# A review of the performance of domestic refrigerators

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## Abstract

This paper reviews the published data on the performance and use of domestic refrigerators throughout the world in the last 30 years. While there is considerable legislation defining maximum temperatures during the production, distribution and retailing of chilled food, as soon as the consumer purchases the food, it is outside of any of these legislative requirements. Inadequate domestic refrigeration or cooling is frequently cited as a possible factor in food poisoning incidents. It is clear from the many published surveys that many refrigerators throughout the world are running at higher than recommended temperatures. Since even these recommended temperatures are higher than the 0 to 1°C that is usually the recommended temperature range for storing fish and seafood, meat and many chilled products the current situation is even more detrimental to maintaining the high quality life of chilled foods. Despite numerous surveys around the world, how refrigerator temperatures and cleanliness impacts on consumer health remains to be fully assessed.

*Key words*

Fridge, consumer handling, temperature control, food safety, domestic hygiene.

## 1. Introduction

Since the late 1980's there has been a considerable increase in legislation throughout the world defining maximum temperatures during the production, distribution and retailing of chilled food. However, as soon as the consumer purchases the food, it is outside of any of these legislative requirements. After a chilled product is removed from a retail display cabinet it is outside a refrigerated environment whilst it is carried around the store and then transported home for further storage. In the home it may be left in ambient conditions or stored in the refrigerator until required. There has been significant concern in recent years over the role of inadequate temperature control and handling in the home on the number of food poisoning incidents (Ryan, Wall, Gilbert, Griffin & Rowe, 1996).

Numerous surveys have been reported from around the world on the domestic storage of refrigerated foods since 1987 (Table 1). These studies, such as those carried out in Sweden (Marklinder, Lindblad, Eriksson, Finnson & Lindqvist, 2004) and the USA (Redmond & Griffith, 2003), in general, show remarkable similarities in consumer attitudes and handling of chilled foods and the performance of their fridges. Perhaps even more remarkable is that despite numerous recommendations on handling and storage temperatures, consumer use and the performance of refrigerators remain remarkably unchanged throughout the world over the last 30 years!

## 2. Temperatures in domestic refrigerators

Spreen (1925) states that in 1919 the mechanical domestic refrigerator passed from the pioneering to the production stage in the USA. Records showed that from 1919 to 1924 there was a 100% plus increase in sales each year and orders in 1924 were 350% higher than a year earlier in the USA. The refrigerator is now a common household device and very few

45 households in the developed world do not own a refrigerator or fridge-freezer for the storage
46 of chilled foods, in the UK penetration is >99% (AMA Research, 2003).

47 There have been many developments since a new domestic refrigerator was discussed in
48 1923 (Anon, 1923). To quote "Experiments conducted by the National Association of Ice
49 Industries over a period of several months have resulted in a domestic refrigerator that is
50 expected to produce better refrigeration in every sense than any of those on the market. It is
51 constructed along lines which make it remarkably efficient and long lasting. Balsa wood is
52 used for the framework and also serves as insulation. Two inches of the wood are used
53 throughout as insulation. The insulation is lined inside and out with five-sixteenths of an inch
54 of artificial stone made from a special waterproof composition with mangasite as a base. The
55 result is a refrigerator which is literally hermetically sealed." There have been considerable
56 developments in the energy efficiency and the refrigeration systems used in domestic
57 refrigerators (Radermacher & Kim, 1996) however these developments have often been
58 divorced from the temperature within the storage compartment. The temperature at which a
59 refrigerator operates is critical for the safe storage of chilled food. Recommendations in the
60 UK concerning the microbiological safety of foods advise that maximum temperatures in
61 domestic refrigerators should not exceed 5°C (Richmond, 1991).

62 Studies on the temperature performance of domestic refrigerators can be divided into those
63 reporting investigations during consumer use and those carried out in the laboratory.

64 ***2.1 Under domestic conditions***

65 A number of surveys of consumer handling of refrigerated foods have been carried out over
66 the last 30 years (Table 1) and air temperatures in domestic refrigerators have been measured
67 in a sub-set of these (Table 2).

In the most comprehensive UK study to be carried out so far (Evans, Stanton, Russell & James, 1991), nearly all the participants when asked what actual temperature their refrigerator operated at were unable to give a value and gave answers based on the method they used to set the temperature dial. A large number of people (32.8%) set their refrigerators according to the weather, setting the refrigerator to a lower temperature (higher setting) in the summer. It was interesting to note that although 38 participants had a thermometer in their refrigerator only 30 actually used the information to set their refrigerator temperature.

There appears to be a difference in awareness of recommended refrigerator temperature settings between countries. In an Australian telephone survey (Jay, Comar & Govenlock, 1999) only 15.5% of respondents knew the temperature of their fridge. A Swedish survey (Marklinder *et al.*, 2004) found a good level of awareness amongst its survey group, with 85% of respondents knowing the recommended refrigeration temperature (in this case 8°C). However, not all of those consumers put their knowledge into practice, the survey found 40% of food storage temperatures exceeded the maximum recommended temperature for the food being stored. Also only 25% knew, or regularly measured, the temperature of their refrigerator. A later Irish study found that only 22% of consumers were aware of the correct temperature to operate their refrigerator (Kennedy, Jackson, Blair, McDowell, Cowan & Bolton, 2005a) and 23.2% had a refrigerator thermometer. Ghebrehewet & Stevenson (2003) found that after home-based hygiene training the proportion of consumers that were aware of correct operating temperatures rose from 31.7 to 78.4%.

Not all studies have actually measured refrigerator temperatures. In some of those that have (Table 2), it is very clear how the temperatures were measured, where the sensors were positioned and for how long the measurements were carried out. In others far less data are provided in the publications so results may not be strictly comparable. To evaluate

93 temperatures within refrigerators in the UK Evans *et al.* (1991) used a miniature data logger
94 with three air and two product sensors was placed into the refrigerator to monitor
95 temperatures every 8 s and to record mean temperatures every 5 minutes for a period in
96 excess of seven days. Air temperature sensors were positioned in the top, middle and bottom
97 sections of the refrigerator and a simulated food product (87 mm diameter by 28 mm high
98 disc of 'Tylose'; a food substitute; in a petri dish) placed on the middle shelf. Sensors were
99 placed in the geometric centre and centrally on the surface of the Tylose disc.

100 In the Evans study an evaluation of temperatures within each refrigerator showed that the
101 mean temperature over 7 days (evaluated from top, middle and bottom sensors) ranged from
102 -1°C to 11°C. The overall mean air temperature for all the refrigerators in the survey was
103 6°C, with 70% of refrigerators operating at average temperatures above 5°C (Fig. 1).

104 An investigation carried out in Northern Ireland found similar results with 71% of
105 refrigerators having a mean internal temperature above 5°C (Flynn, Blair & McDowell,
106 1992). Temperatures were measured by placing 25 ml glass bottles filled with water on the
107 top, bottom and middle shelves. The bottles were left for an unspecified time before the
108 temperature of the water was measured with a T-type thermocouple.

109 A Dutch study (Lezenne Coulander, 1994, cited by Notermans *et al.*, 1997) found 70.4% of
110 refrigerators above 5°C, though only 3.2% at or above 9°C. However the method of
111 temperature determination is not known. In New Zealand (O'Brien, 1997) placed
112 thermocouples on the top and bottom shelves, closed the door of the refrigerator and waited
113 for 2 minutes before recording the temperatures. Sixty percent of the 50 refrigerators
114 surveyed were outside the 0 to 4°C range recommended in New Zealand. Sergelidis,
115 Abrahim, Sarimvei, Panoulis, Karaioannoglou & Genigeorgi (1997) reported that 25% of the
116 136 domestic refrigerators investigated in Greece had temperatures above 10°C. However,
117 again the method of temperature measurement was not reported. Worsfold & Griffith (1997)

used a small data logging system strapped to a perishable product to record the air temperature around the product during transport and during storage in a domestic refrigerator. The position within the refrigerator was not therefore controlled. Recordings were taken at 1 minute intervals and products remained in the refrigerator for an average of three days at an overall average temperature of 5.9°C.

In a study of temperatures inside refrigerators, using an unreported measurement method, used by elderly UK consumers (aged 65+) 70% of a total of 645 fridges surveyed were running above 5°C (Johnson, Donkin, Morgan, Lilley, Neale, Page & Silburn, 1998). Only one was reported to be too cold at -2°C and too warm temperatures correlated with people not living alone and those with low incomes.

A USA survey of product temperatures during retail, transport to the home and in the home (Audits International, 1999), using an unspecified method, showed that in only 27% of the 939 refrigerators surveyed were product temperatures above 5°C after transport home and storage for 24 h. Product temperatures were above 8.3°C in 4% of those refrigerators. The minimum product temperature recorded after 24 h was -6°C while the highest was 21°C.

Peck, Goodburn, Betts & Stringer (2006) cite an unreferenced French survey of 2001/2002 as finding that 47% of yogurt samples in an unspecified number of refrigerators surveyed were at temperatures above 6°C, and more than 75% of meat product samples were above 4°C. Five percent of the refrigerators surveyed were reported to be operating at temperatures above 10°C.

Temperatures at the top, middle and bottom of 119 refrigerators in France were recorded, at a 2 to 8 minute interval over 7 days, using a data logger by Lauguerre, Derens & Palagos (2002). In the study a two-dimensional analysis (crossed table) was used in order to verify the relationship between factors (characteristics of refrigerator, use conditions and

characteristics of participants) and between factor and overall temperature. It was found that there was no direct relationship between these, particularly in terms of temperature settings and refrigerator temperatures. Seven percent of refrigerators with high temperature settings still had a low temperature (<2.5°C) while 6% of refrigerator that had low temperature settings, still had a high temperature (>10°C). Analysis of the refrigerators located near heat sources did not enable conclusions to be drawn concerning this effect on temperature since the overall temperature varied from low to high. However, no built-in refrigerators had temperatures under 2.5°C. The investigation showed that statistically there was no relationship between temperatures measured using a thermometer at a given moment or using a data logger over a 7-day period. An increasing number of refrigerators are sold with a single point temperature display however these authors stated that 'the temperature measured using a thermometer does not represent the true operating conditions of the refrigerator'.

Ghebrehewet & Stevenson (2003) found that after home-based hygiene training and the distribution of refrigeration thermometers the proportion of refrigerators operating above 5°C fell from 37 to 15.8%. However the method of measuring the temperature, positions and time span is not mentioned. At that time a review of all European studies showed that overall the average air temperature in European fridges would appear to be 6.64°C (Nauta, Litman, Barker & Carlin, 2003).

Since that review, further surveys have been carried out around the world, again with similar results. A 2004 survey of New Zealand Food Safety Authority survey (Anon, 2007), carried out by the Institute of Environmental Science and Research (ERS), found a third of the 53 refrigerators surveyed operating above the recommended temperature range of between 1°C and 5°C. A detailed survey of food temperatures of products stored in Swedish consumers fridge's found that 22% of minced meat samples were stored above 8°C and 44% of ham samples (Marklinder *et al.*, 2004). Refrigerator temperatures from -7.9 to 20.7°C were

measure in Ireland by Kennedy *et al*. (2005a, b) using a data logger placed on the middle shelf and recording every 10 minutes for 72 hours. While in Portugal (Azevedo, Regalo, Mena, Almeida, Carneiro, Teixeira *et al*., 2005) temperatures, measured at one point using a digital thermometer, were found to be greater than 12.1°C in two refrigerators and between 10.1 and 12.0°C in ten others of the 86 surveyed. In another study, Terpstra, Steenbekkers, de Maetelaere & Nijhuis (2005) used a glass thermometer kept for 24 hours inside a plastic bottle of water that was placed in the bottle rack in the door of refrigerators. The temperatures measured ranged from 3.8 to 11.5°C. They found that high refrigerator temperatures were prevalent in households without older (>60 year old) people.

In the latest UK study Breen, Brock, Crawford, Docherty, Drummond, Gill *et al*. (2006) used a liquid in glass thermometer housed in a 23 mm diameter cylinder of food gel, which was claimed to mimic the thermal behaviour of a food. It appears that only one temperature, at an unstated position in the refrigerator and time, was taken. They recorded temperatures from 1 to 12°C with a mode of 5°C and 33% above 5°C.

In analysing the data from most of the various surveys reported over the last 30 years Peck *et al*. (2006) concluded that 61.2% of refrigerators throughout the world run at temperatures above 5°C.

An analysis of percentage time spent between certain temperatures carried out in the Evans UK study (Evans *et al*., 1991), showed that the greatest proportion of time (80.3%) was spent between 3 and 8.9°C. Only small amounts of time were spent above 9°C. However, only 4 refrigerators (1.6%) in the whole survey operated below 5°C during all the monitoring period and 33.3% of refrigerators spent all their time above 5°C. A further analysis showed that in 69.9% of refrigerators the warmest place was in the top and in 45.1% the coolest place was in the middle (Table 3). However, the top of the refrigerator was not always the warmest and the bottom the coldest place (Table 4). Bakalis, Giannakourou, & Taoukis (2003) found the

192 warmest place in the door with the lowest temperature being in the middle position of some
193 refrigerators and the upper tray in other. While Laguerre & Flick (2004) found the highest
194 temperature could sometimes be in the top and at other times in the middle of the same
195 refrigerator. A New Zealand survey found that in almost three-quarters of the 53
196 refrigerators surveyed higher temperatures were on the top shelf rather than on the bottom
197 shelf (Anon, 2007). A Swedish survey reported that those consumers that made an effort to
198 store food in the coldest location usually believed that location to be the top shelf (Marklinder
199 *et al*., 2004).

200 In the Evans *et al*. (1991) study mean temperature range within a refrigerator was found to
201 vary between refrigerator types. There are three main types of refrigerator design. The older
202 style ice-box refrigerators have a box-plate evaporator within the refrigerator (which is often
203 used to store frozen food for a short time). Larder refrigerators have a back-plate evaporator,
204 as do fridge-freezers (which can either have one compressor supplying both fridge and
205 freezer, or two separate compressors). In Evans *et al*.'s (1991) study, ice-box refrigerators
206 were found to have the smallest temperature range (average 1.8°C); whereas the range in
207 temperature in fridge-freezers and larder refrigerators was nearly twice as great (average of
208 3.4°C in fridge-freezers and 3.7°C in larder refrigerators) (Table 5). A survey carried out in
209 China found higher ranges in temperature within domestic refrigerators with only 2.3% of the
210 refrigerators surveyed operating with a temperature range of less than 6°C: 34.1% had
211 differences of 8-12°C, 34.1% in the range 12-14°C and 29.5% differences greater than 14°C
212 (Shixiong & Jing, 1990).

213 ***2.2 Under controlled conditions***

214 Little data seems to have been published on the temperature performance of domestic
215 refrigerators under controlled conditions. Data can be found on energy consumption

(Dlugoszewski & Minczewski, 1984), evaporator coil design (Karpinski, 1984), and the shelf life advantages to be gained with product stored in a special refrigerator containing a 0°C chamber with fan air circulation (Olsson, 1988). Current standards for domestic refrigerators contain some temperature tests that are carried out under controlled conditions on empty, closed refrigerators. In domestic use refrigerator doors are opened, refrigerators are not usually empty but range from near empty to crammed full and often food at ambient temperature, or above, is placed in them.

Some data has been published from experiments carried out on examples of three types of refrigerator (James & Evans, 1992b). These were a 6 cubic foot dual compressor fridge-freezer (No.1), a 6 cubic foot single compressor fridge-freezer (No.2), and a 4 cubic foot free standing domestic refrigerator with an ice-box compartment (No.3).

When tested empty and set to the manufacturers recommended setting, temperatures in the ice box refrigerator (No.3) were uniform and low with a minimum of -1.4°C on the bottom shelf and a maximum of 5.9°C in the door. Average temperatures were between approximately 0.5 and 1.5°C on the shelves and just above 3°C in the door with a cycle of less than 0.5°C. There was a much larger temperature range in the two fridge-freezers 1.7 to 14.3 in No.1 and -6.7 to 10.7 in No.2. Average temperatures were far less uniform in the chilled food compartment of the fridge-freezers. In fridge-freezer No.1 the average temperature of the top shelf was up to 5°C higher than that measured on the middle shelf which was the coolest area in the appliance. Highest average temperatures of approximately 7.5 and 10°C were measured on the top shelves of the fridge-freezers. In fridge-freezer No.2 the average temperature on the bottom shelf reached -2°C at the minimum point in the temperature cycle.

Loading 12 packs (dimensions 100 x 150 x 25 mm) of “Tylose” (the Karlsruhe Test Substance, a simulated food) that had been pre-cooled to 5°C into the ice box refrigerator

241 reduced the mean temperatures by between 1.2 and 2.0°C. The temperature change caused
242 by loading was similar in magnitude in fridge-freezer No.2 where the mean temperature of
243 the top shelf rose by 0.7°C and the mean at other positions dropped by between 0.5 and
244 1.1°C. It was also noted that the length of the refrigeration cycle increased from
245 approximately 0.75 h to 1 h. In fridge-freezer No.1 the magnitude of the temperature cycle
246 was substantially reduced. The magnitude and position of the maximum temperature was
247 also influenced by loading from a value of 14.3°C and located on the top shelf to a reduced
248 value of 9.8°C and a location on the bottom shelf.

249 Food is often loaded warm into refrigerators after purchase from retail stores. Loading a
250 small amount of warm (20°C) food, 2 joints (approximately 17.5 by 7.6 by 3.6 cm, 195±10 g)
251 and 2 drumsticks (approximately 12 by 6 by 3 cm, 120±10 g) of simulated chicken (Tylose)
252 showed up the poor cooling performance of domestic refrigerators. Over 2 h was required in
253 the ice box refrigerator to reduce the surface temperature of the drumsticks and portions to
254 7°C compared with over 5 h in the fridge freezer. Drumsticks in the domestic refrigerator
255 always cooled faster than the larger portions. However, in the fridge-freezer portions on the
256 middle shelf cooled faster than drumsticks positioned on the top shelf.

257 Laguerre & Flick (2004) measured the air temperature at 25 different positions in an empty
258 refrigerator with an evaporator fitted inside the vertical back wall and at three positions on
259 the internal walls. The mean air temperature over 24 h was 6.3°C with a minimum value of
260 3.8 and a maximum of 8.3°C. At any time there was typically a 4°C range in temperatures
261 between extreme values and a temperature cycle (approximately 1.5 h) of approximately 4°C
262 at any measurement point. The mean wall temperatures at the top, middle and bottom were
263 9.1, 5.4 and 5.7°C respectively. In the refrigerator a 4.8 cm diameter Saveloy sausage took
264 6 h to cool from 20 to 6°C.

Sun, Singh & O'Mahony (2005) investigated the effect on quality of storing steak, minced beef patty and salmon in five refrigerators with different environmental conditions (average temperature and temperature fluctuation). All the refrigerators had a compartment specifically for storing fresh meat products. Average temperatures in the five compartments ranged from -4.8 to +1.7°C and all the standard deviations were less than 1.0°C. The microbial condition of the steak and mince was acceptable for 8 days and the salmon for 4 days in all five refrigerators. In the refrigerator operating at -4.8°C all the products were acceptable after 10 days. However, although not mentioned in the paper all the samples must have been partially frozen at this storage temperature. The authors state that panellists preferred samples stored under or near ultra-chilled conditions rather than samples stored under standard refrigerated conditions.

## 3. Hygienic status

Many cases of food poisoning originate in the domestic environment and can be associated with improper food handling and ineffective hygiene by consumers. Redmond & Griffith (2003) reviewed some of the many studies that have been carried out. A number of pathogenic bacterial were found in kitchens and specific sites were most highly contaminated. The handle on a refrigerator door is used many times during a day and is not regularly cleaned. It is not therefore surprising that of the five sites they sampled, Hayson & Sharp (2006) state "the highest mean Enterobacteriaceae count was found on the refrigerator handle ($6.1 \times 10^4 \pm 4.2 \times 10^3$ cfu $ml^{-1}$)." Accumulated dirt and grime in recessed areas of door handles was considered to produce a hygiene risk especially for children whose small figures would penetrate further.

Some recent surveys have published specific data on the hygienic status of domestic fridges. In France, Dieuleveux, Collobert, Dorey & Guix (2005) specifically looked for *Listeria* spp.

289 in sixty household refrigerators. They only found a strain of *Listeria innocua* in the
290 vegetable compartment of one. However, an Irish survey of the hygienic status of domestic
291 refrigerators (Kennedy *et al*., 2005a) found a wide range of undesirable bacteria and
292 pathogens. Fifty two percent of refrigerators contained at least one pathogen. A higher
293 general incidence of pathogens and higher Aerobic Plate Counts (APCs) were found in urban
294 consumers refrigerators than those of rural consumers, and consumers under 25 were more
295 likely to have one or more pathogens present in their refrigerators. Interestingly the
296 refrigerators of consumers from socioeconomic group ABC1 had significantly higher APCs
297 than those belonging to members of the C2DE group. Further analysis by Kennedy *et al*.
298 (2005b), found that "conscientious food handlers were statistically less likely to have higher
299 TVCs (Total Viable Counts), "any pathogen", *Staphylococcus aureus* or *Salmonella enterica*
300 in their refrigerator". A follow up study (Smyth, Kennedy, Twohig, Miajlovic, Bolton &
301 Smyth, 2006) concluded, "that the average Irish household refrigerator harbours potential
302 enterotoxin-producing *S. aureus* that may or may not be of animal origin and, accordingly, is
303 a potential reservoir for staphylococcal food poisoning." Further assessments have shown
304 high APC contamination levels (Jackson, Blair, McDowell, Kennedy & Bolton, 2007).
305 Values ranged from 2.91 to 8.78 $\log_{10}$ cfu $cm^{-2}$ with an average of 7.4 $\log_{10}$ cfu $cm^{-2}$ in the
306 342 refrigerators sampled. Almost a quarter of refrigerators yielded coliform contamination
307 levels greater than 3 $\log_{10}$ cfu $cm^{-2}$ and *Escherichia coli* was isolated from just over 1% of
308 refrigerator surfaces. A small Japanese study (Ojima, Toshima, Koya, Ara, Kawai & Ueda,
309 2002) found high coliform counts in the vegetable storage tray of refrigerators, which they
310 associated with contamination from unwrapped raw fruits and vegetables, and cited as a
311 possible source of cross-contamination of fruits and vegetables that are eaten uncooked.

312 In the USA, Li-Cohen & Bruhn (2002) reported that their survey of 2000 (33% response rate)
313 randomly selected households "suggest that women, lower-income households, people 65

314 years and older, and non-college graduates practice safer food handling methods than men,
315 higher-income households, people younger than 65 years, and college or postcollege
316 graduates."

317 Interestingly (according to one survey) French women's immediate thoughts on home
318 hygiene put food hygiene and conservation low in their considerations (Marrakchi, Stahl,
319 Berthelot, Squinazi, Audurier, Boudene *et al*., 2002). Spontaneously, the word "hygiene"
320 called to mind cleanness (46%), house keeping (20%), but food hygiene or body hygiene was
321 mentioned by only 3% of women. The three most spontaneously mentioned places at home,
322 as requiring strict hygiene, were the kitchen (83%), bathroom (78%), and restroom (67%).
323 The refrigerator was spontaneously mentioned by only 4% of surveyed women, but was rated
324 as 9-10, on the risk scale, by 82% of the same women. The bad conservation of food was
325 mentioned by only 8% of women, at the same rank as the presence of pets.

326 It is not therefore surprising that a survey of consumers in Portugal (Azevedo *et al*., 2005)
327 found that only 6% of those surveyed cleaned their fridge weekly, while more than 80%
328 cleaned only monthly or less frequently. Of these only 8% were cleaning with appropriate
329 proprietary cleaning products. However, the incidence of listeria in these fridges was low,
330 *Listeria monocytogenes* was only found in 3 out of 86 refrigerators. Zickrick, Wittenberg &
331 Kiewel (1995) found high bacterial levels, >100 cfu $cm^2$, on the inner floor areas of 30.6% of
332 the 59 domestic refrigerators they investigated. They recommended that an adequate
333 cleaning and disinfection system would be advisable for this region and the inner door
334 surface for prophylactic improvement of refrigerator hygiene. Welsh studies (Parry, Slader,
335 Humphrey, Holmes, Guildea & Palmer, 2005) have shown that household kitchens with dirty
336 refrigerators are no more likely to give rise to an episode of salmonella infection than clean
337 kitchens. The presence of visible dirt was not found to be a risk factor for sporadic
338 salmonella infection (Parry, Palmer, Slader & Humphrey, 2002).

339 Increasingly the use of predictive microbial growth models is revealing potential problems
340 with the temperature levels found in domestic refrigerators. Nauta *et al*. (2003) predicted
341 probable levels of *Bacillus cereus* in packages of vegetable puree at the moment the
342 consumer takes the product from their refrigerator. A psychrotrophic strain was predicted to
343 end up above a threshold level of 5 $\log_{10}$ cfu $g^{-1}$ in 0.9% to 6.3% of the vegetable puree
344 packages. This indicated that even if the puree was stored at 4°C in the domestic refrigerator
345 and use-by-date (UBD) was respected, the threshold level may be passed. Notermans,
346 Dufrenne, Teunis, Beumer, Giffel & Peeters Weem (1997) predicted that 7 to 10% of milk
347 consumed in the Netherlands contained levels of *B. cereus* that exceeded safety criteria.
348 They concluded that storage conditions were an important factor and that Dutch consumers
349 did not always meet the prescribed storage conditions,

350 **4. Conclusions**

351 Despite all these surveys, how fridge temperatures and cleanliness impacts on consumer
352 health remains to be fully assessed. What is clear is that many refrigerators throughout the
353 world are running at higher than recommended temperatures. Since even these recommended
354 temperatures are higher than the 0 to 1°C that is usually the recommended temperature range
355 for storing fish and seafood, meat and many chilled products the current situation is even
356 more detrimental to maintaining the high quality life of chilled foods. At present domestic
357 storage of chilled foods would appear to be the weakest link in the entire chill-chain.

358 A recent risk assessment of chilled foods carried out for the UK Food Standards Agency
359 (Peck *et al*., 2006) concluded that on average a UK household replaces its refrigerator/fridge-
360 freezer every 7.75 years and that while the "improved energy efficiency of UK domestic
361 refrigeration equipment is documented (it) is not clear how the replacement of equipment has
362 affected, if at all, UK domestic refrigerator performance". This suggests that regular

363 comprehensive surveys of the performance of domestic refrigerators are required, and that in
364 the particular case of the UK it is high time to reassess current knowledge. However, it is not
365 clear how representative this is of replacement practices in other parts of the world. Data
366 from the USA indicates that the average lifetime of a typical refrigerator there is between 14
367 and 18 years (Kim, Keoleian & Horie, 2006).

368 There are no technical reasons why the temperature performance of domestic refrigerators are
369 not substantially better than they are at present. In 1992 a group of mechanical engineering
370 students at the University of Bristol were given the task of designing a domestic refrigerator
371 with the improved temperature specification shown in Table 6. Gigiel, Douglas, Fawcett,
372 Lewis & Watson (1994) reported that the prototype produced more than met the specification
373 (Table 6) and "had the potential as a viable product in the market place".

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501 Figure legends:

502 Table 1. Published surveys of domestic storage of refrigerated foods carried out in the last 30
503 years in date order

504 Table 2. Air temperatures measured in surveys of domestic refrigerators in homes

505 Table 3. Position of highest temperature within refrigerators investigated (source: Evans et
506 al., 1991)

507 Table 4. Positions of lowest and highest mean temperatures in refrigerators investigated
508 (source: Evans et al., 1991)

509 Table 5. Temperature range in refrigerator types investigated (source: Evans et al., 1991)

510 Table 6. Typical and improved performance specification for a domestic refrigerator

511 Fig. 1. Overall mean temperatures for all refrigerators in survey (source: Evans et al., 1991)

**Figure 1**

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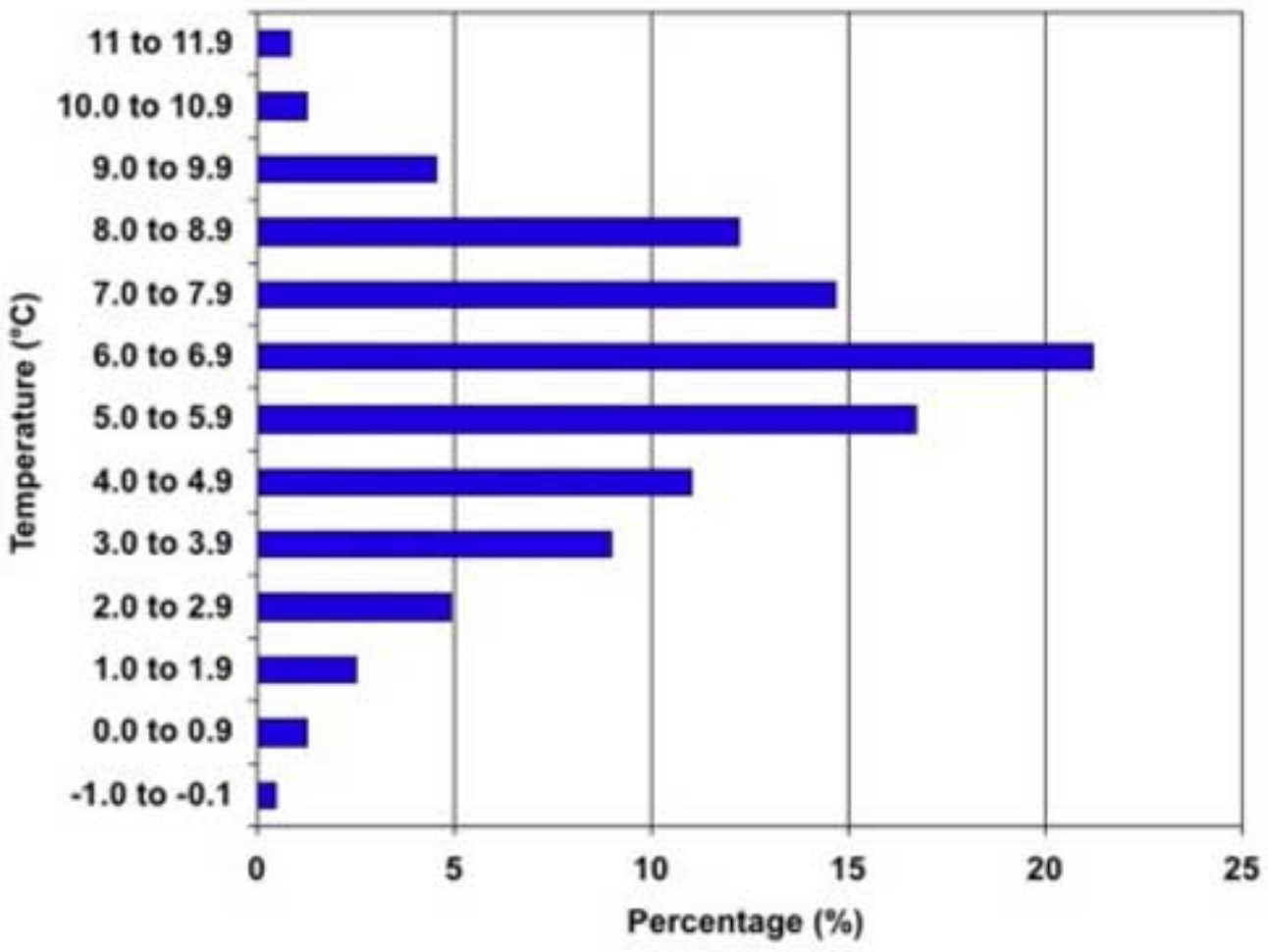

**Table 1**

| Country | Reference |
|---|---|
| US | Van Garde & Woodburne, 1987 |
| China | Shixiong & Jing, 1990 |
| UK | Rose *et al.*, 1990 |
| UK | Evans *et al.*, 1991 (published in Evans, 1992; James & Evans, 1992a; James & Evans, 1992b) |
| Northern Ireland | Flynn *et al.*, 1992 |
| France | Victoria, 1993 (cited by Laguerre *et al.*, 2002) |
| The Netherlands | Lezenne Coulander, 1994 (cited by Notermans *et al.*, 1997) |
| New Zealand | O'Brien, 1997 |
| Greece | Sergelidis *et al.*, 1997 |
| UK | Worsfold & Griffith, 1997 |
| USA | Daniels, 1998 |
| UK | Johnson *et al.*, 1998 |
| Australia | Jay *et al.*, 1999 |
| US | Audits International, 1999 |
| France | Laguerre *et al.*, 2002 |
| Northern Ireland | Jackson, 2003 |
| US | Redmond & Griffith, 2003 |
| UK | Ghebrehewet & Stevenson, 2003 |
| New Zealand | ESR, 2004 (cited by Anon, 2007) |
| Sweden | Marklinder *et al.*, 2004 |
| Ireland | Kennedy *et al.*, 2005 |
| Portugal | Azevedo *et al.*, 2005 |
| Greece | Koutsoumanis & Taoukis, 2005, Taoukis *et al.*, 2005 |
| Netherlands | Terpstra *et al.*, 2005 |
| UK | Breen *et al.*, 2006 |

**Table 2**

| Reference | Country | n= | Measurement | $T_{min}$ | $T_{mean}$ | $T_{max}$ | % in temperature range |
|---|---|---|---|---|---|---|---|
| Van Garde & Woodburne, 1987 | US | - | Not known | | | | 21%≥10°C |
| Rose *et al*., 1990 | UK | 75 | Not known | | <5 | 15 | 6%>5°C |
| Evans *et al*., 1991 | UK | 252 | Data logger (3 levels: T, M, B) | 0.9 | 6.0 | 11.4 | 70%>5°C |
| Flynn *et al*., 1992 | Northern Ireland | 150 | Thermometer (3 levels: T, M, B) | 0.8 | 6.5 | 12.6 | 71%>5°C |
| Victoria, 1993 * | France | 102 | Thermometer (3 levels: T, M, B) | | | 14 | 70%>6°C |
| Lezenne Coulander, 1994 ** | Netherlands | 125 | Thermometer | | | | 30%<5°C, 42% 5 to 7°C, 26% 7 to 9°C, 2% >9°C |
| O'Brien, 1997 | New Zealand | 50 | Thermometer (2 levels: T, B) | 0 | 4.9 | 11 | 60%>4°C |
| Sergelidis *et al*., 1997 | Greece | 136 | Thermometer | | | | 50%>9°C |
| Worsfold & Griffith 1997 | UK | 108 | Data logger (1 position) | 2 | 5.9 | 12 | 50%>5°C |
| Daniels, 1998 | USA | 106 | Not known | | | | 69%>5°C |
| Johnson *et al*., 1998 | UK | 645 | Thermometer | -2 | 7 | 13 | 70%>5°C |
| Laguerre *et al*., 2002 | France | 119 | Data logger (3 levels: T, M, B) | 0.9 | 6.6 | 11.4 | 80%>5°C |
| Ghebrehewet & Stevenson, 2003 | UK | 901 | Not known | | | | 69.3% 0 to 4°C, 27.9% 5 to 9°C, 2.8% >10°C<br>84.2%[a] 0 t0 4°C, 14.8%[a] 5 to 9°C, 1.0%[a] >10°C |
| ARS, 2004 *** | New Zealand | 53 | Not known | | | | 33%>5°C |
| Bakalis *et al*., 2004 | Greece | 110 | Data logger (3 levels: T, M, B and door) | | | | 26%<4°C, 28% 4 to 6°C, 23% 6 to 8°C, 15% 8 to 10°C, 8% 10 to 12°C |
| Kennedy *et al*., 2005 | Ireland | 100 | Data logger (1 level M) | -7.9 | 5.4 | 20.7 | 59%>5°C |
| Azevedo *et al.,* 2005 | Portugal | 86 | Digital thermometer | | | | 70%>6°C |
| Taoukis *et al*., 2005 | Greece | 250 | Data logger | -2 | 6.3 | | 50%>6°C, 10%>10°C |
| Terpstra *et al*., 2005 | Netherlands | 31 | Glass thermometer | 3.8 | | 11.5 | 68%>7°C |
| Breen *et al*., 2006 | UK | 24 | Glass thermometer in gel | | 5.0 (mode) | | 33%>5°C |

* cited by Laguerre *et al*. (2002), ** cited by Notermans *et al*. (1997), *** Cited by Anon (2007), [a] 2nd visit

**Table 3**

| Position | % of refrigerators | |
|---|---|---|
| | Highest mean temperature | Lowest mean temperature |
| Top | 69.9 | 20.3 |
| Middle | 8.1 | 45.1 |
| Bottom | 22.0 | 34.6 |

**Table 4**

| Refrigerator type | % of lowest mean temperatures in: | | | % of highest mean temperatures in: | | |
|---|---|---|---|---|---|---|
| | Top | Middle | Bottom | Top | Middle | Bottom |
| Ice box | 48.1 | 41.6 | 10.4 | 28.6 | 11.7 | 59.7 |
| Fridge-freezer | 10.6 | 45.5 | 43.9 | 84.6 | 8.9 | 6.5 |
| Larder | 0.0 | 50.0 | 50.0 | 100.0 | 0.0 | 0.0 |

**Table 5**

| Range in temperature (°C) | Ice box | Fridge-freezer | Larder |
|---|---|---|---|
| Minimum temp range | 0.2 | 0.1 | 0.5 |
| Maximum temp range | 7.0 | 12.04 | 9.0 |
| Mean temp range | 1.8 | 3.4 | 3.7 |

**Table 6**

| Criterion | Typical current values | Improved specification | Achieved |
|---|---|---|---|
| Variation of temperature with time | ±5°C | ±1°C | ±0.3°C |
| Variation of temperature with position | ±5°C | ±1°C | ±0.2°C |
| Cooling time for 3kg of warm food from 45°C | 720 min | 120 min | 45 min |
| Temperature recovery of partially loaded refrigerator after a 5 min door opening | 60 min | 30 min | 4 min |
| Temperature recovery of partially loaded refrigerator after a 10 min door opening | 180 min | 30 min | 12 min |