FOOD, AGRICULTURE AND FISHERIES, AND BIOTECHNOLOGY

FRISBEE

Food Refrigeration Innovations for Safety, Consumers' Benefit, Environmental Impact and Energy Optimisation Along the Cold Chain in Europe

Grant Agreement N°245288
Type of funding scheme: Large Collaborative Project

Deliverable D.2.2.3 : Analysis of potential of novel refrigeration technologies suitable for selected industries for application and improvement of food quality, energy consumption and environmental impact

Deliverable Information
Dissemination : Public
Nature : Report
Contractual Delivery Date : 31/08/2011
Actual Delivery Date : 02/12/2011

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Document Information

Project : FRISBEE
Document : Deliverable 2.2.3
Reference : DEL 2.2.3 S1
Filename :FRISBEE DEL 2-2-3 Analysis of potential of novel technologies S1.doc
Last saved on : 02/12/2011 16:21 by Jacques Bertrand

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Release Details

Release	Date	Comments
Draft 01	26/10/2011	First draft
Draft 02	28/11/2011	Second draft after assessment round
Release 01	02/12/2011	First release after approval by Project Manager
Submitted	02/12/2011	Submitted to the Commission

Distribution List

- On the project Portal
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Contents

1. Glossary

AC	Air conditioning
ATP	Agreement on the International Carriage of Perishable Foodstuffs and on the Special Equipment to be Used for such Carriage
CAS	Cells Alive System
COP	Coefficient of Performance
COSP	Co-efficient of System Performance
GWP	Global Warming Potential
HFC	Hydro fluorocarbon
HFOs	Hydrofluoro olefins
HPSF	High Pressure Shift Freezing
IQF	Individually Quick Frozen
MRF	Magnetic Resonance Freezing
NIST	National Institute of Standards and Technology
ODP	Ozone Depleting Potential
PCM	Phase Change Material
PETD	Pulse electro-thermal de-icers
SLPM	Standard Litres Per Minute
VCS	Vapour Compression System
VPC	Vascular Perfusion Chilling
ZBLAN	Zirkonium Barium Lanthanum Aluminium Natrium

2. Summary

Throughout the report options to reduce energy consumption, reduce emissions of greenhouse gasses and improve temperature control using future refrigeration processes are discussed. The report has been divided into 2 sections:

1. Technologies that are refrigeration technologies in their own right.
2. Technologies that are product oriented technologies.

'Future' refrigeration processes are defined as those that are not currently used or cannot be widely purchased today. Details of current refrigeration processes (i.e. those that can be purchased today) are available in DEL 2.2.2.

A summary of the technologies examined in the report and their future potential is presented in tables 1 to 3.

Table 1. Comparison of technologies and their relative potential.

Technology	Time to commercial application (estimated)	Potential to save direct emissions	Potential to save indirect emissions	Potential to improve food quality	Potential to improve food temperature control	Likely initial cost against ’conventional’ technologies	Ease of use and installation against ’conventional’ technologies	Maintenance cost against ’conventional’ technologies	Will future legislation potentially affect uptake of technology?	Most likely application	Most likely capacity range
	Years	Ranked High-Medium-Low	Ranked High-Medium-Low	Ranked High-Medium-Low	Ranked High-Medium-Low	Higher-Similar-Less	Simple-Similar-Greater	Higher-Similar-Less	Yes-No	Freezing-cooling-AC	0.1kW → 1-10kW → 10kW
Acoustic refrigeration	5-10	High	Low	Low	Low	Higher	Simple	Not known	Yes	Freezing-cooling	0-1
Air cycle refrigeration	5-10	High	Certain conditions	High	Medium	Higher	Medium	Less	Yes	Freezing-AC	>10
Ammonia (sealed hermetic) compressors	2-3	High	High	Low	Low	Higher	Simple	Similar	Yes	Freezing-cooling-AC	>10
Antifreeze proteins	>10	Low	Medium	Medium	Low	Higher	Greater	Not known	No	Freezing	All
Barocaloric refrigeration	>10	High	Low	Low	Low	Higher	Simple	Not known	Yes	Cooling	0-1
Dehydrofreezing	3-5	Low	Low	Medium	Low	Higher	Greater	Not known	No	Freezing	All
Ejector or jet pump	0	High	Low	Low	Low	Higher	Greater	Less	Yes	Cooling	All
Electrocaloric	5-10	High	Low	Low	Low	Higher	Simple	Not known	Yes	Cooling	0-1
Eutectic packaging	2-5	Low	Medium	High	High	Higher	Simple	Higher	No	Freezing-cooling	All
Heat pipes and spot cooling	0	Low	Medium	Medium	Medium	Higher	Simple	Higher	No	All	All
HFOs (Hydrofluoroolefins)	2-5	High	Low	Low	Low	Higher	Simple	Not known	Yes	Cooling-AC	All
Hydraulic refrigeration	0-5	High	Medium	Low	Low	Higher	Greater	Not known	Yes	Cooling-AC	>10
Hydrofluidisation	0-5	Medium	Low	Medium	High	Higher	Greater	Not known	No	Freezing-cooling	All
Ice nucleation proteins	>10	Low	Low	Medium	Low	Higher	Greater	Not known	No	Cooling	All

Technology	Time to commercial application (estimated)	Potential to save direct emissions	Potential to save indirect emissions	Potential to improve food quality	Potential to improve food temperature control	Likely initial cost against ’conventional’ technologies	Ease of use and installation against ’conventional’ technologies	Maintenance cost against ’conventional’ technologies	Will future legislation potentially affect uptake of technology?	Most likely application	Most likely capacity range
	Years	Ranked High-Medium-Low	Ranked High-Medium-Low	Ranked High-Medium-Low	Ranked High-Medium-Low	Higher-Similar-Less	Simple-Similar-Greater	Higher-Similar-Less	Yes-No	Freezing-cooling-AC	0.1kW → 1-10kW → 10kW
Magnetic field freezing/CAS (Cell Alive System)	0-5	Low	Low	High	Low	Higher	Greater	Higher	No	Freezing	<10
Magnetic refrigeration	3-5	High	Medium	Low	Low	Higher	Simple	Less	Yes	Cooling	0-1
Nanoparticles	2-5	Low	Medium	Low	Low	Higher	Simple	Not known	No	Freezing-cooling-AC	All
New foods	>10	High	Medium	Medium	High	Higher	Greater	Less	Yes	Freezing-chilling	All
Novel building fabric	3-5	Low	Medium	Medium	Medium	Higher	Simple	Not known	No	AC	0-1, 1-10
Optical cooling	>10	High	Low	Low	Low	Higher	Not known	Not known	Yes	Cooling	0-1
Perfusion	5	Low	High	Medium	Low	Higher	Greater	Not known	Yes	Cooling	>10
Pressure shift freezing	5-10	Low	Low	High	Low	Higher	Greater	Higher	No	Freezing	<10
Pulsed electrical thermal de-icers	5-10	Low	High	High	High	Higher	Greater	Not known	No	Freezing	>10
Secondary systems (novel)	1-5	High	Low	Low	Low	Higher	Greater	Not known	Yes	Cooling-AC	1-10
Solar	5-10	High	High	Low	Low	Higher	Greater	Greater	Yes	Cooling-AC	0-1, 1-10
Stirling cycle variations	0-5	High	Medium	Low	Low	Higher	Simple	Not known	Yes	Freezing-cooling	0-1
Supercooling	3-6	Low	High	High	Low	Lower	Simple	Less	No	Cooling	All
Thermionic refrigeration	5-10	High	Low	Low	Low	Higher	Simple	Not known	Yes	Cooling	0-1
Thermoelectric generation	5-10	High	High	Low	Low	Higher	Greater	Less	Yes	Cooling	0-1

Technology	Time to commercial application (estimated)	Potential to save direct emissions	Potential to save indirect emissions	Potential to improve food quality	Potential to improve food temperature control	Likely initial cost against 'conventional' technologies	Ease of use and installation against 'conventional' technologies	Maintenance cost against 'conventional' technologies	Will future legislation potentially affect uptake of technology?	Most likely application	Most likely capacity range
	Years	Ranked High-Medium-Low	Ranked High-Medium-Low	Ranked High-Medium-Low	Ranked High-Medium-Low	Higher-Similar-Less	Simple-Similar-Greater	Higher-Similar-Less	Yes-No	Freezing-cooling-AC	0.1kW → 1-10kW → 10kW
Ultrasound assisted freezing	>10	Low	Medium	High	Low	Higher	Greater	Not known	No	Freezing	<10
Vortex tube cooling	0-5	High	Low	Low	Low	Higher	Simple	Not known	Yes	Cooling	0-1
Water in vapour compression	0	High	Medium	Low	Low	Higher	Similar	Not known	Yes	AC	>10

Table 2. Technologies examined and their application area.

	Area where technology can be applied:					
Technology	Production	Storage	Transport	Retail	Commercial service	Domestic
Acoustic refrigeration				✓	✓	✓
Air cycle refrigeration	✓		✓			
Ammonia (sealed hermetics) compressors				✓	✓	
Antifreeze proteins	✓					
Barocaloric refrigeration					✓	✓
Dehydrofreezing	✓					
Ejector or jet pump	✓	✓	✓	✓	✓	✓
Electrocaloric					✓	✓
Eutectic packaging		✓	✓	✓	✓	✓
Heat pipes and spot cooling	✓	✓	✓	✓	✓	✓
HFOs (Hydrofluoroolefins)	✓	✓	✓	✓	✓	✓
Hydraulic refrigeration	✓	✓				
Hydrofluidisation	✓					
Ice nucleation proteins	✓					
Magnetic field freezing/CAS (Cell Alive System)	✓				✓	
Magnetic refrigeration				✓	✓	✓
Nanoparticles	✓	✓	✓	✓	✓	✓
New foods	✓	✓	✓	✓	✓	✓
Novel building fabric		✓		✓		
Optical cooling					✓	✓
Perfusion	✓					
Pressure shift freezing	✓					
Pulsed electrical thermal de-icers	✓	✓	✓	✓	✓	✓
Secondary systems (novel)			✓			
Solar			✓			
Stirling cycle variations					✓	✓
Supercooling	✓					
Thermoelectric generation			✓			
Thermionic refrigeration					✓	✓
Ultrasound assisted freezing	✓					
Vortex tube cooling	✓				✓	
Water in vapour compression	✓	✓	✓	✓	✓	

Table 3. Application of technologies to products considered within Frisbee

	Product:				
Technology	Apple	Pork	Fish	Spinach	Ice cream
Acoustic refrigeration	✓	✓	✓	✓	✓
Air cycle refrigeration					✓
Alternative refrigeration systems	✓	✓	✓	✓	✓
Ammonia (sealed hermetics) compressors	✓	✓	✓	✓	✓
Antifreeze proteins				✓	✓
Barocaloric refrigeration	✓	✓	✓	✓	✓
Dehydrofreezing	✓				
Ejector or jet pump	✓	✓	✓	✓	✓
Electrocaloric	✓	✓	✓	✓	✓
Eutectic packaging	✓	✓	✓	✓	✓
Heat pipes and spot cooling	✓	✓	✓	✓	✓
HFOs (Hydrofluoroolefins)	✓	✓	✓	✓	✓
Hydraulic refrigeration	✓	✓	✓	✓	✓
Hydrofluidisation	✓	✓	✓	✓	
Ice nucleation proteins	✓	✓	✓	✓	✓
Magnetic field freezing/CAS (Cell Alive System)	✓	✓	✓	✓	✓
Magnetic refrigeration	✓	✓	✓	✓	✓
Nanoparticles	✓	✓	✓	✓	✓
New foods	✓	✓	✓	✓	✓
Novel building fabric	✓	✓	✓	✓	✓
Optical cooling	✓	✓	✓	✓	✓
Perfusion		✓	✓		
Pressure shift freezing	✓	✓	✓	✓	✓
Pulsed electrical thermal de-icers	✓	✓	✓	✓	✓
Secondary systems (novel)	✓	✓	✓	✓	✓
Solar	✓	✓	✓	✓	✓
Stirling cycle variations	✓	✓	✓	✓	✓
Supercooling	✓	✓	✓	✓	
Thermoelectric generation	✓	✓	✓	✓	✓
Thermionic refrigeration	✓	✓	✓	✓	✓
Ultrasound assisted freezing	✓	✓	✓	✓	✓
Vortex tube cooling	✓	✓	✓	✓	✓
Water in vapour compression	✓	✓	✓	✓	✓

3. Introduction

The aim of this subtask was to study refrigeration technologies and equipment throughout the food cold chain and to assess the potential of novel technologies in terms of energy consumption, environmental impact and temperature control (D2.2.3):

> Subtask 2.2.3 Prospective study on novel refrigeration technologies (Month 6-12) (LSBU) Available novel refrigeration technologies suitable for selected industries will be explored and prospects for application and improvement of food quality already reported in previous studies, energy consumption and environmental impact will be evaluated. D.2.2.3

Throughout the report options to reduce energy consumption, reduce emissions of greenhouse gasses and improve temperature control using future refrigeration processes are discussed. Technologies are divided into two sections:

1. Technologies that are refrigeration technologies in their own right.
2. Technologies that are product oriented technologies.

‘Future’ refrigeration processes are defined as those that are not currently used or cannot be widely purchased today. Details of current refrigeration processes (i.e. those that can be purchased today) are available in DEL 2.2.2.

4. Novel technologies to improve temperature control and emissions in the cold chain considered individually

Technologies are considered under the following headings (in alphabetic order):

1. Technologies that are refrigeration technologies in their own right.
2. Technologies that product oriented technologies.

Technologies have been ranked as follows:

Time to commercial application (estimated)	Years
Potential to save direct emissions	Ranked High-Medium-Low
Potential to save indirect emissions	Ranked High-Medium-Low
Potential to improve food quality	Ranked High-Medium-Low
Potential to improve food temperature control	Ranked High-Medium-Low
Likely initial cost against ’conventional’ technologies	Higher-Similar-Less
Ease of use and installation	Simple-Similar-Greater
Maintenance cost against ’conventional’ technologies	Higher-Similar-Less
Will future legislation potentially affect uptake of technology?	Yes-No
Most likely application	Freezing – cooling – air-conditioning
Most likely capacity range	0-1kW → 1-10kW → 10kW

The rankings applied are somewhat subjective as in many cases sufficient evidence is not available to quantify the assessments. Therefore it should be noted that the assessments are the opinions of the authors.

5. Technologies that are refrigeration technologies in their own right.

5.1. Acoustic refrigeration

Time to commercial application (estimated)	5-10 years
Potential to save direct emissions	High
Potential to save indirect emissions	Low
Potential to improve food quality	Low
Potential to improve food temperature control	Low
Likely initial cost against 'conventional' technologies	Higher
Ease of use and installation	Simple
Maintenance cost against 'conventional' technologies	Not known
Will future legislation potentially affect uptake of technology?	Yes
Most likely application	Freezing, cooling
Most likely capacity range	0-1kW

Although thermoacoustic refrigerators have the potential to cover the whole spectrum of refrigeration down to cryogenic temperatures, it is most likely to be used for low capacity equipment initially (Tassou et al 2010).

The main benefits are that they use environmentally safe, inert gasses such as air, Argon and Helium. Systems can be open or closed; closed systems have shown the greatest potential to date. Two variants of the closed system are available:

1. Closed, standing wave system:
   The driver is typically a loud speaker. Sound waves are used to create a resonant standing wave within the “stack”. As the gas oscillates back and forth within the stack it creates a temperature difference along the length of the stack due to expansion and compression by the sound wave.
2. Closed, travelling wave system:
   This type of travelling wave device was used on the Ben and Jerry’s ice cream cabinet. The driver for this system is a motor and piston. Unlike the standing wave system, the temperature difference for this system occurs in a regenerator rather than a stack. The system is designed so that the air will oscillate between the hot and cold heat exchangers through the regenerator matrix as the pressure is increased and decreased.

Work at Penn State University has developed a demonstrator acoustic refrigerator for storage of ice cream which is currently undergoing further development with the view to future commercialization (Poese et al, 2004).

Prototype units have been developed, the most famous being the Ben and Jerry’s ice cream freezer (2004). Work is still needed to increase COPs to the level of vapour compression systems (Defra ACO403). Flow through systems (also referred to as open systems) would eliminate heat exchangers and reduce system complexity and cost but more research is required into this configuration (Tassou et al 2010). Efficiency achieved so far is 0.1 to 0.2 of Carnot’s efficiency; conventional systems achieve 0.33 to 0.5 (Wetzel and Herman 1997).

Inefficiency in systems already built and tested is generally cited as being a result of inadequate tolerances in assembled apparatus, whereas heat exchangers are cited as the cause for high cost and complexity.

Future developments are considered to be to improve and optimise design and performance (Wetzel and Herman 1997). Developments are needed in the design of stacks, resonators and compact heat exchangers for oscillating flow.

Development of flow-through (open) systems could also eliminate heat exchangers and reduce system complexity and cost (Tassou et al 2010) but these require acoustic dampers which result in significant restrictions to gas flow.

Unless legislation prevents the use of more efficient vapour compression systems (for environmental or safety reasons) the efficiency of acoustic refrigerators will need to be improved to exceed that of vapour compression systems to enable uptake of this technology (Tassou et al 2010).

5.2. Air cycle

Time to commercial application (estimated)	5-10 years
Potential to save direct emissions	High
Potential to save indirect emissions	Certain conditions
Potential to improve food quality	High
Potential to improve food temperature control	Medium
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Medium
Maintenance cost against ’conventional’ technologies	Less
Will future legislation potentially affect uptake of technology?	Yes
Most likely application	Freezing, air-conditioning
Most likely capacity range	>10kW

Air cycle is one of the oldest refrigeration technologies. Air cycle machinery was used on board ships in the 1800s to maintain food temperature. However, the large reciprocating machinery was rapidly replaced at the beginning of the 1900s by smaller lighter systems using other refrigerants as new technology developed. Today high-speed turbo machinery is available that is compact and lightweight and therefore the use of air as a refrigerant is once again a commercial possibility.

The principal of the air cycle is that when air is compressed its temperature and pressure increases (1-2) (Figure 1**Error! Reference source not found.**). Heat is removed from the compressed air at constant pressure and its temperature is reduced, ideally while providing useful heat to high temperature processes (2-3). The air is then expanded and its temperature reduces as work is taken from it (3-4). The air then absorbs heat (gaining temperature) from low temperature processes at constant pressure, (4-1) where it starts the cycle again.

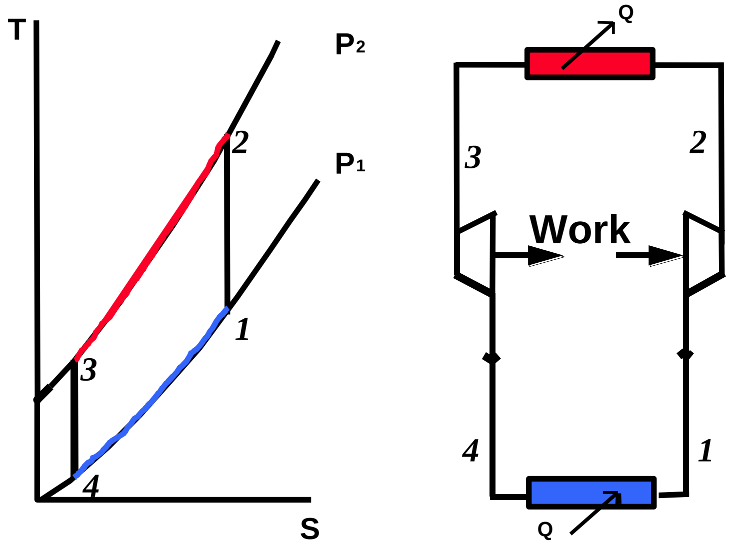


Figure 1. Air cycle on a T-S (Temperature-Entropy) diagram and shown diagrammatically.

The application of air cycle to food processing has many advantages such as safety, lack of flammability and the lack of environmentally damaging gasses. Air cycle can be energy efficient at low temperatures or if heating as well as cooling is utilized.

A number of theoretical studies have indicated the potential for air cycle in food processing operations (Gigiel, Chauveron, and Fitt, 1992; Russell, Gigiel, and James 2000; Russell, Gigiel and James, 2001). Integrated heating and refrigeration is one of the applications with the highest theoretical potential. Theoretically air temperatures up to 300°C can also be obtained suitable for direct cooking or the production of steam. Alternatively fast freezing of small products using the low temperatures available from air cycle systems will result in faster freezing, improving food quality and either a smaller freezer, or a larger throughput through an existing freezer (Foster et al, 2011).

Air cycle has advantages for transport applications due to its low weight, use of a natural refrigerant, reliability, good performance at part load conditions and robustness. Spence et al (2004, 2005) developed an air cycle demonstrator using commercially available parts. Due to having to use less than optimal components the fuel consumption was higher than for a vapour compression unit at full load (200%) and lower at part load (80%). Using a model to investigate the effect of using more optimal components a COSP at full load of 0.53 at -20°C and 7.8 kW was predicted that was 7% lower than an equivalent vapour compression system.

5.3. Ammonia (sealed hermetics) compressors

Time to commercial application (estimated)	2-3 years
Potential to save direct emissions	High
Potential to save indirect emissions	High
Potential to improve food quality	Low
Potential to improve food temperature control	Low
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Simple
Maintenance cost against ’conventional’ technologies	Similar
Will future legislation potentially affect uptake of technology?	Yes
Most likely application	Freezing, cooling, air-conditioning
Most likely capacity range	>10kW but suits all

Ammonia is widely used in industrial (vapour compression) refrigeration systems for warehousing and process cooling (Pearson 2008). It offers better efficiencies than HFC systems (9 - 17 %) (Tyschen 2003). However, the uptake of Ammonia is hampered by legislation (in some countries more than others) and on smaller systems also by a lack of components (Palm 2008).

The OSCAR project (2003) carried out some short-term testing of 60% ammonia 40% dimethyl ether vapour compression systems in the 3 – 20kW range and built using standard HFC compressors and copper tubes. Although no corrosion of copper was identified with a refrigerant water content less than 400ppm, the electrical insulation on the windings of the compressor was removed in a very short-time; sometimes after just hours (Palm 2008, Hansen 2006).

There are a wide range of safety restrictions imposed on Ammonia systems throughout the European Union and America, but the range of legislation appears to have had no measureable effect on the accident rate which has remained similar to that with HFC refrigerants and between countries (Pearson 2008).

For future uptake commonality and rationality in legislation; trained personnel and safety standards are essential and a common level of certification or licence to use the technology may be one solution (Rolfsman 2010). However, legislation should not be unduly prohibitive as Ammonia remains an environmentally friendly and efficient refrigerant (Lindborg 2009).

Components must be developed to enable the use of smaller scale Ammonia vapour compression systems in other sectors of the industry such as food service. Priorities for this are hermetic compressors and expansion valves.

5.4. Barocaloric refrigeration

Time to commercial application (estimated)	>10 years
Potential to save direct emissions	High
Potential to save indirect emissions	Low
Potential to improve food quality	Low
Potential to improve food temperature control	Low
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Simple
Maintenance cost against ’conventional’ technologies	Not known
Will future legislation potentially affect uptake of technology?	Yes
Most likely application	Cooling
Most likely capacity range	0-1kW

The barocaloric effect is analogous to the magnetocaloric effect but does not require strong permanent magnets (although does require more energy to apply and remove the pressure). Barocaloric refrigeration is very similar to magnetic refrigeration and experimentation to date appears to have been carried out in conjunction with or alongside research into the magnetocaloric effect, and with the same materials. In the same way a magnetic refrigerator produces a cooling effect by applying and removing a magnetic field, barocaloric refrigeration produces a cooling effect by applying and releasing pressure on solid materials (which exhibit barocaloric behaviour). Some research has focused on using pressure to improve the magnetocaloric effect whilst other research has seen barocaloric effect as an alternative to magnetic cooling which could overcome the need for powerful permanent magnets in magnetic refrigerators.

Applied pressure has been shown to change the entropy of a (manganite) solid in a significant way without the need for a magnetic field. The combined caloric effect of magnetic field and hydrostatic pressure on manganites offers some promise for magnetic refrigerators, but the practical realisation is not likely to be simple (Szymczak, 2010). The pressures and materials currently being applied are producing a temperature change of up to 10K/kBar (Hossain 2004). Currently the energy required to achieve these pressures does not make the process attractive but potentially efficiency improvements could possibly in future make the process more realistic. No references were found to quantify a cooling duty or temperature change achieved and most research measures the effect at cryogenic temperatures. Since the barocaloric effect is generally investigated as a means to enhance magnetic refrigerators, it is likely that the magnitude of the barocaloric effect is small compared to the magnetocaloric refrigeration performance already achieved.

The technology is still at the experimental phase and materials and pressure cycles are being optimised. Even when optimised the method is only likely to find application improving the magnetic refrigerators used in specialist applications. The pressures currently being applied (effect measured in materials 10K/kBar) are likely to make systems prohibitively large and expensive for the very small cooling duties likely to be achieved. The main applications for barocaloric refrigeration are in the domestic sector.

5.5. Ejector or jet pump

Ejector or jet pump refrigeration systems are thermally driven and are simple with no moving parts. Their COPs are low and so they are only really suitable for areas where there is sufficient waste heat to drive the ejector. This is most likely to be food factories and transport. Temperatures achieved by the systems are generally not below 0°C, although lower temperatures are possible if refrigerants such as CO_2 and hydrocarbons were applied.

Time to commercial application (estimated)	0 years
Potential to save direct emissions	High
Potential to save indirect emissions	Low
Potential to improve food quality	Low
Potential to improve food temperature control	Low
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Greater
Maintenance cost against ’conventional’ technologies	Less
Will future legislation potentially affect uptake of technology?	Yes
Most likely application	Cooling
Most likely capacity range	All

5.6. Electrocaloric

Time to commercial application (estimated)	5 – 10 years
Potential to save direct emissions	High
Potential to save indirect emissions	Low
Potential to improve food quality	Low
Potential to improve food temperature control	Low
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Simple
Maintenance cost against ’conventional’ technologies	Not known
Will future legislation potentially affect uptake of technology?	Yes
Most likely application	Cooling
Most likely capacity range	0-1kW

Electrocaloric cooling is the electrical analogue of magnetocaloric cooling. Electrocaloric materials change their temperature when exposed to electric fields. The resulting changes in entropy and temperature of the material are known as the electrocaloric effect (Nesse et al 2008). The technologiy does not use a conventional refrigerant and so have claimed environmental benefits. Energy savings are expected by some researchers but as the technology is still at the developmental stage no evidence was found to support this. In 2006 researchers from Cambridge University reported in ‘ Science’ that thin films of perovskite PZT showed a giant electrocaloric effect with the materials cooling down by up 7°C in a field of just 25 volts (Mischenko et al, 2006). The electrocaloric phenomena has been known since 1930 (Scott, 2011) but the technology remains at the experimental science stage with a small number of experimental prototypes and patents in existence. There are two main threads to current research, cryogenics and room temperature, this study is only concerned with the latter. Polymeric materials such as copolymers of PVDF and triflouroethylene are the most promising materials but it is expected that crystals such as ammonium sulphate could give even better results if their ionic conductivity were greatly reduced. (Scott, 2011)

At typical refrigeration temperatures a 6.5K temperature difference can be achieved; larger temperature differences (20 to 30K) have only been measured at much warmer temperatures 350 – 400K (Scott, 2011). However, for commercially available BaTiO3-based multilayer films, it has been claimed that an ideal GEC heat pump could deliver a cooling power of $22.5W.kg^{-1}$ and it is hoped that through optimisation of materials and design $2875W.kg^{-1}$ could be achieved (Maidment)

Giant Electro Caloric Effects and Large Electro Caloric Effects have been measured in thin film materials but not at temperatures useful for typical domestic refrigeration and not on a scale suitable to meet the cooling demands of domestic refrigeration.

The technology is a long way from practical use in the cold chain. Current challenges include fabricating multilayer films of the correct materials and then building a fridge and heat exchangers around them. (Maidment). In addition Scott (2011) identifies the following:

- Optimisation of engineering design such as efficient and reliable thermal switching from source to sink under each cycle.
- Optimisation of copolymers of PVDF and research of alternative materials such as ammonium sulphate crystals.
- Extension of the temperature range.

Maidment claims that if current research produces materials to meet its predictions, 20kW should be possible; though this is a long way from the current 22W.

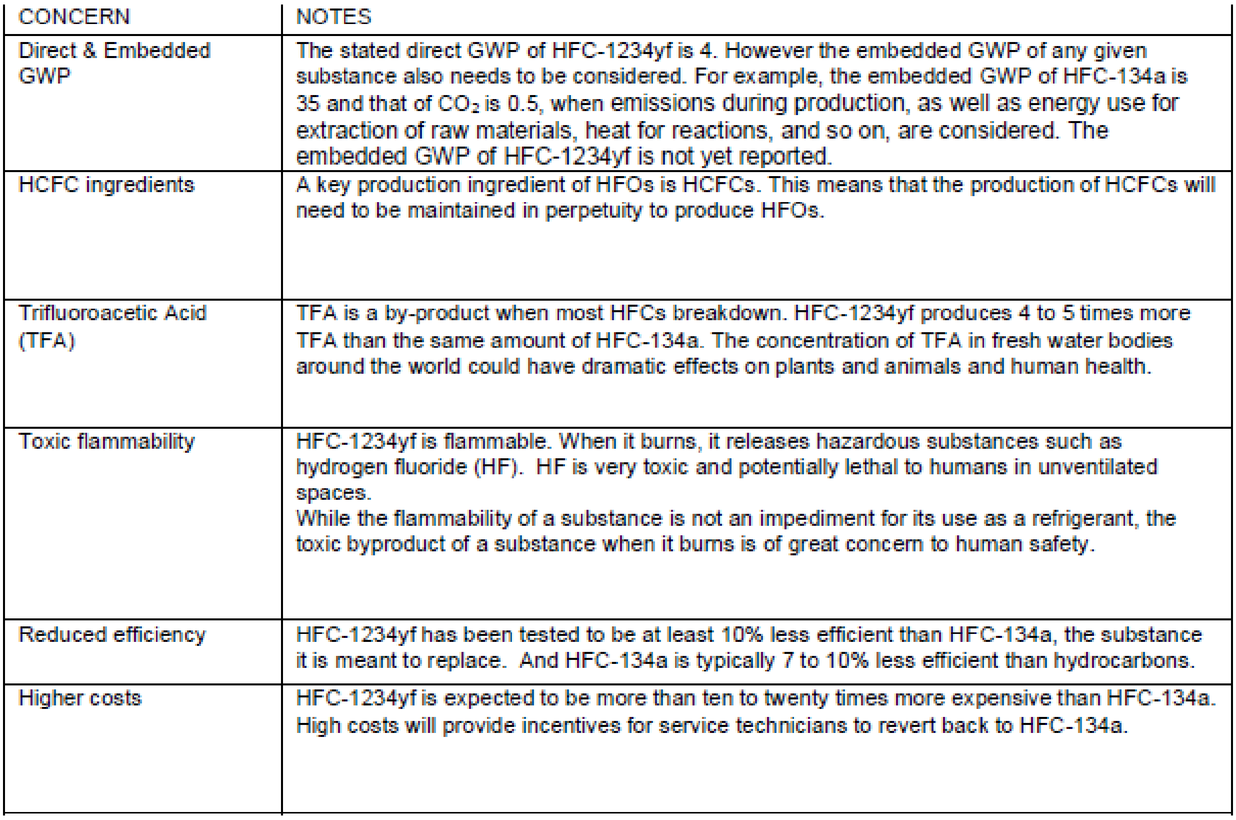
5.7. HFOs (Hydro-fluoro-olefins)

HFO (Hydro-fluoro-olefins) have recently been developed by the refrigerant manufacturers. These refrigerants were initially developed for car AC as R134a was to be phased out in Europe in new vehicles starting in 2011, with a complete phase-out by 2017. The European rules require any new refrigerants must have a global warming potential of less than 150.

To date there is limited information on the use of the main HFOs in use (R1234yf and R1234ze). HFOs have a single double bond and it has been suggested that any contaminant in a refrigeration system may cause the refrigerant to break down. To date there has been limited refrigerant available outside of the motor car industry for trials and so data are scarce. Greenpeace (2010) raise a number of issues with the use of HFOs (Table 4).

Time to commercial application (estimated)	2-5 years
Potential to save direct emissions	High
Potential to save indirect emissions	Low
Potential to improve food quality	Low
Potential to improve food temperature control	Low
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Simple
Maintenance cost against ’conventional’ technologies	Not known
Will future legislation potentially affect uptake of technology?	Yes
Most likely application	Cooling, air-conditioning
Most likely capacity range	All

Table 4. Environmental, Human Safety and Financial Concerns regarding HFC-1234yf (HFOs) (from Greenpeace, 2010).



CONCERN	NOTES
Direct & Embedded GWP	The stated direct GWP of HFC-1234yf is 4. However the embedded GWP of any given substance also needs to be considered. For example, the embedded GWP of HFC-134a is 35 and that of CO_2 is 0.5, when emissions during production, as well as energy use for extraction of raw materials, heat for reactions, and so on, are considered. The embedded GWP of HFC-1234yf is not yet reported.
HCFC ingredients	A key production ingredient of HFOs is HCFCs. This means that the production of HCFCs will need to be maintained in perpetuity to produce HFOs.
Trifluoroacetic Acid (TFA)	TFA is a by-product when most HFCs breakdown. HFC-1234yf produces 4 to 5 times more TFA than the same amount of HFC-134a. The concentration of TFA in fresh water bodies around the world could have dramatic effects on plants and animals and human health.
Toxic flammability	HFC-1234yf is flammable. When it burns, it releases hazardous substances such as hydrogen fluoride (HF). HF is very toxic and potentially lethal to humans in unventilated spaces. While the flammability of a substance is not an impediment for its use as a refrigerant, the toxic byproduct of a substance when it burns is of great concern to human safety.
Reduced efficiency	HFC-1234yf has been tested to be at least 10% less efficient than HFC-134a, the substance it is meant to replace. And HFC-134a is typically 7 to 10% less efficient than hydrocarbons.
Higher costs	HFC-1234yf is expected to be more than ten to twenty times more expensive than HFC-134a. High costs will provide incentives for service technicians to revert back to HFC-134a.

5.8. Hydraulic refrigeration

Time to commercial application (estimated)	0-5 years
Potential to save direct emissions	High
Potential to save indirect emissions	Medium
Potential to improve food quality	Low
Potential to improve food temperature control	Low
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Greater
Maintenance cost against ’conventional’ technologies	Not known
Will future legislation potentially affect uptake of technology?	Yes
Most likely application	Cooling, air-conditioning
Most likely capacity range	>10kW

Hydraulic refrigeration systems are vapor - compression systems that achieve the compression and condensation of the refrigerant by entraining refrigerant vapor in a down-flowing stream of water. They utilise the pressure head of the water to compress and condense the refrigerant.

The main benefits are that mechanical compressors or lubricants are not required and the condenser is replaced by the water stream. The system is similar to vapour compression, system except that a water stream replaces the compressor and condenser. The refrigerant gas from the evaporator is entrained into the water stream at the top of the water column. As the water flows down the column, the refrigerant is compressed and cooled simultaneously. The condensed high pressure liquid refrigerant is then separated from the water stream at the bottom of the column and returned to the evaporator via an expansion device. The compression ratio is therefore a function of the height of the water column and the amount of cooling a function of the water temperature.

The process is already in use on an industrial scale in the US to compress air (where a free flow of water has been available) but has also been successfully applied to refrigeration systems. The major downside of the process is the large vertical height of the water column required. Systems are under development but commercial availability of refrigeration systems using hydraulic compression is unlikely in the medium term. Even when commercialised, this technology will require more space and height than conventional systems. Its application will therefore be limited to Industrial systems. Separation of refrigerant and water stream are likely to be the major challenge practically (Rice and Hosterman).

Chau et al (2001) designed and tested a multi-stage hydraulic refrigeration system using n-butane as the refrigerant. They concluded that hydraulic refrigeration had potential as an alternative to conventional vapor-compression systems in applications where direct-contact heat exchange in the evaporator was desirable.

Systems are under development but commercial availability of refrigeration systems using hydraulic compression is unlikely in the medium term. Even when commercialised, this technology will require more space and height than conventional systems. Its application will therefore be limited to industrial systems.

5.9. Magnetic refrigeration

Time to commercial application (estimated)	3-5 years
Potential to save direct emissions	High
Potential to save indirect emissions	Medium
Potential to improve food quality	Low
Potential to improve food temperature control	Low
Likely initial cost against 'conventional' technologies	Higher
Ease of use and installation	Simple
Maintenance cost against 'conventional' technologies	Less
Will future legislation potentially affect uptake of technology?	Yes
Most likely application	Cooling
Most likely capacity range	0-1kW

Technologies such as magnetic cooling have potential advantages such as no harmful refrigerants and potentially high efficiencies above those of vapour compression technologies. Magnetic refrigeration takes advantage of the magnetocaloric effect; the ability of some metals to heat up when they are magnetized and cool when demagnetized. Much of the original work and most prototypes developed were based on the use of gadolinium magnets that are rather expensive. More recent work has looked for new materials that are cheap, have suitable transition temperatures and exhibit a large megnetocaloric effect. Magnetic refrigeration has the prospect of efficient, environmentally friendly and compact cooling for a wide field of applications.

Astronautics Corporation in America and Chubu Electric Power Co Inc in Japan have both produced rotary magnetic refrigerator systems. The highest COP reported for a near room temperature, permanent magnet system was 2.4. This was based on a 560W cooling capacity at zero temperature span. For a 5K temperature span and 20°C sink temperature, the COP reduced to 0.6 and the cooling duty to 159W (Lewis et al, 2007).

Gschneidner and Pecharsky (2008) predict that production of near room temperature, magnetic refrigeration systems will grow to 1000 units by 2015, by which time they would consider the technology to be commercialised.

Camfridge (backed by Cambridge University) began a project with Whirlpool in 2009 and expect to have a magnetic cooling system for the domestic sector built as a demonstration unit in time for the Olympic games in 2012. (Whirlpool, 2009; Wilson et al, 2006).

Successful commercialisation will require (Lewis et al, 2007):

- “magnetic refrigerants” with a larger magneto caloric effect to be produced in large quantities.
- Permanent magnets need to be stronger, smaller and cheaper.
- Improvements could be made to the cycles.
- Improvements to the engineering design of the systems.

5.10. Nanoparticles

Time to commercial application (estimated)	2-5 years
Potential to save direct emissions	Low
Potential to save indirect emissions	Medium
Potential to improve food quality	Low
Potential to improve food temperature control	Low
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Simple
Maintenance cost against ’conventional’ technologies	Not known
Will future legislation potentially affect uptake of technology?	No
Most likely application	Freezing, cooling, air-conditioning
Most likely capacity range	All

Nanofluids are engineered colloidal suspensions of nanoparticles (1-100 nm) in a base fluid. The size of the nanoparticles imparts some unique characteristics to these fluids, including greatly enhanced energy, momentum and mass transfer, as well as reduced tendency for sedimentation and erosion of the containing surfaces. To enhance heat transfer, nanofluids were developed, based on mainly copper and aluminium nanoparticles of above 20nm size (Eastman et al, 1996). Theoretically, these nanoparticles have a high thermal conductivity and, hence, should improve the heat transfer near the laminar sub-layer (Jana et al 2007; Lee et al, 2007; Ko et al 2007). Recent experimental work at NIST (USA) with varying concentrations of nanoparticle additives indicate a major opportunity to improve the energy efficiency of large industrial, commercial cooling systems. NIST have shown that dispersing low concentrations of copper oxide particles (30 nanometers in diameter) in a common polyolester lubricant and combining it with R134a improved heat transfer by between 50 and 275%. Success in optimising mixtures of refrigerants, lubricants and nanoparticle additives could be beneficial. High-performance mixtures could be swapped into existing chillers, resulting in immediate energy savings. Due to improved energy efficiency, next-generation equipment would be smaller, requiring fewer raw materials in their manufacture.

5.11. Novel building fabric

The use of novel materials such as those incorporating phase change materials could be a means to even out summer/winter variations in cooling demand. Materials incorporating PCMs are available for offices and residential building but not currently for cold stores. Although simple to install the size and weight may be problematic in some installations.

Time to commercial application (estimated)	3-5 years
Potential to save direct emissions	Low
Potential to save indirect emissions	Medium
Potential to improve food quality	Medium
Potential to improve food temperature control	Medium
Likely initial cost against 'conventional' technologies	Higher
Ease of use and installation	Simple
Maintenance cost against 'conventional' technologies	Not known
Will future legislation potentially affect uptake of technology?	No
Most likely application	Air-conditioning
Most likely capacity range	0-1kW, 1-10kW

5.12. Optical cooling

Time to commercial application (estimated)	>10 years
Potential to save direct emissions	High
Potential to save indirect emissions	Low
Potential to improve food quality	Low
Potential to improve food temperature control	Low
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Not known
Maintenance cost against ’conventional’ technologies	Not known
Will future legislation potentially affect uptake of technology?	Yes
Most likely application	Cooling
Most likely capacity range	0-1kW

Optical cooling systems have no moving parts and this could make it more reliable than conventional refrigeration systems (same justification used for acoustic). Claims are made that with development it could replace Stirling coolers but the most likely application is on radiation balanced lasers where it will be used to compensate for internal heat generation.

Although unlikely to be of practical benefit in the cold chain, optical cooling could be used to extend solid state cooling achieved with thermoelectric systems into lower temperature regions; in cryogenic and spacecraft applications, optical cooling may bring size and weight advantages over thermoelectric or mechanical systems where the load is less than 1W and the temperature is between 20 and 200K (Mills and Mord 2006).

Optical cooling works in a similar manner to magnetocaloric or barocaloric cooling, this technique also uses a solid-state material as the “refrigerant”. Optical refrigeration is also referred to as “laser refrigeration” or “anti-Stokes fluorescent cooling”. It is a technique for cooling a crystal (doped with Ytterbium or Thulium ions) by exciting the ions with a laser beam (Paschotta 2011). The crystal is pulsed with light from a laser. The energy is absorbed, and then emitted as fluorescence. When the energy of the fluorescence photons is larger than the laser light photons absorbed, there is a net energy loss and the material cools (Graydon 2005).

The physical phenomenon of radiation cooling by anti-Stokes fluorescence was originally proposed in 1929 but only experimentally observed in 1995. ZBLAN glass has been cooled to 208K from room temperature (Epstein et al 1995) and 155K has been achieved with $Yb:LiYF_4$ at a cooling power of 90mW (Seletskiy, 2010). Theory suggests that 77K could be achieved.

It can be applied to microscopic particles as well as macroscopic samples; and may be most practical for these specialist microscopic applications than for scaling up even to small domestic refrigeration.

Further laboratory experimentation is required to increase the cooling duties but this technology is only likely to be suited to cryogenic and space applications; it is unlikely that any developments will make this a useful technology for the cold chain.

5.13. Pulsed electrical thermal de-icers

Recently work has shown that thin, electrically-conductive films applied to surfaces and heated with milliseconds-long pulses of electricity can make ice melt from surfaces. Called thin-film, pulse electro-thermal de-icers (PETD) they create a thin layer of melted water on a surface that melts ice efficiently (Dartmouth College). If this technology can be economically applied to evaporators it has potential for low energy defrosting of evaporators.

Time to commercial application (estimated)	5-10 years
Potential to save direct emissions	Low
Potential to save indirect emissions	High
Potential to improve food quality	High
Potential to improve food temperature control	High
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Greater
Maintenance cost against ’conventional’ technologies	Not known
Will future legislation potentially affect uptake of technology?	No
Most likely application	Freezing
Most likely capacity range	>10kW

5.14. Secondary systems (novel)

Time to commercial application (estimated)	1-5 years
Potential to save direct emissions	High
Potential to save indirect emissions	Low
Potential to improve food quality	Low
Potential to improve food temperature control	Low
Likely initial cost against 'conventional' technologies	Higher
Ease of use and installation	Greater
Maintenance cost against 'conventional' technologies	Not known
Will future legislation potentially affect uptake of technology?	Yes
Most likely application	Cooling, air-conditioning
Most likely capacity range	1-10kW

Secondary refrigeration systems for transport vehicles have been investigated by Smyth et al (2010a) who collaborated with Thermoking. Such systems are claimed to reduce leakage of refrigerants and have a reduced refrigerant charge. Smyth et al (2010b) found that to operate successfully over the range of ATP *(*Agreement on the International Carriage of Perishable Foodstuff and on the Special Equipment to be Used for such Carriage, 2003) conditions the choice of secondary fluid was very critical. Potassium formate/sodium propionate was found to have good refrigeration capacity across the range of ATP conditions but required high pumping power at elevated temperatures which reduced COP. Hydrofluoroether required low pumping power but its poor specific heat capacity adversely affected performance at low high temperatures. The same authors (2010b) increased refrigeration capacity in the primary circuit of a secondary refrigeration system by adding an economiser cycle and modulating the injection ratio to optimise COPs at varied ATP conditions.

5.15. Solar

Solar collectors have some potential to drive sorption systems or thermoelectric power generation (see below). Other cycles such as Rankine cycles could also be considered and coupled with an air cycle.

Solar (photovoltaic) panels could potentially be mounted on the roof of vehicles but would only be effective during parts of the year in most European countries. The weight of the panels is an issue as well as the overall efficiency of the panels.

Absorption systems have also been investigated by Christy and Toossi (2004). They used the engine coolant circuit and exhaust gas to operate the cycle and obtained COPs of 0.6 to 1.

Time to commercial application (estimated)	5-10 years
Potential to save direct emissions	High
Potential to save indirect emissions	High
Potential to improve food quality	Low
Potential to improve food temperature control	Low
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Greater
Maintenance cost against ’conventional’ technologies	Greater
Will future legislation potentially affect uptake of technology?	Yes
Most likely application	Cooling, air-conditioning
Most likely capacity range	0-1kW, 1-10kW

5.16. Stirling cycle variations

Time to commercial application (estimated)	0-5 years
Potential to save direct emissions	High
Potential to save indirect emissions	Medium
Potential to improve food quality	Low
Potential to improve food temperature control	Low
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Simple
Maintenance cost against ’conventional’ technologies	Not known
Will future legislation potentially affect uptake of technology?	Yes
Most likely application	Freezing, cooling
Most likely capacity range	0-1kW

Stirling coolers can operate down to cryogenic temperatures. Stirling coolers are closed-cycle regenerative thermal machines which compress and expand a gas. Free piston machines use a moving magnet or linear machine unit to facilitate heat absorption and heat rejection respectively (but compression and expansion can also be performed by compressive waves, see acoustic refrigeration). Such units can have maximum cooling capacities up to 100W with larger capacity units, up to 300W, reported to be under development. Applications are in domestic and portable refrigerators and freezers as well as a beverage can vending machines. COP between 2 and 3 have been reported for cold head temperatures around 0°C, and values around 1 for cold head temperatures approaching -40°C. Although the rapid start-up and cool down of stirling coolers is often cited as a major benefit, they are generally limited in their application by the low heat transfer co-efficient between the working fluid (gas) and the inside wall of the cylinder/heat exchanger; this generally makes them bulky difficult to implement practically.

5.17. Thermionic refrigeration

Thermionic cooling is based on the ability of a material to change temperature by applying an electric field under adiabatic conditions.

The name thermionic arises from thermionic emission, which is the thermal excitation of hot electrons from a metal surface (Mahan 2001). A thermionic device has two thin films separated by a vacuum layer. If a voltage is passed across the gap, the most energetic electrons on the negative side ‘jump’ across to the positive side. As the electrons leave the negative side they get colder. Potentially such device can be thermodynamically very efficient and could outperform classic direct expansion refrigeration systems.

Thermionic refrigeration is not currently applied to the cold-chain and most cited applications are for solid-state, on-chip cooling or temperature regulation for sensors and other electronic devices.

The major benefits would appear to be reduced direct emissions (no HFC). Energy savings are expected by some researchers but as the technology is still at the developmental stage no evidence was found to support this. Based on a purely theoretical study, Mahan and Woods (1998) propose that efficiencies twice that of existing thermoelectric devices and comparable to existing vapour compression systems could be achieved but note that materials with a suitable work function (<0.3 eV) are not yet available.

Time to commercial application (estimated)	5-10 years
Potential to save direct emissions	High
Potential to save indirect emissions	Low
Potential to improve food quality	Low
Potential to improve food temperature control	Low
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Simple
Maintenance cost against ’conventional’ technologies	Not known
Will future legislation potentially affect uptake of technology?	Yes
Most likely application	Cooling
Most likely capacity range	0-1kW

5.18. Thermoelectric generation

Thermoelectric power generation has also been suggested as a means to provide power on refrigerated transport vehicles. Their advantage is that they have no moving parts and no noise output. Heat to generate power can be sourced from the engine exhaust gas or solar radiation. A company called Hi-Z in Canada is developing the technology and they aim to use 10-20 W modules to generate 5-10 kW to drive a vehicle refrigeration system (Hi-Z, 2008). Hi-Z also claims that although current energy conversion efficiencies are around 5% they could rise to 25%.

Time to commercial application (estimated)	5-10 years
Potential to save direct emissions	High
Potential to save indirect emissions	High
Potential to improve food quality	Low
Potential to improve food temperature control	Low
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Greater
Maintenance cost against ’conventional’ technologies	Less
Will future legislation potentially affect uptake of technology?	Yes
Most likely application	Cooling
Most likely capacity range	0-1kW

5.19. Vortex tube cooling

Vortex tube cooling operates with compressed air as the working fluid and so is environmentally harmless with zero GWP and zero ODP. Compressed air is injected into a swirl chamber and exits via a longer tube as two air streams, one hot and one cold. As the compressed air enters the swirl chamber (or vortex generator) the air accelerates to a high rate of rotation (as much as 1,000,000 rpm). A small amount of the hottest gas is allowed to escape via the conical nozzle at the longer end of the vortex tube and the remaining air returns down the centre of the vortex tube to exit as cold air through the shorter end (Figure 2).

It is believed that a pressure difference occurs through the gas due to the centrifugal force. The resulting compression at the walls, expansion at the centre and heat transfer between the two streams within the vortex tube then result in the cold and hot air stream separation.

Time to commercial application (estimated)	0-5 years
Potential to save direct emissions	High
Potential to save indirect emissions	Low
Potential to improve food quality	Low
Potential to improve food temperature control	Low
Likely initial cost against 'conventional' technologies	Higher
Ease of use and installation	Simple
Maintenance cost against 'conventional' technologies	Not known
Will future legislation potentially affect uptake of technology?	Yes
Most likely application	Cooling
Most likely capacity range	0-1kW

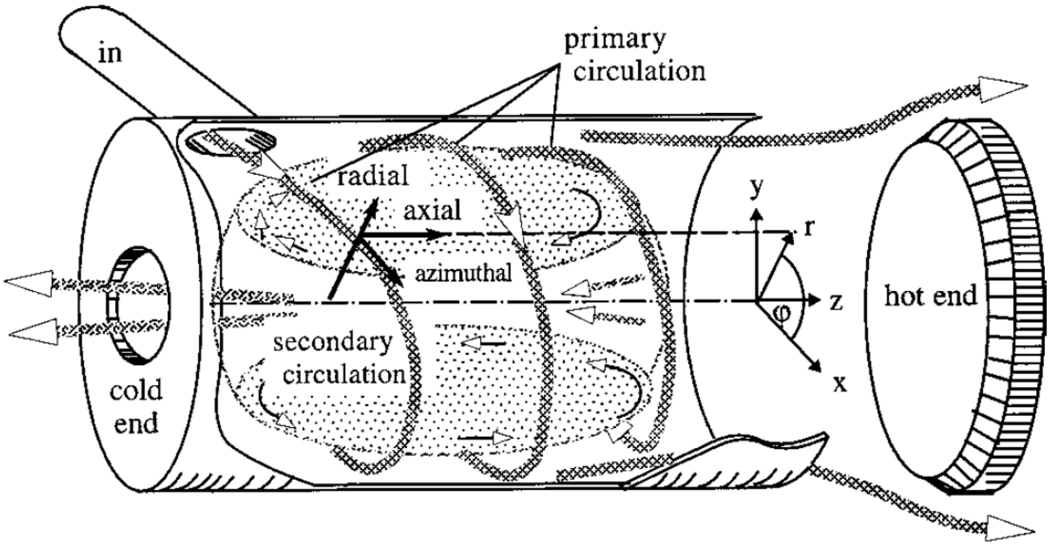


Figure 2. Vortex tube taken from (Ahlborn et al. 2000]).

Vortex tubes are useful where inexpensive, non-toxic spot cooling is required and where a large amount of compressed air is available. Due to the energy cost of compressing the air initially and the in-efficient conversion of that energy into useful cooling by vortex tubes, they do not present a low energy solution.

Vortex tubes are available off-the-shelf with cooling duties up to 1700W (with 43°C temperature drop and an air flow rate of 2833 SLPM at 6.9 Bar) (Newman Tools Inc. Ontario, Canada) (SLPM is standard litres per minute and is a mass flow rate based on air at 0°C and 1.01 Bar).

Unless a large amount of compressed air is available as a "waste" or "free" energy source, vortex tubes will only be suitable for spot cooling or where toxicity or flammability are a greater concern than energy.

5.20. Water in vapour compression

Time to commercial application (estimated)	0 years
Potential to save direct emissions	High
Potential to save indirect emissions	Medium
Potential to improve food quality	Low
Potential to improve food temperature control	Low
Likely initial cost against 'conventional' technologies	Higher
Ease of use and installation	Similar
Maintenance cost against 'conventional' technologies	Not known
Will future legislation potentially affect uptake of technology?	Yes
Most likely application	Air-conditioning
Most likely capacity range	>10kW

The main advantages of water as a refrigerant are that it is non-toxic and non-flammable has a GWP and ODP of zero. Small energy savings are possible over other refrigerants where warm evaporating temperatures (over 35°C) or small (<10K) temperature lifts are required.

The main disadvantage with water in a VCS is that it works under a vacuum so the volumetric cooling capacity is very low and huge volumetric flow rates must be therefore be used. Water requires approximately 200 times larger volumetric flow rates than a conventional (HFC) VCS and about double the compression ratio (Müller).

Operation is similar to conventional VCS but:

- Alternative compressor technology is required.
- It is possible to run with an open system for direct cooling in some applications.
- Pressures required are very much lower, a crude vacuum.
- Volumetric flow rates are significantly larger.

This means that plant becomes very large but on the plus side, pressure vessel testing is not required (Figure 3).

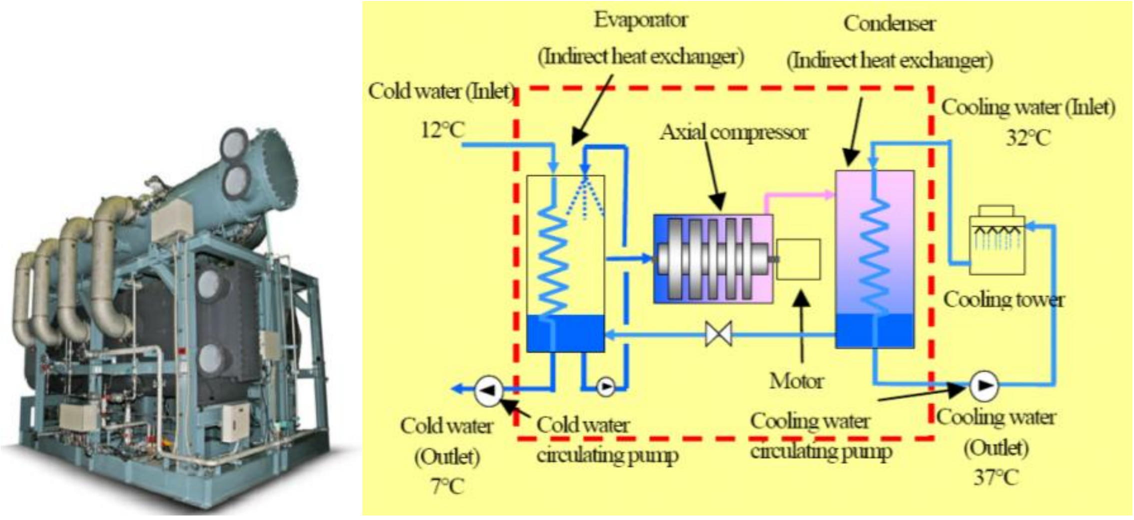


Figure 3. Photo and schematic of an indirect water vapour chiller. Taken from (Tepco 2011).

Water vapour chillers are already in use, but only offer energy savings (when compared with conventional (HFC, HC and Ammonia) systems in a very limited range of applications and cost approximately twice the amount (Kühnl-Kinel). Ammonia is the closest challenger to water and offers better efficiency for most applications where its toxicity and flammability can be accommodated.

Centrifugal or radial compressors offer a pressure ratio of around 2.3 and so 1 to 3 stages area adequate for a water vapour chiller and have been used successfully. However, despite offering lower compression ratios, and so requiring up to 8 stages, new axial flow compressors are now enabling the footprint to be reduced by up to a third (Tepco 2011), (Kühnl-Kinel)

The Tepco system is currently undergoing reliability testing prior to release to market. (Tepco, 2011).

Wave rotor technology (using compression waves to add energy to the working fluid, rather than pistons or turbine blades) is an old technology that has received attention recently as it promises improved efficiency and size reduction of the compressor required for a water VCS chiller. Prototype refrigeration systems have been built and tested using 3-port condensing wave rotors and improvements in COP of up to 22% were measured (Kharazi *et al* 2004). Most of the research was conducted by Michigan State University. The current problems with wave rotors are sealing and thermal expansion (Akbari *et al* 2004).

Further research into wave rotor technology and further reliability testing of the Tepco system could yield useable technology offering energy savings and environmental safety for high temperature, small temperature lift applications or, an environmentally safer refrigerant with slightly higher energy consumption and larger plant size and cost for other applications.

6. Technologies that are product oriented technologies.

6.1. Antifreeze proteins

Antifreeze proteins lower the freezing point temperature. They are present in many fish and invertebrates as well as plants to prevent them freezing in cold weather or cold water. By allowing a food to be stored at a low temperature whilst not being frozen the product latent heat does not need to be removed. This potentially can save energy as most of the heat extracted from products in freezing is from latent heat. Where freezing does occur the antifreeze proteins retard the growth of ice crystals. To date antifreeze proteins have been mainly used to prevent ice crystal growth in products such as ice cream. It has been suggested that the use of antifreeze proteins in meat may reduce drip loss (Payne et al 1994; Payne and Young, 1995).

Time to commercial application (estimated)	>10 years
Potential to save direct emissions	Low
Potential to save indirect emissions	Medium
Potential to improve food quality	Medium
Potential to improve food temperature control	Low
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Greater
Maintenance cost against ’conventional’ technologies	Not known
Will future legislation potentially affect uptake of technology?	No
Most likely application	Freezing
Most likely capacity range	All

6.2. Dehydrofreezing

Dehydrofreezing has mainly been used for fruits and vegetables. A large part of the water (50-60%) in the product is removed prior to freezing using an osmotic solution and this results in a freezing process that is faster and causes less ice crystal damage than a conventional process. Due to less water being contained in the product the refrigeration heat load is also reduced. Texture and flavour are claimed to be superior to those of a conventionally frozen product.
Due to the product being dehydrated there is less water in the product and therefore the latent heat is less. This is claimed to save energy (Mascheroni, 2007). Figure 4 shows the freezing times for a product after varied periods of dehydration. Greater periods of dehydration resulted in shorter freezing times.

Time to commercial application (estimated)	3-5 years
Potential to save direct emissions	Low
Potential to save indirect emissions	Low
Potential to improve food quality	Medium
Potential to improve food temperature control	Low
Likely initial cost against 'conventional' technologies	Higher
Ease of use and installation	Greater
Maintenance cost against 'conventional' technologies	Not known
Will future legislation potentially affect uptake of technology?	No
Most likely application	Freezing
Most likely capacity range	All

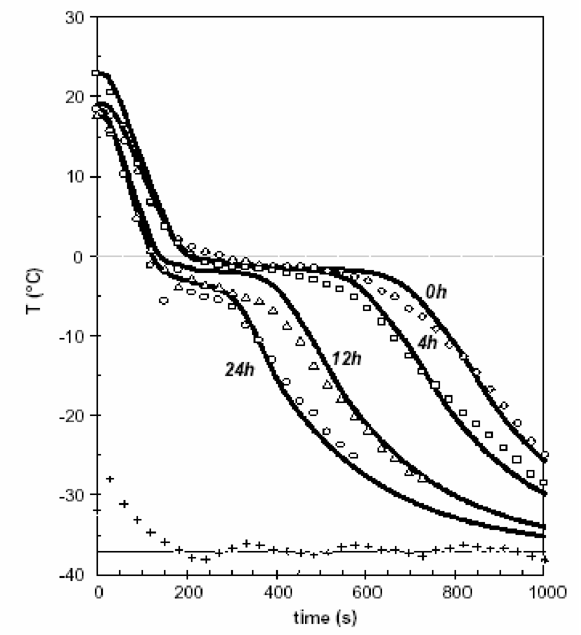


Figure 4. Product being frozen after dehydrofreezing for various times (from Mascheroni, 2007).

6.3. Eutectic packaging

Time to commercial application (estimated)	2-5 years
Potential to save direct emissions	Low
Potential to save indirect emissions	Medium
Potential to improve food quality	High
Potential to improve food temperature control	High
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Simple
Maintenance cost against ’conventional’ technologies	Higher
Will future legislation potentially affect uptake of technology?	No
Most likely application	Freezing-cooling
Most likely capacity range	All

Micro and nanoencapsulated phase changing materials (PCMs) can potentially be incorporated into packaging to minimise the effect of ambient temperature fluctuations on food temperature. A number of challenges exits in the development of such systems including identifying an appropriate temperature window, compatibility of the eutectic material with the matrix, finding materials with high enthalpy transitions and fast and congruent phase changes, and materials with small volume changes and high viscosity upon melting, chemical stability, no toxicity and low cost (Pasupathy et al 2008).

One major problem is containing the liquid phase on melting. A solution to optimize the performance of materials for frozen packaged foods is the use of paraffins and fatty acids and to micro- and nanoencapsulate the PCM into materials that are then incorporated into packaging and machine coatings. Nano-structured new materials comprising calcium silicate with its very high liquid absorbency provides an attractive cost effective solution to the problem (Johnston, et al, 2006). Typically 300–400 wt% PCM can be accommodated in the highly porous matrix. Above the melting point the liquid PCM phase is contained in the pores with the overall NCS–PCM composite remaining as a white powdery solid. This can then be incorporated into packaging materials to provide thermal storage capacity. A very promising encapsulation technology that can make use of polymers and biobased polymers as carrier elements is the high voltage spinning technique (Torres-Giner et al 2008; Fernandez et al, 2008). This technique allows the simple encapsulation of active elements either in uniaxial or coaxial fiber and bead micro and nanostructured morphologies, which can be later implemented with excellent compatibility into plastic and bioplastic packaging and coating elements, by for instance, the technology devised by Lagaron et al. (Lagaron et al, 2007). Lagaron (2011) has succeeded in introducing nanobiostructured PCMs (Phase Change Materials) into renewable materials or onto surfaces by a proprietary process (patent application number 201131063).

6.4. Heat pipes and spot cooling

The cooling of many cooked foods is limited by the rate at which heat can flow from the centre to the surface of the product. Investigations carried out by Ketteringham and James, (2000) showed the benefit of using high heat transfer devices including heat pipes, thermosyphons and solid metal rods to increase the cooling rate of hot foods. The use of high conductivity inserts reduced blast chilling times in mashed potato cooled from 70°C to 10°C and 3°C by between 6% and 29%, with heat pipes producing the greatest effect. The inserts had the potential to produce significant time and energy savings and improvements in food quality and safety.

Heat pipes have potential for spot cooling or for moving heat away from critical points in a refrigeration system or refrigerated equipment. For example they could be used to spot cool in retail display cabinets or could be used to cool cooked food (Figure 5).

Time to commercial application (estimated)	0 years
Potential to save direct emissions	Low
Potential to save indirect emissions	Medium
Potential to improve food quality	Medium
Potential to improve food temperature control	Medium
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Simple
Maintenance cost against ’conventional’ technologies	Higher
Will future legislation potentially affect uptake of technology?	No
Most likely application	All
Most likely capacity range	All

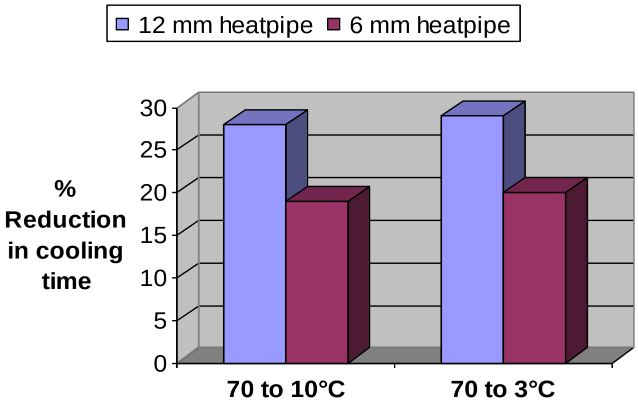


Figure 5. Reduction in cooling time of cooked meal when using aheat pipe (Ketteringham and James 2000).

6.5. Hydrofluidisation

Hydrofluidisation utilises a pump that circulates refrigerant through orifices or nozzles to create agitating jets in a refrigeration vessel. This forms a fluidised bed of highly turbulent liquid that agitates product and generates extremely high heat transfer coefficients at the surface of the products (Fikiin, 1985, 1992, 2003). Suitable refrigerant media include brines, soluble carbohydrates (such as sucrose, invert sugar, glucose (dextrose), fructose and other mono- and disaccharides) with additions of ethanol, salts and glycerol. Freezing rates for fish and vegetables have been shown to exceed those for IQF products with heat transfer coefficients exceeding 900 W m^{-2} K^{-1} (Fikiin, 1992, Fikiin and Pham, 1985). This leads to low weight loss as the surface of the product is frozen extremely rapidly.

Information is not available on energy consumed but for small products that are frozen fast the energy use may be low. For some products, the heat transfer rates may be limited by the heat transfer rate through the product rather than that between the cooling fluid and the product; the increased pump energy required for hydrofluidisation may therefore outweigh the benefits in some circumstances.

Time to commercial application (estimated)	0-5 years
Potential to save direct emissions	Medium
Potential to save indirect emissions	Low
Potential to improve food quality	Medium
Potential to improve food temperature control	High
Likely initial cost against 'conventional' technologies	Higher
Ease of use and installation	Greater
Maintenance cost against 'conventional' technologies	Not known
Will future legislation potentially affect uptake of technology?	No
Most likely application	Freezing-cooling
Most likely capacity range	All

6.6. Ice nucleation proteins

Ice nucleation proteins reduce super cooling and are claimed to reduce freezing time. This is claimed to reduce energy cost and improve food quality mainly in liquid or semi-liquid products (Watanabe et al, 1989; Li and Lee, 1998). Bacteria are the most widely recognised ice nucleation activators (usually of genera *Pseudomonas*, *Erwinia* and *Xanthomonas*) and therefore care needs to be taken in their application to ensure that they are safe, non toxic and non pathogenic (Li and Lee, 1995).

Time to commercial application (estimated)	>10 years
Potential to save direct emissions	Low
Potential to save indirect emissions	Low
Potential to improve food quality	Medium
Potential to improve food temperature control	Low
Likely initial cost against 'conventional' technologies	Higher
Ease of use and installation	Greater
Maintenance cost against 'conventional' technologies	Not known
Will future legislation potentially affect uptake of technology?	No
Most likely application	Cooling
Most likely capacity range	All

6.7. Magnetic field freezing/CAS (Cell Alive System)

Time to commercial application (estimated)	0-5 years
Potential to save direct emissions	Low
Potential to save indirect emissions	Low
Potential to improve food quality	High
Potential to improve food temperature control	Low
Likely initial cost against 'conventional' technologies	Higher
Ease of use and installation	Greater
Maintenance cost against 'conventional' technologies	Higher
Will future legislation potentially affect uptake of technology?	No
Most likely application	Freezing
Most likely capacity range	<10kW

Magnetic resonance freezing (MRF) utilises continuous magnetic wave vibrations which impede ice crystallisation. When cooling is applied this allows water to be supercooled below its freezing point. When the magnetic field is removed the product can freeze rapidly. This has claimed benefits of small ice crystals, little cellular damage and low water loss during the freezing process. Published information on MRF technologies is rather limited with much retained within commercial companies.

The Cells Alive System (CAS) was developed by ABI in Japan. Applying a magnetic field during freezing is claimed to avoid cell wall damage during the freezing process. The CAS vibrates water in foods with magnetic fields. This prevents freezing, even at temperatures as low as -10°C (According to the Patent.). When the magnetic field is turned off, the water in the food instantly freezes. This is claimed to create small ice crystals and less damage to cell walls. It is not clear how ice crystal structure is maintained as ice crystals over time will agglomerate (Oswalt ripening).

There is very little published work on magnetic field freezing. Work by Suzuki et al (2007) created a copy of the commercially available CAS and assessed freezing with and without a magnetic field on quality of sweet potato, spinach, fish, agar gel and water. In assessment of colour, oiliness, smell, umami, fatty taste, strength and texture they found no significant difference between samples frozen with and without a magnet field.

6.8. New foods

The possibility that new foods could be developed was introduced by Cleland (2001). The possibility of producing foods that require less refrigeration during storage, are freeze dried or preserved in a way that prevents quality loss or microbial degradation has been considered a possibility for the future.

Time to commercial application (estimated)	>10 years
Potential to save direct emissions	High
Potential to save indirect emissions	Medium
Potential to improve food quality	Medium
Potential to improve food temperature control	High
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Greater
Maintenance cost against ’conventional’ technologies	Less
Will future legislation potentially affect uptake of technology?	Yes
Most likely application	Freezing-chilling
Most likely capacity range	All

6.9. Perfusion

Meat carcasses must be chilled to below 7°C before leaving the slaughterhouse. Typically this is done by passing refrigerated air over the surface of an eviscerated and dehided carcass. Because the cooling medium is only acting on the outer surface, it can take many hours for the temperature at the centre of the carcass to drop below 7°C. Often fan energy is as high as 30% of the overall energy consumption. In vascular perfusion chilling (VPC), a cold fluid is circulated through the intact vascular system theoretically offering significant reductions in cooling time and negating the need for cooling fans. Reducing the time required to chill carcasses will have substantial benefits to the meat industry in terms of both quality and energy usage. Such a treatment is still in the development stage but systems not aimed to provide full chilling have been used in the USA and Australia to remove blood from carcasses and claim improved hygiene (Dikeman et al, 2003, Wang et al, 1995).

Time to commercial application (estimated)	5 years
Potential to save direct emissions	Low
Potential to save indirect emissions	High
Potential to improve food quality	Medium
Potential to improve food temperature control	Low
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Greater
Maintenance cost against ’conventional’ technologies	Not known
Will future legislation potentially affect uptake of technology?	Yes
Most likely application	Cooling
Most likely capacity range	>10kW

6.10. Pressure shift freezing

Time to commercial application (estimated)	5-10 years
Potential to save direct emissions	Low
Potential to save indirect emissions	Low
Potential to improve food quality	High
Potential to improve food temperature control	Low
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Greater
Maintenance cost against ’conventional’ technologies	Higher
Will future legislation potentially affect uptake of technology?	No
Most likely application	Freezing
Most likely capacity range	<10kW

Two main processes exist; High-Pressure Assisted Freezing and High-Pressure Shift Freezing (HPSF).

High-Pressure Assisted Freezing occurs under constant high pressure whilst temperature is lowered to the corresponding freezing point. Freezing occurs from the outside of the product with ice nucleation in the outer area of the food which grows radially into the centre. There is little evidence that structure or texture are any different from product frozen at atmospheric pressure. Potentially freezing times can be less than at atmospheric pressure.

HPSF is potentially a method to produce frozen food with small ice crystals and consequently little tissue damage and high quality. At atmospheric pressure ice has a freezing point of 0°C. With increasing pressure the freezing point of water is lowered until at 207,500 kPa the freezing point is -22°C. HPSF involves increasing the pressure of a sample and reducing the temperature to create super cooled water. At this point the pressure is released to create ice instantaneously. Figure 6 shows a phase diagram for water showing the process. The pressure can be released slowly over several minutes or rapidly over a few seconds (Figure 7). This produces small ice crystals of granular shape almost instantaneously throughout the sample. When the pressure is released there is a large release of heat of fusion and a consequent rise in sample temperature. Improvements in texture and histological damage of samples have been reported but deteriorations in colour, water holding capacity, and texture of meat products have also been reported and appear to be related to applied pressure (Fernandez-Martın et al, 2000, Massaux et al, 1998). HPSF has the advantage of deactivating some vegetative microbes, with the level of inactivation ranging from about 3 to 8 log cycles.

Although HPSF has many advantages sample sizes are relatively small and the vessels required for the process are expensive and the freezing process is a relatively slow batch operation with small throughputs. Although ice crystals are small and uniform the maintenance of such structures needs uniform temperature control in frozen storage and this may be difficult to practically achieve. Some claims have been made that pressure shift freezing reduces the latent heat of a product but there are few practical data to substantiate this.

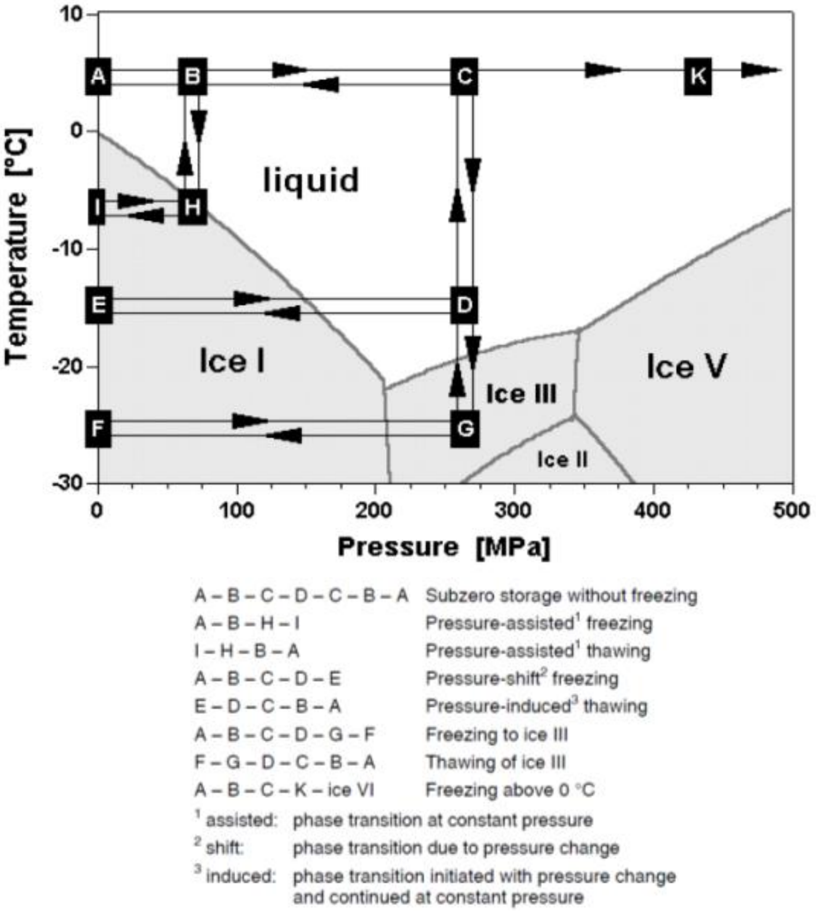


Figure 6. Water phase diagram and high pressure effects on the phase diagram (from Fikiin, 2003).

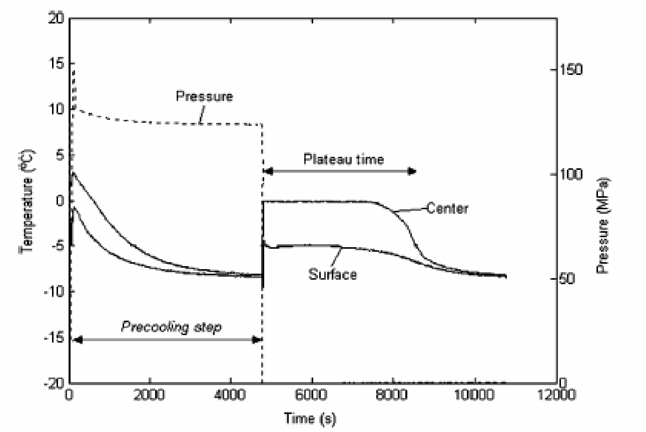


Figure 7. High pressure-shift freezing of an agar gep sample from 120 MPpa/-8°C to 0.1 Mpa. Temperature of the pressure/cooling medium: -8.5°C (from Mascheroni, 2007).

6.11. Supercooling

Supercooling is an analogous to superchilling but where water remains unfrozen. Potentially this is an energy efficient technology as energy is not used to freeze water.

There is limited published information on supercooling and no information has been identified on the energy or carbon implications. Recent work published covers supercooling of garlic (James et al, 2009) strawberries (Martins and Lopes, 2007), tomatoes (Cox and Moore, 1997), cauliflower (Fuller and Wisniewski) and a range of vegetables and fish (James et al, 2011). Earlier work from the 1920s, (Diehl and Wright, 1924) has reported that apples could sometimes be subcooled. Grape, lemons and naval oranges have also been reported by Lucas (1954) to supercool. A summary of products that have been shown to subcool and the level of subcooling are shown in Table 5Table 5. Generally supercooling is accentuated when products are slowly cooled. It is thought that vibration to movement can cause sudden freezing.

Time to commercial application (estimated)	3-6 years
Potential to save direct emissions	Low
Potential to save indirect emissions	High
Potential to improve food quality	High
Potential to improve food temperature control	Low
Likely initial cost against ’conventional’ technologies	Lower
Ease of use and installation	Simple
Maintenance cost against ’conventional’ technologies	Less
Will future legislation potentially affect uptake of technology?	No
Most likely application	Cooling
Most likely capacity range	All

Table 5. Supercooling of products from published literature.

	Degrees of supercooling (°C)	Supercooling point (°C)	Reference
Apples	4		Diehl (1924)
Broccoli	2.3	-4.4	James et al (2011)
Carrot	1.1	-2.7	James et al (2011)
Cauliflower		-6.5 to -9.5	Fuller & Wisniewski (1998)
Cauliflower	3.7	-5.2	James et al (2011)
Cod	3.9	-5.3	James et al (2011)
Garlic	10.3	-13.0	James et al (2009)
Grapes	3		Lucas (1954)
Herring	5.6	-9.2	James et al (2011)
Leek	1.4	-3.3	James et al (2011)
Lemons		-6.1	Lucas (1954)
Oranges	1.5		Lucas (1954)
Parsnip	0.6	-2.8	James et al (2011)
Prawns (previously frozen) – “jumbo”	3.8	-5.9	James et al (2011)
Prawns (previously frozen) – “large”	4.6	-6.5	James et al (2011)
Shallot	3.8	-5.4	James et al (2011)
Squid	6.6	-8.6	James et al (2011)
Strawberries		-0.3 to -4.6	Martins and Lopes (2007)
Tomatoes		-4.3 to -4.5	Cox & Moore (1997)

6.12. Ultrasound assisted freezing

Power ultrasound uses sound energy to accelerate freezing. Ultrasound can create cavitation in cells which promotes ice nucleation and accelerates heat and mass transfer. Ultrasound can potentially fracture ice crystals leading to small crystal sizes and in some cases better product quality. Although the technology has considerable promise for high value product considerable research is still required for industrial application (Zheng and Sun, 2006). Freezing times are less indicating that energy could be saved in the refrigeration process (Figure 8). Longer ultrasound treatments reduced freezing times (Figure 9) as did applying the ultrasound during the phase change period (Mascheroni, 2007).

Time to commercial application (estimated)	>10 years
Potential to save direct emissions	Low
Potential to save indirect emissions	Medium
Potential to improve food quality	High
Potential to improve food temperature control	Low
Likely initial cost against ’conventional’ technologies	Higher
Ease of use and installation	Greater
Maintenance cost against ’conventional’ technologies	Not known
Will future legislation potentially affect uptake of technology?	No
Most likely application	Freezing
Most likely capacity range	<10kW

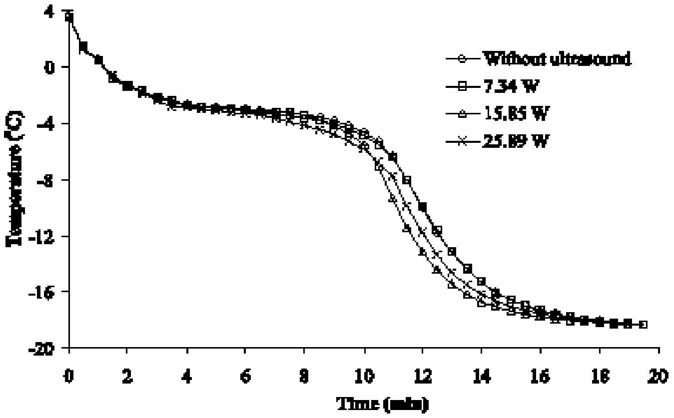


Figure 8. Temperature versus time curves for potato samples under different ultrasonic power levels applied totally for 2 minutes at the coolant temperature of -18 C (from Mascheroni, 2007).

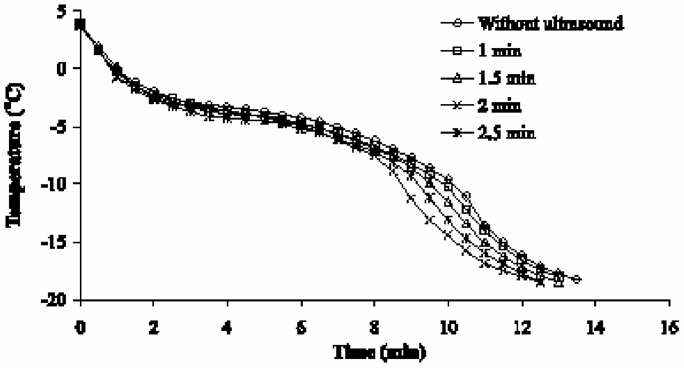


Figure 9. Comparison of freezing curves for potato samples under different exposure times to 15.85 W power ultrasound at the coolant temperature of -20°C (from Mascheroni, 2007).

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