A models use a "freezer" compartment to freeze water icepacks**[11] during the day to be used in the next morning to transport vaccines in a passive cold box.

4.1.4 Energy due to warm load

SolarChill A:

Vaccines should always be between 2ºC and 8ºC to remain effective, even when they are placed into the refrigerator. Therefore, the energy consumption due to warm load into the vaccine compartment is expected to be low.

The major energy consumption due to warm load is expected in the freezer compartment, if present. According to the WHO test protocol, a **minimum water-pack freezing capacity of 1.6 kg of water must be frozen every morning**. This gives an energy of 43ºC x 1.6 kg x 4.18 kJ/kgºC = 287.6 kJ → 79.9 Wh for cool down and 1.6 kg x 334 kJ/kg = 534.4 kJ → 148.4 Wh for freezing, giving a total of **228.3 Wh per day.**

SolarChill B:

The DTI test protocol for SolarChill B (see annex B), stipulates a cool down capacity of at least 4.5 kg of standard test packages per 100 liters refrigerator volume. All test packages must reach temperatures below 10ºC in less than 12 hours.

Nevertheless, the real energy consumption due to warm load will depend on the application: household, selling beverage, milk cooling, etc. For instance, a **commercial refrigerator to sell cold water** is replaced every day with **5 liters of water**. In this case, energy due to the warm load will be: (43ºC-10ºC) x 5 kg x 4.18 kJ/kgºC = 689.7 kJ → **191.6 Wh per day.** SC-B refrigerators could be bigger, but the test temperature could also be lower (32ºC).

[11] The Ice Packs used in the freezer for the vaccine application must be certified by WHO: https://www.who.int/immunization_standards/vaccine_quality/e05_ice_cool_warm_packs/en/ (last login 18/06/2019)

In this sense, the cooling demand of SolarChill B can be higher than for SolarChill A without freezer and might be higher also than SolarChill A with freezer for some applications. Therefore, the energy consumption due to warm load can be a big portion of the total energy consumption and it must be taking into account during the design process of the unit. **Overloading the refrigerator over the designed load, might lead to higher temperatures than allowed in the refrigerator compartment.**

The requirements for vaccine refrigerators are higher than for commercial ones. Hence, SolarChill A might need thicker or low conductivity insulation to protect the vaccines from high temperatures. Nevertheless, due to bigger volumes and higher process loads in the commercial refrigerator, the insulation might be improved in SolarChill too, reducing the size of compressors and solar panels.

TOTAL ENERGY DEMAND PER DAY FOR A 70 LITERS REFRIGERATOR		
Demand due to:		**Energy (i)**
1. **Losses though the wall of 100 mm**		**248 Wh** (846.1 BTU)
2. **Losses through gasket (ii)**		**72 Wh** (245.6 BTU)
3. **Losses through door opening (20 times)**		**16 Wh** (54.6 BTU)
4. **Energy due to warm load**	**a) SC-A without freezer**	**Negligible**
	b) SC-A with freezer	**228 Wh** (minimum) (778.9 BTU)
	c) SC-B, commercial selling (iii)	**192 Wh** (variable) (653.7 BTU)

(i) These values are an approximation. It is recommended to do the calculations for each specific case and not extrapolate from the values above.

(ii) The 72 Wh/day for the gasket is an example from [9], this value can be reduced by improving the gasket seals.

(iii) 5 liters water per day (4.5 kg of test packages according to DTI protocol, annex A)

4.2 Thermal storage

This is one of the most important parts of a SolarChill refrigerator, as it will determine the function of the refrigerator during nights and poor solar irradiation periods. The **main parameters** for the thermal storage are: **material used for PCM, position in the refrigerator (design), and PCM amount to be frozen.**

4.2.1 PCM material

The thermal storage is done with a PCM (Phase Change Material) due to its capacity to store big amounts of energy without changes in temperature (or small changes). **Materials with high latent heat are preferred**.

Water can be used as a thermal storage (PCM). Water is cheap, highly available and has a high latent heat (around **334 kJ/kg** (144 BTU/lb)) and is an environmental friendly material. Furthermore, depending on the design, water can be filled in place, reducing the weight of the unit when being shipped.

Nevertheless, some **caution needs to be taken**:

- The **volume of ice** is higher than water at its liquid state. This needs to be considered in the design to avoid undesirable breakdown due to mechanical stress.
- Those parts that are in contact with water, needs to **be protected against corrosion** and be sealed tight to avoid leakage.
- Freezing point of water is 0ºC. Depending on the application, **measures might to be taken in order to not reach freezing temperatures** in the refrigerator compartment (e.g. vaccines are very sensitive at low temperatures). Subcooling in the ice could increase risk of vaccine damage.

To obtain the "Grade A" WHO freeze-protection certification for the SolarChill A refrigerator, the vaccine compartment temperature must be between 2ºC to 8ºC (see annex A clause 4.2.4).

One solution to have a temperature gradient between the thermal storage and the cold compartment is to use some insulation between these two compartments where the ice will be formed.

Another solution is to use commercial PCM materials with a freezing point different than 0ºC. These PCM's can be used with the SolarChill technology for applications with different target temperatures.

4.2.2 Thermal storage design

There are different ways to design the layout of the thermal storage, which will maintain the refrigerator cool while melting during the hours of inactivity. Figure 6 shows a simplified scheme of the layout of the different volumes of the refrigerator, from inside to outside, the compartment volumes are: refrigerated compartment, compartment with the PCM, and insulation. Figure 7 shows a 3D cut of a SolarChill configuration example with the PCM material (in red) around the refrigerated compartment. The evaporator tubes wrap around the PCM, which is separated from the refrigerator compartment.

The thermal storage lies between the refrigerator compartment and the wall of the refrigerator. There are **two main options to store the PCM**:

- The **PCM is confined in ice-packs**, plastic boxes around the compartment (ice-lining). In this case the evaporator is not in direct contact with the PCM.
- The **PCM is confined in a single volume around the refrigerator compartment**. In this case, the evaporator can be in contact with the PCM, or it can be separated by a thermal conductive wall. Heat is transferred into the water by convection.

The idea of the single PCM compartment unit is that PCM (usually water) is in contact with most of the refrigerator compartment walls. In this case, only a portion of the PCM will be frozen and the rest will be in liquid state to keep a good temperature distribution around the compartment by natural convection (see the SureChill example, figure 8). Furthermore, heat conductivity between the evaporator and the PCM can be increased. These units need more PCM, but have the advantage that can be filled in place, hence reducing the weight of transportation. Other aspects to take into account are: it requires a more careful design to avoid cracking due to the volume expansion of ice, the right materials to avoid corrosion.

Cycling (ON/OFF) control of the compressor to freeze the PCM

The evaporating temperatures can be much lower than the freezing point of the PCM, which is also lower than the refrigerator temperature. Furthermore, the specific heat of air is much lower than the latent heat of the PCM, hence, depending on the design, it can be the situation that the refrigerator compartment reaches the set point to **switch off the compressor before the required amount of PCM is frozen. This situation should be avoided, since it will lead to a lower autonomy when there is poor solar irradiation. The idea is that the heat flows from the compartment to the PCM and from the PCM to the evaporator.**

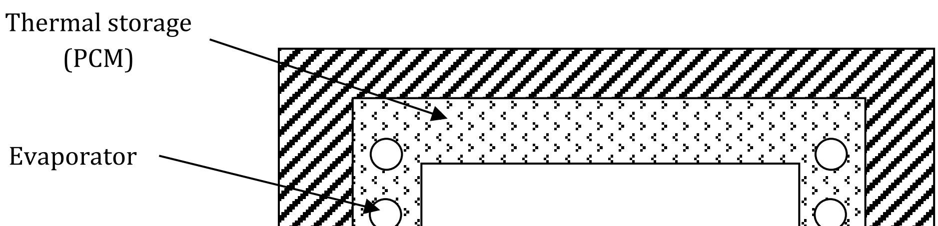


Figure 6: Layout scheme of the different volumes of the refrigerator

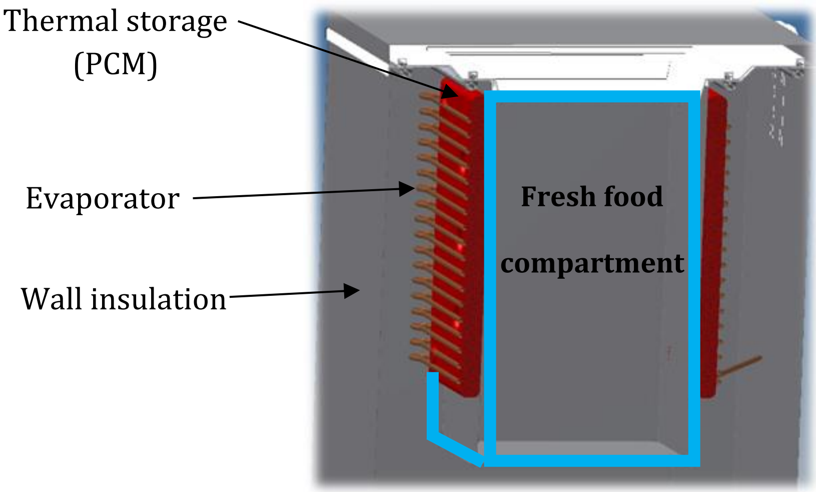


Figure 7: SolarChill chest refrigerator 3D cut (Source: Gunther drawings for the SolarChill project)

After a long period of inactivity, the temperature of the PCM and the refrigerator compartment will reach the ambient temperature. When the refrigerator is switched ON, the temperature of the PCM starts to decrease, and in consequence it decreases also the temperature in the refrigerator compartment. At some point the PCM will start to freeze. **The compressor should be switch OFF when the right amount of ice is created and must be switched ON again when part of this ice has melted.**

The most common way to control the **ON/OFF switching of the compresso**r is a **thermostat**. In this case, a **minimum temperature** is set in the compartment to

switch OFF the compressor, when the temperature in the compartment increases to a **maximum value**, the compressor **is switched ON again**. Minimum set point temperature should be enough to allow the PCM to reach the eutectic point and produce the right amount of frozen PCM before switching OFF the compressor.

Another way is to use an **ice probe** in the PCM vessel, so it is known when the amount of ice (or frozen PCM) is sufficient to guarantee the hold over time requirements. This is the procedure described in the SureChill technology patent [10].

The design for the thermal storage in the patented SureChill technology [10] is based on the property of water having the highest density at the temperature of 4ºC. This is an example of a single PCM compartment unit. The technology and the underlying physical principals are outlined below, but it is responsibility of the manufacture to not violate any intellectual property or to put in contact with the patent owner if they would like to get a license to manufacture with this technology.

Figure 8 shows a scheme of an upright refrigerator side cut for the SureChill technology [10]. In this case, **the entire refrigerator compartment is surrounded by water**, with the evaporator located in the upper part. When the refrigerator is switched ON, the water close to the evaporator starts to cool down. The cold water falls down and the warmer water that was in the bottom goes up. This process is repeated until the water temperature reaches 4ºC. At this point the water below 4ºC is lighter, so the cold water will stay in the upper part and the water at 4ºC will be in the lower part surrounding the refrigerator compartment. At some point the ice will start to grow around the evaporator. Once the ice reaches the ice probe, the compressor is switched off and the water around the refrigerator compartment will maintain the temperature around 4ºC. The block of ice needs to be sufficient to cover the cooling demand during the hold over time specification (> 72 h for SolarChill A and > 48 h for SolarChill B).

One should notice that the amount of water (PCM) in this design might be higher than in other designs, since it is divided in two parts: the thermal storage in the form of ice and the water volume that surrounds the refrigerator compartment.

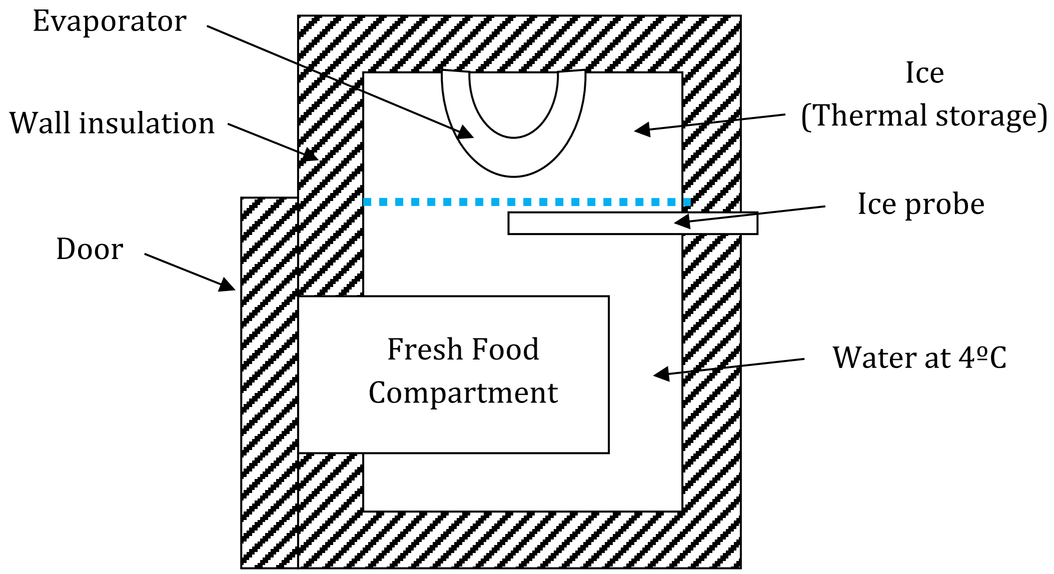


Figure 8: Scheme of the SureChill technology with the upright refrigerator type. (Source: Own prepared based on the design showed at the SureChill patent [10])

SolarChill A design with freezer

The freezer compartment for the SolarChill A does not need to be surrounded with PCM, as the main purpose of the freezer is to produce ice. In this case, the evaporator can directly surround the compartment.

Special control algorithm will be needed to decide which compartment (vaccine or freezer) is cooled down as it might be periods with low power supply. Preference should be given to the vaccine compartment to always have temperatures below 8ºC. Some possible configurations are: **two different compressors can be used for each compartment or only one compressor with two evaporators and an algorithm control with solenoid valves.**

4.2.3 PCM quantity

The amount of thermal storage will depend mainly on the cooling demand, the latent heat of the PCM and the specifications for the hold over time.

Both refrigerator types, SolarChill A and B, should be able to maintain the temperatures inside the specification range for a minimum certain of time with poor solar irradiation. **The poor solar irradiation is 0.35 kWh/m^2 per day, which in**

practice means that the compressor will be off during this period of time (energy might be enough to power the fans).

Frozen PCM for SolarChill A:

The minimum hold-over or autonomy time required by WHO (t_{ho}) is **72 hours** with all temperature sensors (wall and air) below 8ºC.

Equation 2 gives the energy demand that will need to be covered by the thermal storage during the designed autonomy (minimum 72 h). This equation is valid for both, refrigerator with and without freezer, since the ice is not required to be formed during this time.

$$Q_{dem} = Q_{wall} + Q_{door} + Q_{gasket} \tag{2}$$

Where: Q_{wall} is the energy loss through the walls during t_{ho}, in kJ
Q_{door} is the energy loss through the door openings during t_{ho}, in kJ
Q_{gasket} is the energy loss through the gasket during t_{ho}, in kJ

Please notice that units are given in kJ, to convert to Wh, or BTU, use the following equivalences:

$$\mathbf{1\ Wh = 3.6\ kJ}$$
$$\mathbf{1\ BTU = 1.06\ kJ}$$

The latent heat from the frozen PCM must be, at least, equal to the energy demand during the hold over time t_{ho}. Nevertheless, when calculating the required mass of PCM, one should consider that:

- A minimum amount of ice might be needed to maintain the compartment temperatures within the required temperature range.
- At some parts the PCM might not be totally frozen when the period of poor solar irradiation starts.
- Asymmetric fusion around the compartment might happen, leading to some areas where the PCM melts first (e.g. the sun heating one side of the refrigerator)

Therefore, it is recommended to use a security factor when calculating the required frozen PCM. The amount of PCM to be frozen is given by equation 3 in kg:

$$m_{PCM} \geq \frac{Q_{dem}}{L_{PCM}} \cdot \varphi \tag{3}$$

Where L_{PCM} is the fusion specific latent heat of the PCM expressed in kJ/kg (Water → 334 kJ/kg (144 BTU/lb)) and φ is the safety factor. There are no studies on the exact value of this factor, we propose to use a factor between 30% to 50% as a first generic estimate ($1.3 < \varphi < 1.5$).

As an example, using the thermal losses calculated in section 4.1 for a 70 liter refrigerator with 100 mm wall thickness equipped with an improved gasket (~41 Wh per day), the daily energy demand will be 305 Wh → 915 Wh (3294 kJ) during the 72 hours.

Therefore, applying equation 3 for water as PCM and a security factor of 1.5, gives a minimum of 14.8 kg of ice.

As a rule of thumb:
For each 1 Wh, 16.2 grams of water needs to be frozen
100 Wh → 1.62 kg of ice
100 BTU → 0.48 kg (1.05 lb)

Furthermore, depending on the thermal storage design the mass of PCM to be used in the refrigerator can be much higher, even though only part of it will be frozen. For instance, in the Sure Chill technology where part of the water (PCM) is in liquid state during the whole process. This volume of liquid water must be added to the calculated m_{PCM}.

Frozen PCM for SolarChill B:

The minimum hold-over or autonomy time required by DTI protocol (t_{ho}) is **48 hours** with all M-packages below 12ºC. One should notice that the temperature limit is higher than for SolarChill A and that temperatures are taken inside the M-packages instead of in the wall or in the air. Therefore, in this case, the requirements are less strict, not only because the less required autonomy time, but also due to the maximum allowed temperature. Smaller safety values can be selected for SolarChill B, nevertheless, the same value of 1.5 has been used in this example.

As in the previous case, the energy demand is 305 Wh per day, which gives 610 Wh during the 48 h of required autonomy. **Therefore, the minimum amount of ice to cover the energy demand for SolarChill B is 9.9 kg.**

Nevertheless, the **manufacturer could claim that the refrigerator is able to keep cooling a certain amount of product even without energy supply**. In this case, the **energy due to warm load (Q_{prod}) needs to be added to the energy demand**:

$$Q_{dem} = Q_{wall} + Q_{door} + Q_{gasket} + Q_{prod} \tag{2}$$

For a commercial refrigerator that is used to sell cold water, the energy needed to cool down 5 liters per day is 383.2 Wh for 48 hours. The total energy demand in this case is 993.2 Wh, and the minimum amount of ice to cover the energy demand is 16.1 kg. Therefore, these considerations are important when designing the SolarChill unit.

Examples of frozen PCM calculation for 70 liters refrigerator:

1. **SolarChill A (72 h) with and without freezer → 14.8 kg of ice**
2. **SolarChill B (48 h) (SCB requirements) → 9.9 kg of ice**
3. **SolarChill B (48 h) with process load → 16.1 kg of ice**

Thermal losses and assumption in section 4.1 and 4.2.3

4.3 Compressor

The SolarChill technology is based on the Solar Direct Drive principle. This means that the compressor is directly powered by the solar panels, which provide direct current (DC). There are inverters to convert to alternating current (AC), which efficiency has increased in the last years. AC compressors are cheaper than DC, but the electric inverter can be expensive.

At the time of writing this guide, there are very few commercial types of DC SDD compressors available. The **main challenges for the compressor** when connected directly to the PV panels are:

- The **starting current is much higher than the operating current**, so PV panels are oversized to be able to start the compressor

→ Solution: Use electronic soft start devices or use capacitors[12] that are charged before a start attempt

- **Availability of power** varies with the solar irradiance varies **during the day**, so PV panels are oversized to let the compressor work during more hours

→ Solution: variable speed compressors to work at different power inputs

- **Voltage in the PV panel can vary during the day**

→ Solution: use electronic controls to allow compressors to work in a broader voltage range

[12] According to [11] the new ultra capacitors are less expensive and store much more electrical energy than traditional electrolytic capacitors.

SECOP[13,14] has developed a compressor model for solar applications that contemplate these three issues. The model is the **BD35K with the electronic control unit 101N0420**. This model is dominating the market of SolarChill A WHO certified units. The **working voltage range is 10 to 45 V**. The electronic unit has a built-in **soft-start function** that reduces the starting current not to be higher than the operating current (see figure 9). And the so-called **adaptive energy optimizer** (AEO) control **tries to adapt the compressor speed to the available power from the PV panel to work during more hours per day → Reducing PV panel size and costs.**

The **AEO control is a relatively simple regulator** working after the trial and error principle. **Figure 10 shows solar irradiance and the compressor current along the day:**

1. The compressor attempts to start up at the lowest possible speed, 2500 RPM (soft start), which needs less current
2. If there is enough available power and the start is successful, speed is slowly ramped up during a maximum period of time that can be set with the compressor software "tool4cool"
3. After the maximum time for the ramp-up speed is reached, the compressor speed changes to the maximum selected speed (maximum 3500 RPM). The compressor will run at this speed constantly unless stopped by the thermostat or there is a reduction on the available power
4. If for example, a cloud blocks the sun, the voltage breaks down and the compressor stops completely
5. The procedure is repeated after some minutes
6. If there is not enough available power to reach the maximum speed, the compressor will stop and start at a lower speed to restart the process (for instance at the end of the day).

[13] There are other DC compressors in the market, like ASPEN and SIKELAN, but they are not optimized for SDD applications, so additional electronic control units might be needed to make them work efficiently.

[14] Using an efficient (permanent magnet) and reliable (electronic commutator) compressor type might be recommended, however PV panels are less expensive than some years ago, so a little less compressor efficiency could be compensated by slightly better/larger PV panels.

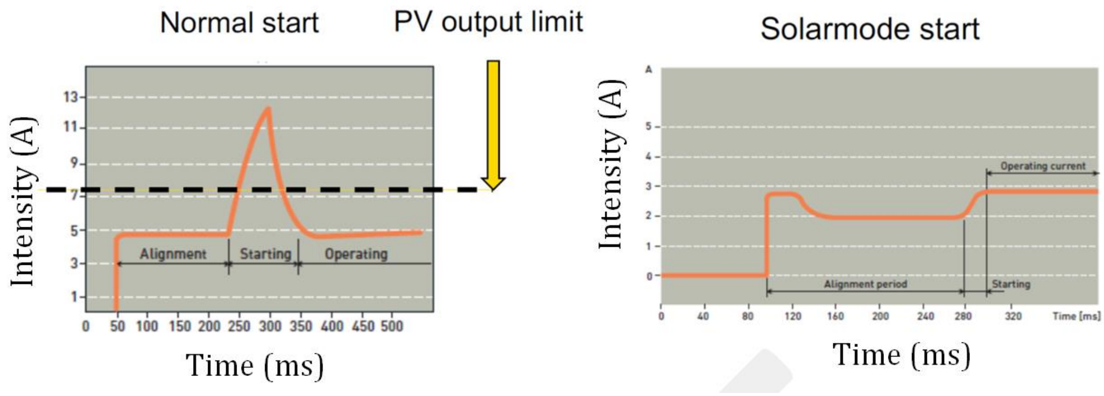


Figure 9: Intensity demand of a normal compressor start and the solar mode start (Source: SECOP presentation [12])

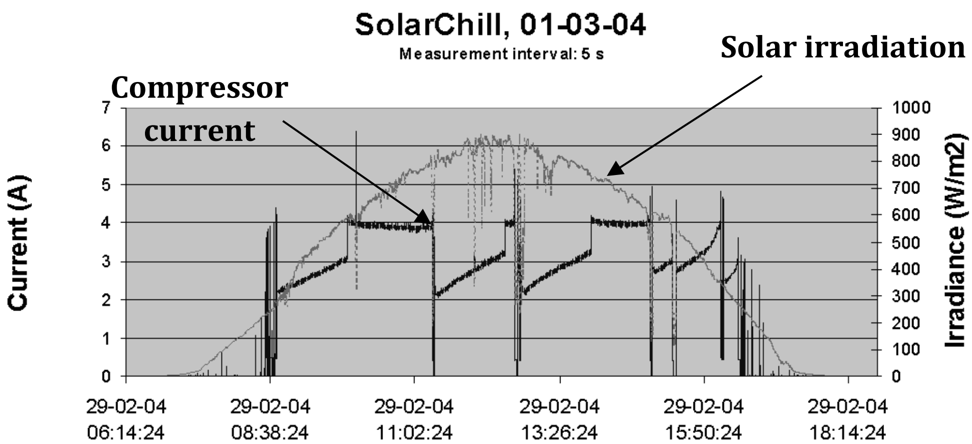


Figure 10: Intensity demand of a normal compressor start and the solar mode start (Source: Per Henrik Pedersen et al. (2005) [13])

In a traditional refrigerator, the size of the compressor is selected depending on the cooling demand and considering that the energy is always available. In the SolarChill technology, the energy is only available during the day, and it will also depend on the time and the weather.

Therefore, during the working hours, the compressor will cover both: the cooling demand of the refrigerator during the day and also will have to freeze the required mass of PCM to cover the cooling demand during night and periods with poor solar irradiation. This will lead to a bigger compressor compared to a similar traditional refrigerator size.

Figure 11 shows the SECOP compressor capacity and power consumption at different conditions. **Considering that cooling capacity is around 90 W** (for an evaporating temperature between -15ºC to -10ºC). Table 1 shows the comparison between the maximum available cooling energy by the compressor with different working hours and the energy demand for different refrigerator types. For instance, **a compressor that is able to work an equivalent time of 6 hours per day at full**

speed will provide a cooling energy of 540 Wh per day, which is enough to cover the cooling demand of the examples seen in the previous sections. The bigger the difference between the cooling energy and the energy demand, the more time the compressor will be off during the day.

If the available cooling energy is higher than the energy demand, the compressor will be OFF during some time per day, even if there is enough power supply to start the compressor. Nevertheless, it requires a higher cooling energy to be able to recover the extra amount of ice melted during a highly cloudy day. For instance, the SolarChill A refrigerator working 8 hours per day is able to provide 415 extra Wh per day, hence, the refrigerator will take around 3.6 days to recover the total ice melted during 3 heavy cloudy days (1.62 kg of ice per 100 Wh).

Table 1: Daily Energy demand and maximum cooling energy for different working times70 liters Refrigerator with 100 mm insulation

	Energy demand/day	**Cooling energy/day (6h)**	**Cooling energy/day (8h)**
SolarChill A	305 Wh	540 Wh	720 Wh
SolarChill A with freezer	533 Wh	540 Wh	720 Wh
SolarChill B (5 liters water per day)	497 Wh	540 Wh	720 Wh

Capacity (ASHRAE LBP) 12V DC, static cooling **watt**

rpm \ °C	-30	-25	-23.3	-20	-15	-10	-5	0	5	7.2	10	15
2,000	16.0	25.6	29.1	36.3	48.5	62.4	78.4	97	118	128	142	
2,500	20.7	30.9	34.8	43.1	57.5	74.5	94.3	117	144	157		
3,000	25.8	37.4	42.0	51.6	68.6	88.9	113	140				
3,500	30.6	43.9	49.0	60.0	79.2	102	129					

Power consumption 12V DC, static cooling **watt**

rpm \ °C	-30	-25	-23.3	-20	-15	-10	-5	0	5	7.2	10	15
2,000	17.5	21.5	22.8	25.4	29.1	32.8	36.5	40.2	44.1	45.8	48.0	
2,500	22.9	27.2	28.6	31.3	35.4	39.5	43.6	48.0	52.5	54.5		
3,000	28.9	34.6	36.4	40.0	45.4	50.9	56.5	62.5				
3,500	33.7	41.1	43.5	47.8	54.1	60.4	67.1					

Figure 11: Capacity and power consumption for the SECOP compressor BD35K (Source: BD35K datasheet [14])

As stated before, SC-B refrigerators might have a larger volume, hence a more powerful or more than one compressor could be needed. The following alternatives can be explored

- Several compressors connected in parallel
- Use larger DC compressors with adapted electronic units to work as SDD (e.g. SIKELAN makes larger compressors than the BD35K)
- Use an AC compressor with DC/AC inverter combined with a motor soft starter

The size needs to be optimized according to the demand. Oversized compressors will lead to higher consumption, requiring bigger solar panels and hence increasing the price of the system. Oversized compressors will work fewer hours during the day, and the system will not be optimized.

The BD35K is the most spread compressor in solar applications. SECOP is working to bring to the market different compressor sizes for solar applications.

4.4 Solar PV system

The solar energy supply is one of the main parts of the SolarChill technology. There are several things to take into account when selecting the photovoltaic (PV) panels, but the two main are:

- **The nominal power** of the PV panels
- The **voltage** at nominal power

These values are usually given for the maximum power point (MPP) at the standard irradiance of 1000 W/m^2 and 25ºC cell temperature, but the irradiance and panel temperature will change during the day and so will do the voltage and power at the MPP.

Figure 12A and 12B show the I-V curve and the corresponding power supply by the solar panel for different solar irradiation. It can be seen that the maximum power (and current) is reduced with the reduction of irradiance, but the corresponding voltage is reduced slightly. **Figure 12C and 12D show the same curves, but for different temperatures.** In this case voltage and power at the MPP point decreases with temperature, but not dramatically. In a hot climate, it is not unusual to have 70ºC cell temperature instead of the 25ºC used in the standard PV module test.

Actually, **the position on the I-V curve will depend on the electric load from the compressor**. Ideally, the working point would be the MPP, so the panel is giving the maximum power for a given irradiance-temperature condition. This is possible for panels connected to the grid or batteries, where the load can be modified to match the MPP point at any condition. But this is not true for **a direct drive compressor, which might work at different points than the MPP**.

The daily simulated solar input used in the SC-A and SC-B test protocols can be seen in figure 13. The total energy supplied is 3.5 kWh/m^2 per day. According to this distribution the solar panel will deliver at the first and last hours of the day just the 5% of the nominal power (1000 W/m^2), and during the mid-day it will deliver 45% of the nominal power.

For instance, a 300 W solar panel will deliver 15 W in the morning and 135 W in the afternoon. For a 12 V PV panel, the corresponding current in the morning and afternoon will be 1.25 A and 11.25 A. Looking at figure 11, the BD35K compressor will not be able to work the first and last hour of the day.

Therefore, the solar input distribution must be taken into account when selecting the solar panels size, since this will determine during how many hours per day will be able to run the compressor (enough current input to start up and normal operation). Table 1 showed an example of the daily cooling energy depending on the number of working hours for the compressor BD35K.

The size of the PV panel will depend on the characteristics of the SolarChill unit and the compressor that will be used. Even though it might change with the design, 360 W is a regular PV panel size for Vaccine refrigerators that work with the compressor BD35K (other sizes are possible).

There are different PV panel modules sizes, for instance, the 360 W could be reach by combination of four 90 W PV panels, or by two 180 W PV panels. A single PV panel to power the refrigerator can reduce costs as there are less connectors, but it might be less convenient when mounting it due to bigger dimensions and weight.

According to the WHO requirements for vaccine refrigerators, the solar module voltage must be up to 45 volts open circuit (voltage at the maximum power point (MPP) is lower than at the open circuit). Apart from the WHO requirements, the PV panel voltage must be compatible with the compressor and other components such as the thermostat and fan. The SECOP BD compressor for solar applications is able to work with range of 10 to 45 V. Other components, such as the thermostats that work within a more reduced voltage range might need a DC to DC voltage regulator to adjust the panel voltage to the required input voltage of the device. One should remember that the voltage might change depending real conditions. Typical nominal voltages for PV panels made for battery systems are 12 or 24 V, while grid connected panels have higher voltages.

Even though, the voltage can change during real operation (temperature, irradiance and electric load), **the laboratory tests are done at constant voltage** (WHO protocol for SC-A and DTI protocol for SC-B). **In this case, the current is adjusted to simulate the maximum available power along the day**.

Apart from the voltage requirements, the power system that will be supplied with the vaccine refrigerator (SC-A) must conform to the WHO standard **E003/PV01**. Some of these requirements are:

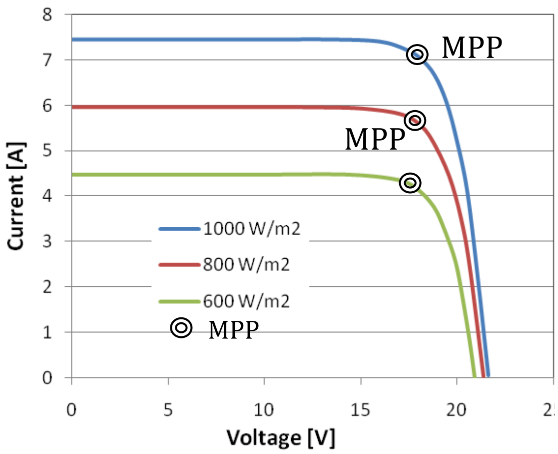
- 20 years warranty with 80% of initial power
- Roof/ground mounts with specific characteristics are to be supplied
- At least least one method to disconnect the refrigerator from the solar power system must be supplied
- System components must fit through an 830 mm wide door opening
- Etc.

Energy harvest control system

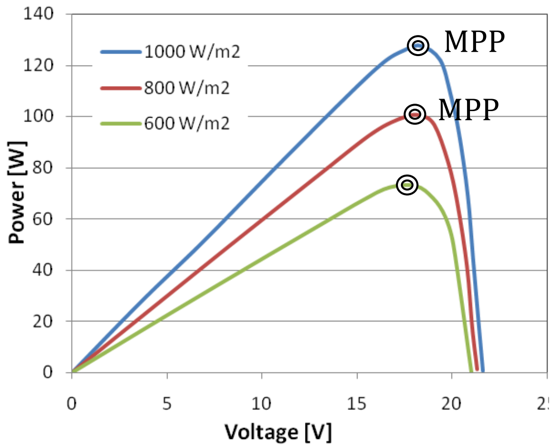
During a normal sunny day, the PV panels are oversized, since they were designed to ensure the well function of the unit during partly cloudy days (3.5 kWh/m^2 per day). This situation leads to **waste capacity of the PV panel, not only when the compressor is OFF and there is still solar irradiation, but also when the compressor is ON and it is not working at the maximum power point (MPP) point of the panel**.

One option to take the maximum benefit from the PV panels is to use an energy **harvest control system to store the energy that is not used in the refrigerator**, so it can be used for other purposes [15], like light, charging a cell phone, etc. The harvest system should be able to harvest the extra energy, but priority has to be given to the refrigerator. For SolarChill A refrigerators, the energy harvest device must be certified by WHO. There is currently only one WHO approved product on the market from Dulas Ltd.

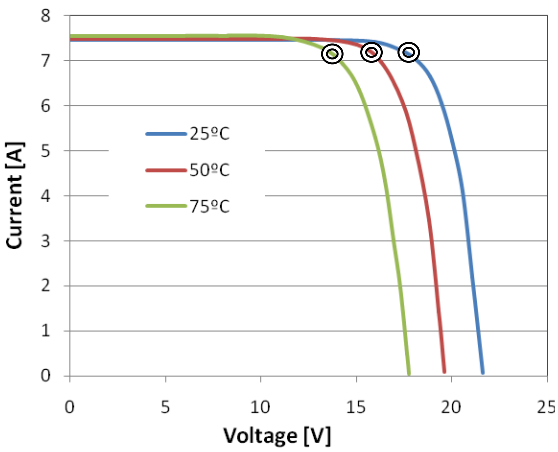
It is important while designing the SolarChill refrigerator to take into account the characteristics of each component. For instance, compressors are able to work at different speeds, and hence work at different solar irradiations, might be able to cover the cooling demand with smaller PV panels.
The selection of wall technology (VIP, PUR) and thickness will also affect the size of the compressor and solar panels, the selection must be a compromise between cost and performance to achieve the requirements of the SolarChill in each application.



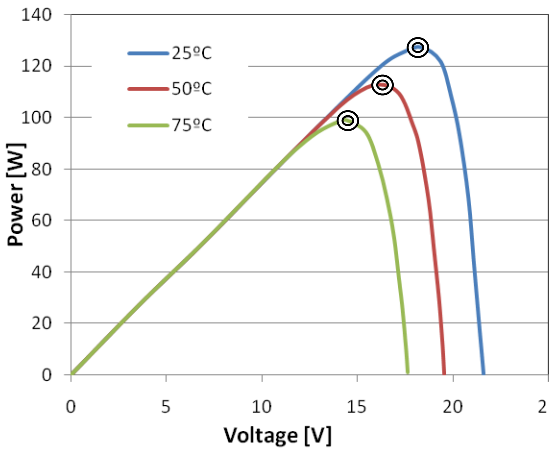
A. I-V curve at 25ºC (different irradiance)



B. P-V curve at 25ºC (different irradiance)



C. I-V curve at 1000 W/m² (different temperatures PV panel)



D. P-V curve at 1000 W/m² (different temperatures PV panel)

Figure 12: I-V and P-V typical curves for a PV panel at different conditions

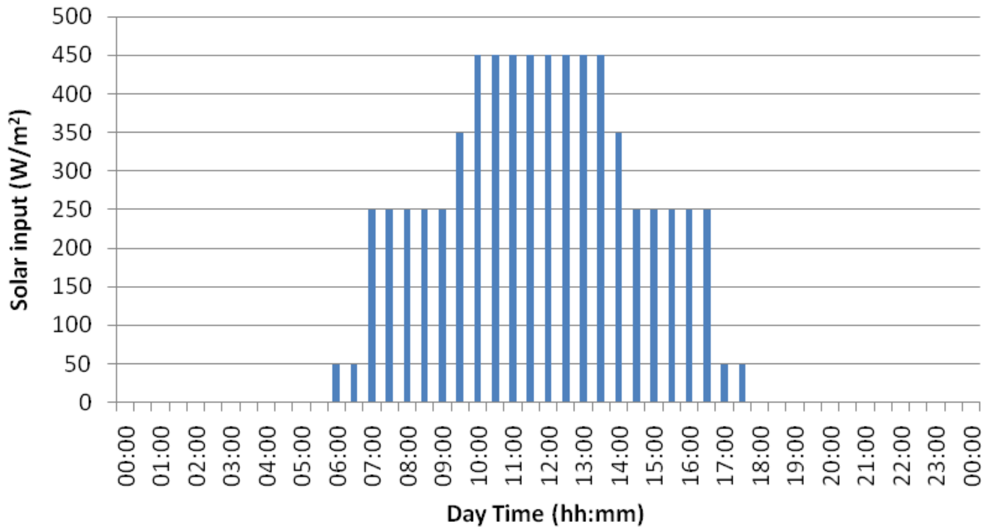


Figure 13: Solar irradiation distribution along the day for the SolarChill A and B test

4.5 Evaporator

In the traditional domestic refrigerators, the evaporator is usually located in the refrigerated compartment. In the SolarChill refrigerators, the evaporator is located outside the refrigerated compartment because it has to freeze the PCM material before the refrigerator compartment reaches the lowest allowed temperature.

Since the freezing point of the PCM is lower than the required temperatures in the refrigerator, the evaporating temperatures might be lower when compared with a traditional refrigerator for the same target temperatures.

As commented in section 4.2.2, the evaporator and PCM are located around the refrigerator compartment. Two options can be considered when placing the evaporator with respect to the PCM:

- **Direct contact**: The surface of the evaporator is in direct contact with the PCM. One example is the SureChill technology explained in 4.2.2
- **Separate**: The surface of the evaporator is not in direct contact with the PCM. For instance, the PCM is inside of water packs, which are distributed around the refrigerator compartment (ice lining) and the evaporator is surrounding the water packs

The evaporating temperature should be low enough to freeze the PCM. Nevertheless, evaporating temperatures too low will decrease the cooling capacity. The optimization of the refrigerant cycle to increase efficiency is important in order to reduce as much as possible the size of the PV panels and reduce cost.

The design of the evaporator will strongly depend on the design of the thermal storage. One must consider that in some design cases, the evaporator will be totally submerged in the PCM (e.g. water). Therefore, special attention needs to be taken to corrosion and also the effect of volume expansion of ice. The expansion of ice could damage the evaporator.

For the SolarChill A with a separate freezer compartment, there are different possible designs. Some of them are:

- Only one evaporator with the freezer compartment placed next to it. In this case the cooling capacity is used at the same time for the PCM/refrigerator and the freezer. With this design, priority cannot be given to the refrigerator compartment.
- Two evaporators for the same compressor. Depending on the control, both evaporators can work at the same time or be selected depending on the needs and the available power. Solenoid valves to select evaporator.
- Two evaporators with two compressors (two independent refrigeration cycles). This control might be more expensive (more components).

4.6 Condenser

As commented before, the compressor of SolarChill refrigerator needs more cooling capacity than an ON-grid refrigerator for the same cooling demand, as it will be switched ON less time per day. Therefore, it will also have to dissipate more heat (power) to the ambient. Furthermore, SolarChill refrigerators are usually small and in many cases are expected to be located in warm and humid climates with sufficient sunshine.

Therefore, in some cases, installing natural convection condensers could lead to high condensing and compressor discharge temperatures, reducing the life of the refrigerator components and reducing the efficiency of the system.

Fan-cooled condensers can be a solution to lower the condensing temperature, but may be more vulnerable to dust and failure. The fan consumption of electricity and voltage range must be taken into account when calculating the size of the solar panels.

4.7 Control unit

As commented in the thermal storage, compressor and evaporator sections, the control of the unit will depend on the design of these components.

To summarize, the important variables to look at, when designing the control unit are:

- Compressor speed: Compressor speed can be adapted to the available solar energy, increasing the number of working hours. For instance, the compressor BD35K incorporates the AEO control based on trial and error principle.
- Compressor ON: The compressor can be switched ON when the temperature inside of the refrigerator compartment is higher than a certain limit. One should take special attention not to melt a big portion of the PCM before the set value is reached. SureChill patented technology uses an ice probe located in the PCM to know when the compressor should be switched ON and OFF.
- Compressor OFF: The compressor can be switched OFF when the temperature inside of the refrigerator compartment is lower than a certain limit. The PCM should be frozen without getting too low temperatures in the refrigerator compartment (special attention to SolarChill A).
- Logic control for SolarChill A with freezer: Priority should be given to the vaccine compartment. See section 4.5 for different refrigeration cycles designs.

4.8 General recommendations

The SolarChill technology is usually installed in remote areas in different climatic conditions and no reliable electricity supply, if at all. Therefore, users might not be used to refrigerators, and much less to SolarChill refrigerators.

The general WHO PQS specifications [2] for SDD vaccine refrigerators might also be applied to other SDD refrigerators. The build quality of the appliance and all ancillary components must be consistent with the conditions under which these appliances are used, including, but not limited to, the following:

- Transport by air, sea and over rough, dusty road surfaces.
- High temperatures during transport, storage and operation.
- Low temperatures during transport, storage and operation.
- High humidity during transport, storage and operation.
- Operating locations with high wind and high density of dust particles.
- Operating locations near corrosive marine environments.
- Users with inconsistent training.
- Users with no specific maintenance tools.
- Appliance design must account for performance degradation over the 10 year target life-time of the appliance in order to sustain acceptable target temperatures.

Due to remoteness, it is important to offer the unit with a good user and technician manual, so they can solve eventual problems that might appear during operation.

The expected use of the SolarChill appliance is crucial to determine in the design phase, such as daily/seasonal load variations, if not some customers may become disappointed.

Reference

[1] SolarChill - Development, Testing and Technology Transfer http://skat.ch/wp-content/uploads/2017/03/Solar_Chill_leaflet_update_final.pdf

[2] WHO/PQS/E003/RF05.5 (2018), PQS performance specification: Refrigerator or combined refrigerator and water-pack freezer: Solar direct drive without battery storage. (Can be found at http://apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/categorypage.aspx?id_cat=17)

[3] WHO/PQS/E003/RF05-VP.4 (2016), PQS Independent type-testing protocol: Refrigerator or combined refrigerator and water-pack freezer: Solar direct drive without battery storage. (Can be found at http://apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/categorypage.aspx?id_cat=17)

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[7] Sankarshan Vermaa , Harjit Singha (2018), Vacuum insulation in cold chain equipment: A review. 2nd International Conference on Sustainable Energy and Resource Use in Food Chains, ICSEF 2018

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[11] Michael K. Ewert, et.al. (2002), Photovoltaic Direct-Drive, Battery-Free Solar Refrigerator Field Test Results. Conference: Solar 2002 - American Solar Energy Society, At: Reno, Nevada.

[12] SECOP Presentation (2016) "R600a SolarChill Vaccine Coolers" of SECOP at the Atmosphere Natural Refrigerants in Chicago.

[13] Per Henrik Pedersen, Søren Poulsen & Ivan Katic (2005), SolarChill - a solar PV refrigerator without battery

[14] NIDEC, SECOP, BD35K Direct Current Compressor R600a 12/24V DC, 10-45V DC Solar

[15] PATH (2017), Energy Harvesting Controls for Solar Direct-Drive Cooling Systems, Laboratory testing report

Annex A: SolarChill A requirements checklist

This annex summarizes the requirements set at PQS performance specification **E003/RF05.5 [2].** Please in case of doubt or for complete details check the original document. The documents and other useful information can be found:

http://apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/categorypage.aspx?id_cat=17

Requirement 4.13 consist on the PQS Independent type-testing protocol **E003/RF05-VP.4**

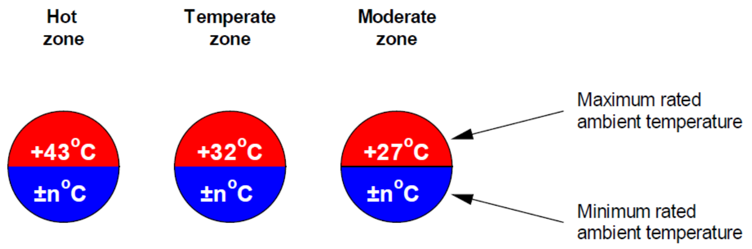
Clause	Description	Compliance
	CE mark, UL mark and/or equivalent internationally accepted evidence of conformity assessment.	
4.1	Meet the stated performance requirements at **3.5 kWh/m²/day** and hot zone **(+43°C)**	
4.2	Performance	
4.2.1	Maintain (2ºC to 8ºC) when **operating at (+43°C) and +10°C or lower.** **Sticker is attached** to the front of the appliance.	
4.2.2	(DC) electricity generated with solar energy.	
4.2.3	Designed so that no part which is outside the acceptable temperature range can be used to store vaccines.	
4.2.4	Freeze protection classification. **Sticker attached** to appliance front (see below) **Grade A**, user-independent freeze protection (UIFP). During the freeze protection test in **E003/RF05-VP.4 test 7 and 8:** temperatures cannot be below -0.5°C at any time not be < 0°C for more than 1 hour After incursion below 0ºC the unit must come back to normal operation in less than 2 hours anywhere within the compartment. Test number 7 in test protocol (freeze protection classification)	
4.2.5	Freezing capacity: minimum of 1.6 kg and not less than 2.4 kg per 50 liters of gross freezer volume must be frozen per 24 hours Test 4 in **E003/RF05-VP.4**	
4.2.6	Water-pack storage compartment capacity hold a minimum of 3.2 kg of fully frozen water-packs (or minimum 4.8 kg per 50 liters of gross freezer volume) and at least twice the daily water-pack freezing capacity determined by **E003/RF05 VP.4** (test 4) The water-packs must comply with **E005/IP01**.	

4.2.7	Vaccine compartment under the required temperature day/night. Freezing compartment: The net amount of fully frozen water-packs remaining under worst-case overnight test conditions and day/night cycling per **E003/RF05 VP.4 (test 5)** will be visually estimated and reported. Vaccine compartment need to stay within the temperature range always.	
4.2.8	**Thermostat:**set to prevent freezing in temperature range. **Cannot be adjusted by the user**. A means for adjustment by a technician is acceptable. Bulb and capillary tube thermostats are not acceptable.	
4.2.9	Unit must be equipped with a **30-day temperature logger device** that supports the transfer of data to another system for analysis purposes. It has to be WHO certified **E006/TR06.** Each refrigerator will also be equipped with a **permanent externally readable thermometer**. Three options accepted, look PQS document **E006/TH02** and **E006/TH06**	
4.2.10	A minimum of one **green LED** indicator light is required to be located on the front or top of the appliance to alert users that the cooling system is actively operating.	
4.2.11	Minimum **autonomy of three days**, according to **E003/RF05 VP.4 test 6** (temperatures inside operating range, 2ºC to 8ºC) Will be limited to installation sites where the refrigerator autonomy meets or exceeds the installation site autonomy requirements Freezer autonomy minimum overnight (0.5 day) at the solar radiation reference period	
4.2.12	Operate at a continuous **minimum ambient temperature of +10.0°C or lower** whilst maintaining the acceptable temperature range (2ºC to 8ºC) Freeze-prevention circuit may be required to protect against freezing at low ambient temperatures.	
4.2.13	Compatible **Type 2** solar power system to directly power the appliance is specified in **E003/PV01,** with power capacity (Watts) equal to or greater than the power system capacity used for PQS prequalification testing. If supplied, the legal manufacturers must certify compliance. Solar module voltage up to 45 volts open circuit (Voc at Standard Test Condition of solar radiation 1000W/m^2, cell temperature +25°C, air mass 1.5) Manufacturer to certify in writing that the power system conforms to **E003/PV01**.	

4.2.14	To alleviate humidity damage legal manufacturers are to include refrigerator design features and/or provide containers for vaccine storage. **Condensate and defrost drainage** must be provided in all refrigerator and freezer compartments. If used, the defrost switch (or switches) must be accessible to the user without tools but must be protected from accidental changes in position.	
4.2.15	The door or **lid must be fitted with a lock**. Two keys are to be supplied with every unit.	
4.2.16	The legal manufacturer must certify compliance that internal and external cabinet, lid and frame are protected against corrosion as appropriate to **EN ISO 6270-1 / ASTM D2247 / EN 13523-26**, **EN ISO 6270-2 / EN 13523-25**, **ISO 6272 / EN 13523-5** and **ISO 2409: 2013.**	
4.2.17	The legal manufacturer must certify compliance with **IEC 60335-1**, **IEC 60335-2-24** and **IEC 60364-1**.	
4.2.18	**Stick with refrigerant and warning for R600a**. Must label hazardous materials and include a Safety Data Sheet (according to **GHS Rev.5**) The appliance must carry the following **additional information** fixed to the front of the cabinet: manufacturer and model number (unless already located on the front of the unit), serial number, date of manufacture, PQS identification number, applicable service phone number and website URL. This label to remain readable for the expected life of the appliance.	
4.2.19	**Label** (one of languages in 4.11) near the top of the door on upright appliances, designed to last the lifetime of the appliance: **Vaccine storage instructions and water-pack freezing instructions**. If removable baskets are required to avoid freezing temperatures fix a **multilingual warning** within the refrigerator instructing users to "***Store vaccine in baskets only***", or other appropriate instruction. (Grade A refrigerators does not need basket for freeze protection)	
4.2.20	Electromagnetic compatibility: must certify compliance with the requirements of the latest edition of **IEC 61000-6-1** and **IEC 61000-6-3**.	
4.3.1	The ambient temperature range during transport and storage is -30°C < +70°C when the product is inactivated.	
4.3.2	The ambient humidity range during transport, storage and use is 5% < 95% RH, non-condensing.	
4.4.1	Minimum dimension should not exceed 710 mm Maximum dimension must not exceed 1700 mm maximum diagonal (corner to corner) must not exceed 1850 mm.	

4.4.2	Lift by hand. Designed so no single worker carry more than 25 kg	
4.5.1	Electrical components must be compatible with a **Type 2** solar power (**E003/PV01)**. The appliance is to be equipped with a locking female and male coupler system ("plug and play")	
4.5.2	Providean ***on* and *off* power switch** that is readily accessible to the user, either on the outside of the appliance cabinet or in a wall-mounted switch within one meter of the appliance.	
4.6.1	The product must be **useable by the widest practicable range of active health workers** regardless of age, gender, size or minor disability, including colour blind users and long-sighted people without glasses.	
4.6.2	Visual displays may be positioned on the front of the unit preferably as close to eye level as possible. They may be mounted on top of the unit at a height not exceeding 1.3 metres (look exceptions). The on and off and/or defrost switch, if present, should be recessed or otherwise protected from accidental change in position.	
4.7.1	Refrigerants such as R600a or (GWP) ≤ 11 and zero (ODP)	
4.7.2	Thermal insulation foaming agents (Montreal Protocol)	
4.7.3	The appliance and its constituent components, must not contain lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated biphenyl ethers (PBDE).	
4.8	Two-year replacement **warranty**	
4.9	designed to achieve a low-maintenance life of not less than 10 years	
4.9.1	As a minimum, each appliance to be **supplied with 10 spare fuses** of all fuse size and type used in the appliance. The spares fuses are to be attached within or on the appliance. **Publish a list of spare parts** recommended for purchases of 10 and 50 appliances and power systems.	
4.10	Provide information to the buyer on the hazardous materials contained within the system and suggestions for resource recovery/recycling and/or environmentally safe disposal	
4.11	Include a **separate user manual and technician installation manual** in Arabic, English, French, Mandarin Chinese, Russian and Spanish. An English version of all instructions and manuals are required to be supplied at time of laboratory testing. (**Look at PQS doc** for requirements)	
4.12	If requested, all legal manufacturers are required to have the capability of providing in-person training in the countries where their product is deployed.	

4.13	Verification in accordance with PQS Verification Protocol **E003/RF05-VP.4.**	
5	Materials used for packaging -- free of ozone-depleting compounds. Adequate protection of the goods for carriage by air, sea and/or road, including remote locations under adverse climatic and storage conditions and high humidity. The packaging is to be not less than 17kN edge crush resistance with minimum 60% remaining with 90% humidity at a temperature of +70°C (tropical conditions). To avoid destructive unpacking prior to installation, legal manufacturers are encouraged to add a re-sealable observation opening in their packaging to aid inspectors in finding labelling and/or placing additional markings prior to installation. Instructions on the packaging alerting inspectors to use of the opening and what information will be revealed are also advised.	
	Prepare **dossier** according to Clause 7 of **E003/RF05.5**	



Cold climate tolerance rating is specified in 5°C increments:
- *Hot zone:* <n> must be between +25°C and -10°C
- *Temperate zone:* <n> must be between +15°C and -10°C
- *Moderate zone:* <n> must be between +10°C and -10°C

All circles are to be 100mm diameter. Font Arial **bold.**

Refrigerant label

Black font on pale blue background or white font on dark blue background

Font: Arial **bold** - 18 point minimum

R600a warning symbol

Black font on yellow background

Font: Arial **bold** - 18 point minimum

Annex B: SolarChill B test protocol

SolarChill B

DTI Labtest method and criteria

Rev 5. Ivan Katic 2018-07-30

Introduction and scope

Solar Chill B is a direct drive solar powered refrigerator for cooling and storage of food and drinks in areas without grid electricity. SolarChill cabinets contain a thermal storage to keep the content cool during nighttime and during very cloudy periods

SolarChill B is intended for households and for small-scale commercial use.

This document describes a proposed test method and pass criteria, and is based on discussion within the SolarChill partnership in September 2012 with recent updates.

The test method is partly based on the existing standard WHO/PQS/E003/RF05-VP.4 (August 2016), which is a standard for testing solar powered refrigerators and water-pack freezers without battery storage. The standard deals with performance, quality and safety, and includes tests for evidence of conformity, power consumption, day/night temperature cycling etc.

The above-mentioned standard was developed for verifying the performance of *vaccine coolers* and is rather demanding and complex. In order to adapt the test method to household/commercial coolers (SolarChill B), some alterations to the power supply, temperature requirements, test packages, and packing plan have been made in this draft. Those changes to the test procedure are mainly based on the existing standard IEC 62552-2:2015 for household refrigerators and freezers.

These alterations have been made to ensure the verification of proper food safety and hygiene, and the relevance of the tests with respect to the intended application, which is refrigeration of perishable foods and drinks. In principle, the described method could also be used for testing solar powered coolers with a battery or any other kind of energy storage.

Power supply equipment

The laboratory tests are conducted by simulated solar power calculated by a step by step procedure following a solar irradiance table defined in section 5.3 of ref [1], representing a partly cloudy day:

3.5 kWh/m^2/day reference period

1 hour at 50 w/m^2
2.5 hours at 250 w/m^2
0.5 hours at 350 w/m^2
4 hours at 450 w/m^2
0.5 hours at 350 w/m^2
2.5 hours at 250 w/m^2
1 hour at 50 w/m^2
12 hours at 0 w/m^2

Table 1 Solar radiation reference day for PV power supply simulation

The following power supply methods are applicable:

- A PV module array simulator or DC supply with remote control from a PC may be used to accurately adjust current and voltage according to the manufacturer´s data sheet. This is the most correct and universal method.
- A PV module simulator or a DC power supply with stepwise current limitation may be used for devices *without maximum power point tracking* of the module´s power curve. The voltage limit should be set to the nominal operating voltage of the PV module(s) specified by the manufacturer, calculated for a typical module temperature of 50°C. The current limit is set to a fraction of the nominal operating current of the specified module(s) relative to full sun (1000 W/m^2). Example:

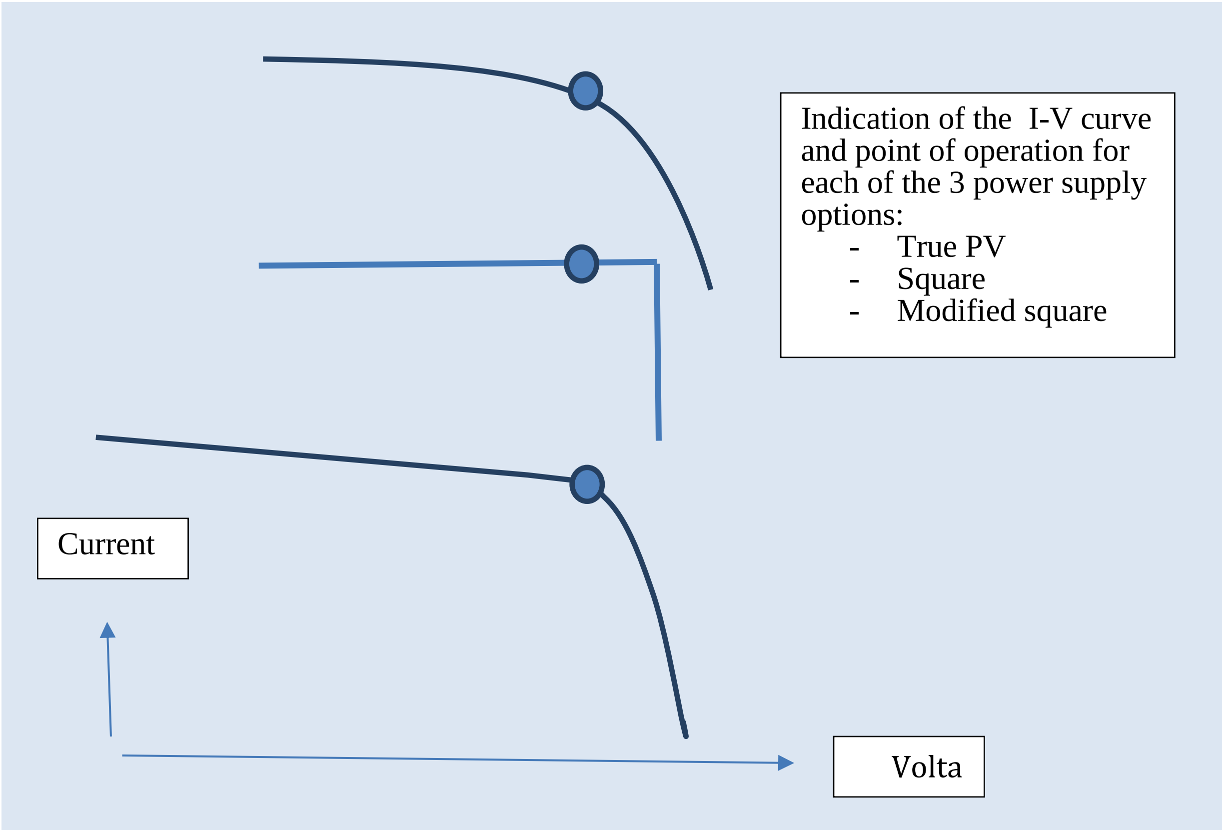
  Nominal short circuit current 9A

  Simulation at 350 w/m^2 results in a current limit of 0,35 x 9 = 3,15 A

- The simple PV emulation method above can be modified with appropriate series resistors or diode arrays in order to adjust the current-voltage characteristics to approximate the real PV characteristic curve. The resistance and number of diodes is adjusted experimentally to fit the I-V curve as good as possible.

Due to possible interference between the power control circuit in the device under test and the regulated power supply, it must always be checked that the apparatus is running as intended before the test is commenced and the manufacturer should be consulted on the final setup.

The following figure illustrates the three principles for simulated PV power supply:



Type-test requirements

The following tests should be carried out by an independent ISO 17025 testing laboratory. One sample of the appliance is required for testing.

The climate chamber temperature will be set to hot or temperate zone as per manufacturer´s specification. The specific tests listed below apply equally to temperate zone and hot zone appliances defined in [1]. Relevant test chamber temperatures are given in the following format; T: 32°C for temperate zone and H: 43°C for hot zone. The humidity in the test chamber during the tests should be between 45 – 75 % RH.

All refrigerator temperatures and power measurements are done with readings and accuracy according to IEC 62552-2:

- Ambient temperature regulation of climate chamber must be within +/- 0.5 K.
- Temperature readings in the cabinet must be within +/- 0.5 K.
- Energy consumption measurements must be within 1% accuracy.

Be sure that the sampling rate of current and voltage is sufficient (less than 10 s), if a DC kWh meter (with its own integrator) is not used for measurement of the energy consumption.

The test should be initiated with the thermostat presetting made by the manufacturer. The setting may be changed to come as close as possible to 4°C mean target temperature in stable running conditions [2].

Temperature is recorded in three levels with air temperature probes. The target temperature is the warmest permissible storage temperature of each level, according to table 2.

Compartment	Fresh-food	
Temperature alias	t_{1m}, t_{2m}, t_{3m}	t_{ma}
Target temperature [°C]	$1 \leq t_{1m}, t_{2m}, t_{3m} \leq 9$	≤ 5

Table 2 Storage temperature limits

Where:

t_{1m} is the average temperature in the lower part of the volume

t_{2m} is the average temperature in the middle of the volume

t_{3m} is the average temperature in the upper part of the volume

t_{ma} is the average temperature of the three above

Test sequences:(arranged so the total time can be minimized)

Sequence	#1	#2	#3	#4
Purpose	General documentation and pre-cooling of the thermal storage	Thermostat function and energy consumption	Cooling capacity (load test)	Autonomy time
Power	Unlimited	Unlimited	Daily sun 3.5 kWh/m^2	Daily sun 0.35 kWh/m^2
Instrumentation	-	3 temp. probes Energy meter	3 temp. probes 3 M packages Energy meter	3 temp. probes 3 M packages Energy meter
Filling	-		Light load	Light load
Ambient Temperature	Normal room temperature	32°C or 43°C climate chamber	32°C or 43°C climate chamber	32°C or 43°C climate chamber

Test 1: Type-examination

The purpose of this test is to identify the sample, measure the volume and record any problems before testing in climate chamber. Type-examination is carried out as follows:

a) Unpack the product. Using the manufacturer's installation instructions only, set up the system components. Record any problems encountered.
b) Check for similarities with previously tested products to ensure a re-badged version of an identical product is not tested. Also ensure to inspect the product for any defects, damage, or problems which make it difficult or impossible to test the product.
c) Measure volume of all storage compartments. Storage capacity is measured in accordance with §7.2.4 (ref 2), volumes outside any load lines shall be deducted. The storage capacity is reported.
d) Plug in the appliance and set the power (current and voltage) to PV nominal value and device thermostat to 4°C or medium setting (to check for any functional damage and pull down temperature for subsequent test in climate chamber. This may take days depending on thermal storage capacity)
e) Tabulate the following information for the appliance being examined.

Identification:

- Model
- Legal manufacturer or reseller
- Product type
- Country of origin
- Conformity assessment markings
- Temperature rating against which the appliance is to be tested.

Interface requirements:

- The terminals where the PV array is to be connected to the refrigerator should be clearly indicated and marked with polarity and voltage limit. Protection against wrong polarity, e.g. plug and play connectors.

- PV power supply maximum 60 V DC in any condition (SELV - Safety Extra Low Voltage)

- No special tools should be required for assembling of the different parts of the wiring system. (Preferably an adjustable spanner and a slotted screwdriver would be sufficient).

- All terminals and connections should be adequately electrically isolated.

Materials:

- The refrigerant should be a natural refrigerant. No fluorocarbon refrigerants are accepted in SolarChill technology.

- The thermal insulation foaming agent should comply with the limitations set by the Montreal Protocol on the elimination of ozone-depleting materials. No fluorocarbons (F-gases)are allowed.

- The refrigerator, PV array or any other component should not contain heavy metals or other dangerous substances

- *Instructions for users:*

    - User and maintenance instructions should cover the following aspects:

        - Installation procedures
        - Operation guidance (e.g. how long it takes to cool down, not to connect any battery, how it works during night time, how it works during very cloudy days and how it sounds)
        - Basic guidelines for food storage, shelf life, and hygiene.
        - Simple daily, weekly, and monthly maintenance tasks
        - Regular preventative maintenance checks
        - Diagnostic and repair procedures
        - Itemized list of spare parts including part numbers

- Warranty
- End-of-life resource recovery and recycling procedures

The instructions are to be written for users and repair technicians in English as well as the native language where the product is to be sold. Preferably the manual should be elaborated with pictograms and/or pictures enabling a vast majority of intended users to comprehend the above listed topics.

Acceptance criteria:

Inspection indicates full conformity with all major specification requirements as outlined in this test. Setup must be straightforward and trouble-free.

Test 2: Stable running with constant power

Power:DC source(Constant nominal power)

The purpose of this test is to measure the energy consumption when there is an unlimited energy source available (to compare with plug-in appliances) and furthermore to check the thermostat function.

The test is carried out as follows:

a) Set the test chamber temperature to the relevant temperature; T: +32^{0}C (or H: + 43^{0}C).

b) Set the power (current and voltage) to PV nominal value and device thermostat to 4°C and monitor 3 internal temperatures as per table 2.It may take some time to adjust the thermostat setting.

c) When the empty refrigerator´s food storage compartment is stabilised to an average temperature (t_m) near 4 °C (as per table 2)it is ready for energy measurements.

d) Monitor energy consumption for 24 hours and go to test 3.

Acceptance criteria: Measured thermostat hysteresis must be less than 3 K.(measured as average temperature excursion)

HINT: Place M-Packs and additional mass in the climate chamber, so they are ready for next step.

Test 3: Cooling capacity running with solar power

The purpose of the test is to simulate normal use of the refrigerator when running on solar power on a semi cloudy day and with loading of a typical batch of warm goods (Measurement of temperatures and energy consumption). Based on section 7 in ref[2].

a) Simulated power supply sequence is set to start with the last solar (table 1) value: 12 hrs @ 0W.

b) The cabinet is loaded with a quantity of light load test packages: 4,5 kgpr100 litre storage volume measured rounded off to the nearest 500 g. The light load is stabilized at test chamber temperature before loading. The light load consists of three M-packages(with sensors) and additional test packages of 500 g and 1000 g.

c) The light load is distributed symmetrically around the M-Package sensing points (t_1, t_2 and t_3) and, if possible, with the same quantity in each stack. If it is not possible to place the same quantity of light load in each stack, the largest quantity must be placed in the stacks also containing M-packages. M-packages must always be placed side by side with another 500 g test package. All packagesareplacedhorizontally.

d) When introducing the light load, the refrigerator door is kept <u>open for three minutes.</u>

e) The time to cool down the load is calculated for the M-package last reaching 10 °C. Report this value and remove the light load.

f) Monitor daily operation for 3 days or until the daily energy consumption is stable.

g) Review thetemperature for each sensor over the measurement period. Record the highest and lowest temperatures reached during the test.

Acceptance criteria:

- The time for the last M-pack to reach 10°Cmust not exceed 12hours.

Test 4: Autonomy time (heavily clouded condition)

The purpose of this test is to document how sensitive the device is to periods of very low solar irradiance where the compressor does not run at all, but internal fans, thermostats etc. can still function. (Based on [1])

The autonomy time test is carried out as follows:

a) After temperature stabilization has occurred, reduce the power supply at the end of the last compressor ON cycle immediately before the 0 W/m^2 period of the cycle. If the compressor already cycled off at this point record the elapsed time since the end of the previous compressor-on cycle (t). The power supply is reduced to 10% of the former table values by reducing the current, but keeping voltage at its original value.

b) Monitor the temperature of the M-packages. At the moment when the upper temperature limit of any M-package in any compartment has been exceeded by 12^0C, record the elapsed time since switch off and add this to the value (t) recorded in step 2. Record the position of the first M-package exceeding 12^0C.

Acceptance criteria:

A minimum autonomy time of 48 hours.

Test and reporting summary:

TEST	Pass criteria	Measured and reported parameters	Other
Test 1: Type-examination	Full conformity with all major specification requirements	Volume [l]	Photo documentation
Test 2: Stable running with constant power	Thermostat hysteresis must be less than 3 K	Hysteresis [K] Energy consumption [kWh/day]	Temperature and power curves
Test 3: Cooling and normal running with solar power	The cooling time of warm load must not exceed 12 hours.	Energy consumption [kWh/day] Minimum temperature Maximum temperature Pull down time HH:MM	Temperature curves
Test 4: Autonomy time	Minimum autonomy time of 48 hours	Autonomy time HH:MM	Temperature curves

References:

1. WHO/PQS/E003/RF05-VP.4, Refrigerator or combined refrigerator and water-pack freezer: Compression-cycle. Solar direct drive without battery storage.
2. IEC 62552-2:2015 Household refrigerating appliances - Characteristics and test methods - Part 2: Performance requirements