A Comparative Assessment of Refrigerator Test Methods

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Synopsis

During the development of revised refrigerator Minimum Energy Performance Standards for Australia, intensive refrigerator testing was undertaken to a number of international test methods. Experience suggests a range of recommendations to improve testing methods.

Abstract

In 1999 Australian Federal and State governments adopted a policy of matching world's "best practice" for efficiency standards (or Minimum Energy Performance Standards or MEPS) for residential appliances and commercial and industrial equipment. The policy involves reviewing mandatory MEPS programs in force around the world, assessing the requirements on a common basis (typically in terms of the Australian/New Zealand or AS/NZS test procedures) and selecting the most stringent levels currently in force (or in the process of adoption) for implementation in Australia.

The first major product investigation in Australia using this approach was for refrigerators and freezers; US MEPS levels for 2001 are now finalised for implementation in Australia in 2004. The initial levels under AS/NZS were determined using a theoretical modelling approach based on known differences in the Australian and US test methods. A series of 9 refrigerators were tested to AS/NZS, ISO and US test methods for refrigerators to determine actual differences in energy consumption and to confirm in broad terms the results of the initial modelling approach. This paper presents a range of findings regarding possible improvements within each of the major test methods that will help improve repeatability and reproducibility. It also suggests a new approach to refrigerator testing that will provide greater flexibility, will enable more accurate modeling of real use in a range of climates and that may assist in the harmonization or at least converging the major international domestic refrigeration testing methods. The paper underlines the importance of test procedures in the implementation of energy policy.

Background

Codes and standards programs, where legislation and regulation are used to improve product energy efficiency, are amongst the most cost effective and widely used measures employed to reduce greenhouse gas emissions. The Australian program embraces two mandatory elements:

- Comparative energy labelling enabling consumers to choose energy efficient products when considering a purchase; &
- Minimum energy performance standards (MEPS) where government enforces predetermined energy efficiency levels for specified products.

Mandatory appliance labelling commenced in 1986 with refrigerators and freezers and by 1990 air conditioners, dishwashers, clothes dryers and clothes washers were also labelled. However, introducing MEPS has proven to be more difficult. In the early 1990's Australian state and federal governments commissioned expert reports to explore MEPS for domestic appliances (GWA 1993) and selected industrial and commercial equipment (Energetics et al 1994). In October 1999 MEPS commenced for three domestic products: refrigerators, freezers and electric storage water heaters. MEPS electric motors, packaged commercial air conditioning and fluorescent lamp ballasts remain to be finalised but firm commencement dates are proposed for 2001 (ballasts in 2003/4) (Holt et al 2000).

Policy Approach to MEPS

The approach to setting the 1999 MEPS levels can be labelled a "statistical approach"; looking at the models available on the market and performing a regression analysis to determine the relationship between energy use and model adjusted volume. The original proposal for refrigerators and freezers would have eliminated 50% of models current in 1992, though the delay in implementation dramatically decreased the energy savings and greenhouse reductions attributable to the implementation of this 1999 MEPS level (GWA, 2000). The relative leniency, in comparative terms, of the Australian levels is due to a combination of the inherent limitations of a statistical MEPS approach in a dynamic market and unforeseen delays due to an absence of agreed process (see Holt et al 2000 for a more detailed discussion on this aspect).

A growing recognition of the need to improve process lead to the 1998 government policy directive, contained in the National Greenhouse Strategy, to expand and extend the existing appliance and equipment codes and standards program (NGS 1998). In 1999, the Ministerial Council responsible for energy efficiency agreed to consider:

"*….developing MEPS for Australia that match best practice levels imposed by our major trading partners for internationally traded products that contribute significantly to Australia's growth in greenhouse gas emissions*" (NAEEEC, 1999, p8).

By adopting an existing MEPS level from a major trading partner, the arguments regarding the "feasibility" of meeting the proposed MEPS level can be essentially transcended. The existence of a "default" MEPS levels from a major trading partner provides a focus for both government and industry and allows the discussions to quickly move forward into the negotiation of detail regarding any adjustments that are necessary for local product configurations and differences in the test method. It does, however, prevent going further to the adoption of lowest life-cycle cost options: to date these have always been at lower levels than world best practice MEPS. It is likely too, that this approach will continue to result in a significant lag between the introduction of a new best standard somewhere else in the world and its adoption in Australia.

Details on the timetable for the various stages of the new process are provided in Holt et al (2000). The balance of this paper concentrates on elements of the work undertaken to complete the review of international MEPS levels and how these were translated into equivalent levels under the AS/NZS test procedure for refrigerators and freezers in Australia during 2000 and the lessons learned from the intensive testing and associated data analysis.

Identifying the most stringent MEPS level

Refrigerators and freezers were the first product to be subject to this new policy approach in Australia. A review by Energy Efficient Strategies (EES) (for the AGO) of the MEPS levels for refrigerators and freezers in mid 1999 revealed that, at that time, the US MEPS levels proposed for July 2001 appeared to be the most stringent level proposed or in force around the world (US MEPS levels can be found in DOE 1997). Canadian and Mexican MEPS levels for refrigerators are generally harmonised with US requirements, although the implementation dates vary.

At about this time Japan had just released details of its "Top Runner" program, which has some stringent requirements for refrigerators, especially those incorporating new technology such as variable speed drives and vacuum panels. The Top Runner program, developed in 1999, identified the most efficient models on the Japanese market in 1999 for a range of products and set this level as a sales weighted target for all manufacturers at a future date (refrigerator target is 2004). The program is nominally "voluntary", but the implementation method is quite coercive in nature and can be regarded as effectively "mandatory". Little information was available on the new test method at the time of the initial analysis, so it was not possible to compare these levels under the Australian test method without extensive investigative testing. The new Japanese method is similar to ISO in terms of compartment temperatures and ambient temperature, but has the added complication of door openings, which makes simulation modelling very difficult. The presence of test packs for convectively cooled appliance types but not for forced air models also makes direct comparisons difficult for the former types.

Korea has had MEPS in place since about 1996, but the levels in force in 1999 were weaker than the US 2001 levels. In late 2000 Korea also announced new MEPS levels for refrigerators, although these have not yet been analysed.

The EU MEPS levels for refrigerators that came into force in 1999 were generally more stringent than the Australian MEPS levels for 1999, but were not as stringent as US 1993 MEPS levels (Harrington 1994), especially for frost free products (forced air) which are now dominant on the Australian market (the European market is still dominated by convectively cooled refrigerator products). US 2001 MEPS levels were considerably more stringent than the US 1993 levels. A recent proposal to mandate current

Class A efficiency as a MEPS for refrigerators and freezers in Europe is outlined in another ECEEE 2001 paper by Dr Paul Waide of PW Consulting.

Other MEPS levels reviewed in the international comparison were Chinese Taipei (Taiwan), China and Russia, although obtaining technical details of the latter two proved difficult. Details of all MEPS levels in force as at mid 1999 and a detailed comparison of the test methods in each country used can be found in APEC (1999).

Initial Conversion of US 2001 MEPS levels for refrigerators to AS/NZS4474

Initial US 2001 MEPS levels under the AS/NZS test method were estimated through modelling undertaken by Energy Efficient Strategies (EES) in late 1999. These were offered to industry as the default levels for Australia in 2004 in the absence of an agreement between government and industry. The approach taken in the EES model was to calculate the US MEPS levels under the US test method for each model on the Australian market. The equivalent energy consumption for each model was then estimated under the AS/NZS energy using EES's thermodynamic model. A linear regression of energy consumption against adjusted volume was then applied to estimate a new MEPS line under the AS/NZS test method that was broadly equivalent to the US MEPS level. Elements of the EES model (EES 2000a) include:

- US MEPS were modelled using imperial units (US DOE metric conversions are not exact);
- US Fahrenheit temperature targets were used (US DOE metric conversions are not exact);
- The condenser temperature was assumed to be 12K above test-room ambient;
- The evaporator temperature was assumed to be 7K below compartment temperature at $-18^{o}C$ varying to 15K below at $+5^{o}C$;
- The model assumed that 5% of frost free energy was used in auxiliaries (ie energy not affected by changes in ambient conditions; 10% for cyclic refrigerator-freezers, 0% for others);
- Overall energy adjustments for separate freezers in the US test method (0.85 of tested energy for vertical freezers, 0.7 for chest freezers) were reversed out during the conversion;
- Relative heat gains into each compartment are estimated on difference between the ambient test temperature and the average compartment target temperature;
- Changes in compressor efficiency are based on an idealised Carnot engine where COP for a particular condition = $(T_{evap}) / (T_{cond} - T_{evap})$ (note: all temperatures are in kelvin) and the change in COP is given by $\Delta COP = COP_{US} / COP_{AS/NZS}$

Testing Program

An intensive testing program was undertaken on a total of 9 two door refrigerator-freezers. The testing was contracted to SGS, are an independent international testing organization with a laboratory in Melbourne. They are accredited by the National Association of Testing Authorities, Australia (NATA) to undertake refrigerator testing. All units tested ranged in capacity from 330 to 650 litres: all but one were frost free models. Three of the units were sourced directly from the USA (110 Volt 60Hz models destined for the US domestic market). US models were selected on the basis of commercially available models that were close to the US 2001 MEPS line. The purpose of the physical tests was to test the accuracy of the initial modelling undertaken by EES and to resolve a number of minor issues regarding adjustments and differences in the test methods between US and AS/NZS. Exploratory tests were also undertaken to examine the energy impact of specific differences the test methods. The primary focus of the physical tests was comparison of AS/NZS and the US test methods (which have many similarities), but most units were also tested to ISO8561. The broad elements of each of the test methods is shown below in Annex A (more details are in APEC 1999).

Key Results

The modelling undertaken by EES to convert between the AS/NZS and US test methods was very successful. For 6 of the 9 models, the tested AS/NZS and US energy consumption values were in close agreement with the EES model estimates (within 3% of the actual values). However, there were a number of cases where the conversion was in disagreement. On closer examination, the reasons for this were quite clear - the thermodynamic model assumes that the optimal energy consumption at the target temperatures can be attained under both test methods; however, this is not always the case.

The US test method requires that both controls be moved *together* to obtain test points for interpolation; this effectively means that the unit is tested as if there is a single control. A unit's energy consumption is minimised under the US test method where the fresh food and freezer temperatures pass through a point of +7.22°C/-15°C when both controls are moved together. The tested energy and the modelled energy diverge as the internal temperatures attained during the US test move further from the US target temperatures. In these cases the differences in energy were smaller than modelled. The AS/NZS test method is unaffected by this aspect as both controls can be adjusted as required to obtain the desired target temperatures.

In a couple of cases (US imported machines) the AS/NZS target temperatures were unattainable simultaneously in each compartment (for example to meet the fresh food requirement of +3°C under AS/NZS, the warmest freezer temperature attainable was -18°C which is much colder than the target requirement of -15°C); in these cases the differences in energy were larger than modelled. However, this is not surprising as the temperature balance and operational design is poor and ill suited to the conditions of normal use. Suppliers of the machines in question noted that the controllers supplied to the US market were generally low cost and did not offer the range of control offered on equivalent export models.

The range of tests undertaken on most models were:

- AS/NZS test as published;
- ISO test as published (25°C ambient, also 32°C on selected models);
- US CFR430 test Appendix A as published;
- US test varying the internal fresh food temperature from <+3°C to the warmest setting with constant freezer temperature (fresh food temperature impact test);
- Constant control settings while varying ambient from +30°C to +34°C;
- Constant control settings while setting supply voltage at 230V then at 240V (ambient at +32.2°C = US condition) (Australian models only, US models all tested at 110V/60Hz only).

Key test results are shown in Table 1.

Table 1 Summary of energy test results for selected units

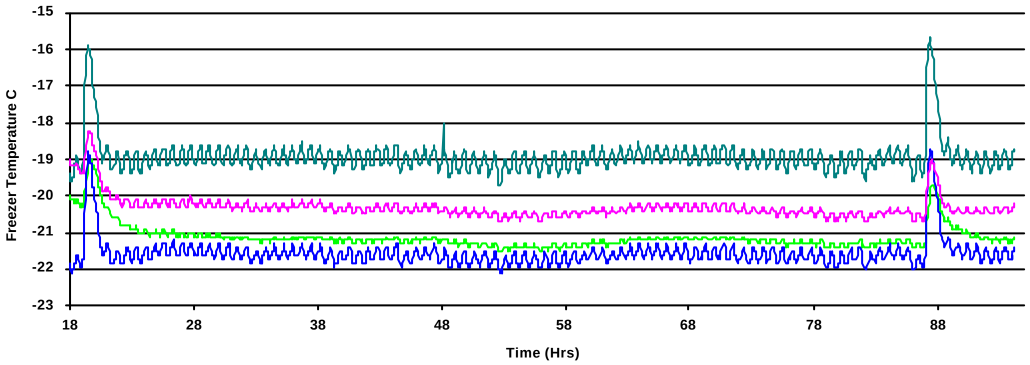
MODEL	FZ[a] AS 3°C/-15°C	FZ[a] AS 7.2°C/-15°C	FZ[a] US 7.2°C/-15°C	Difference actual **	US/AS modelled	ISO Measured
Unit 1	857.4 *	741.0	725.5	0.874	0.920	N/A
Unit 2	896.0	825.5	812.0	0.930	0.940	853
Unit 3	654.2	616.6	725.5	0.955	0.922	651
Unit 4	639.9	598.8	602.9	0.946	0.919	492 #
Unit 5	525.4	487.4	500.5	0.942	0.912	450 ##
Unit 6	N/A	N/A	N/A	1.000 ***	0.917	N/A
Unit 7	613.3 *	506.8	480.8	0.837	0.907	N/A
Unit 8	610.6 *	536.9	519.8	0.891	0.911	N/A

Notes: (a). FZ indicates freezer temperatures – AS indicates 4 probe positions to AS/NZS4474.1 and US indicates 3 (or 5) probe positions to CFR430. Target fresh food/freezer compartment temperatures shown. Units kWh/year. Units 6, 7 and 8 were US models. Results for cyclic/manual defrost model excluded, others frost free. See discussion below regarding ISO energy results and comparisons.
* Freezer temperature is at about -18°C for this energy, hence larger than modeled difference.
** This difference excludes the impact of the freezer thermocouple positions, assumes idealised target temperatures are achieved in both compartments under both test methods.
***Estimate based on US test result data which passes through +3°C and -15°C. Under the US test the internal temperatures were far from the US target, hence the difference between US and AS is smaller than expected
\# For this test the freezer temperature achieved a 2 star freezer rating only, but had the ability to achieve 3 star.
\#\# Unit 5 ISO test at 32°C ambient was 640 kWh.

ISO and AS/NZS test measurements

During all tests the temperatures were recorded at 2 minute intervals to provide some comparative data under the different test methods, most notably with and without test packs in the freezer compartment. The following figures show the results on a single model for both the freezer and the fresh food compartments. The x axis is nominal time from the start of the test and the figures all commence with a defrost cycle. The y axis is the compartment temperature in °C.

Figure 1: ISO test (25^{o}C) showing 4 individual freezer test pack temperatures



Note: At this control setting this unit only just qualifies as a 3 star freezer (max ≤-18^{o}C), even though the average temperature of the 4 test packs is -20.9^{o}C once stable after the defrost.

Figure 2: ISO test (25^{o}C) showing 3 fresh food air temperatures

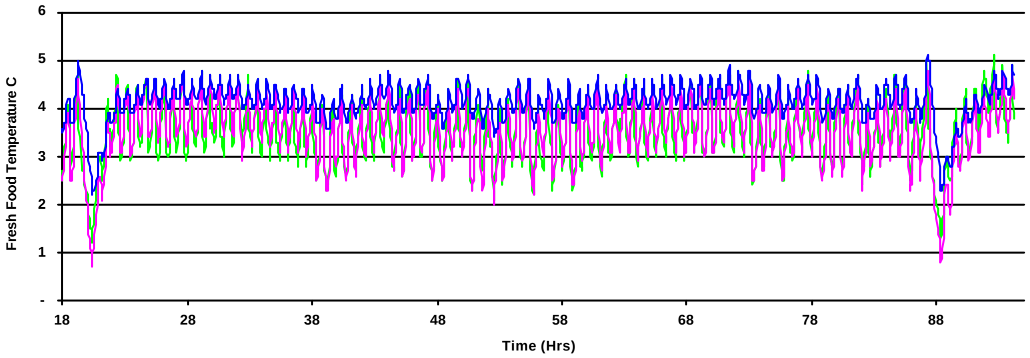


Figure 3: AS/NZS test (32^{o}C) showing 4 individual freezer air temperatures

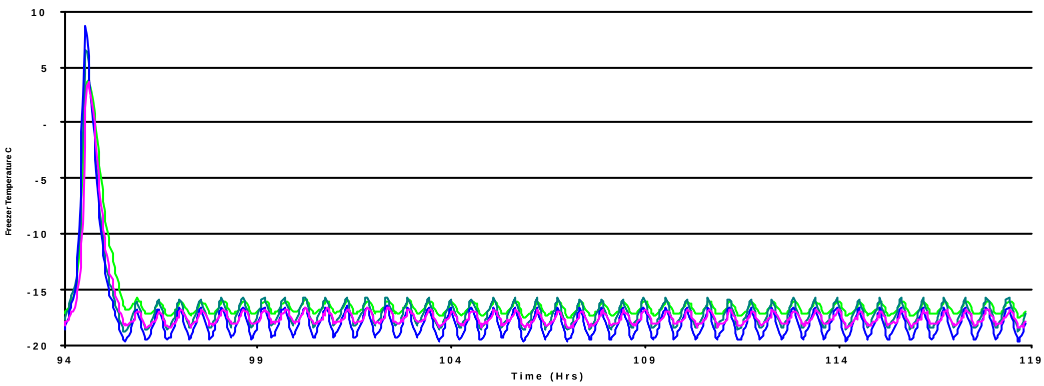
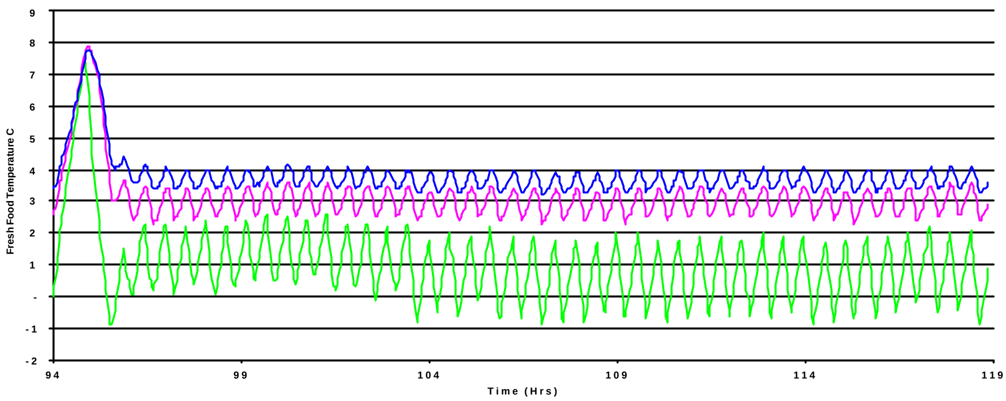


Figure 4: AS/NZS test (32^{o}C) showing 3 individual fresh food air temperatures



Salient observations on these test results (and similar tests on other units) are as follows:

- ISO freezer test packs tend to stabilise at quite different temperatures – the difference between the warmest and coldest test pack is typically 2.5^{o}C.
- In contrast, under the AS/NZS test the air temperatures in the freezer compartment are quite uniform for all 5 thermocouples (generally within 1^{o}C).
- The ISO method of temperature determination (maximum temperature of the warmest test pack) tends to be a very poor overall indicator of the freezer operating temperature and, therefore, of the heat gain into the freezer compartment. In this example (Figure 1) the "ISO" method of determining freezer temperature is –18.5^{o}C, whereas the average temperature of all the test packs when stable is –20.9^{o}C (this is significantly colder than an average user would run a freezer in practice). This makes ISO test data difficult to use in thermal modelling tools.
- The freezer temperature variation as a result of compressor cycling is slightly smaller when using ISO test packs (about 1^{o}C) compared to air temperature sensors (typically up to 2^{o}C).
- Freezer test pack temperatures under ISO tend to drift up and down by up to 0.5^{o}C even under "stable" conditions (see Figure 1) whereas under the AS/NZS method the air temperature are usually very stable once equilibrium is reached (see Figure 3). It has been noted that some ISO tests take 10 to 20 hours to stabilise after a defrost cycle whereas air temperatures under AS/NZS are typically stable within a few hours. If defrost periods were less than 10 hours (typical of timer defrost models), it is unlikely that the freezer temperatures would ever fully stabilise under ISO.
- Fresh food temperatures under both ISO and AS/NZS tend to vary over the test period (see figures 2 and 4) and there is significant stratification within the compartment; again an average (under AS/NZS) rather than a maximum average (under ISO) is probably more indicative of the actual temperature in the compartment (and therefore of the heat gain), although the differences are not as marked as in the freezer compartment (the ISO fresh food temperature appears to be about 1^{o}C warmer than the average temperature under AS/NZS and this has a much smaller impact on total energy consumption for equivalent settings).
- Depending on the design of the model under test (ie the location of the main thermostat) a unit with a test pack load in the freezer (ISO) will tend to over cool the fresh food compartment while trying to pull down the freezer compartment to temperature during the recovery cycle (see Figure 2). This tends not to occur to any degree when there are no freezer test packs (AS/NZS) (see Figure 4). A main thermostat located in fresh food compartment would mean much slower pull down of the freezer test packs under ISO.
- The current ISO definition of defrosting cycle is from the start of the defrost heater to the moment "…when the refrigeration process is re-established". ISO8561 allows temperature rises in the freezer and fresh food compartment to –15^{o}C and +7^{o}C respectively (compared to target temperatures of –18^{o}C and +5^{o}C) during the defrosting cycle (ISO8561 Table 2). During a defrost cycle, the compartment temperatures will reach a maximum at the end of the operation of the defrost heater (or very soon after). In most models the compressor is re-started almost immediately after the defrost heater is stopped, therefore at the moment "when the refrigeration process is re-established" the freezer and fresh food compartments will be at their maximum temperature and cannot generally comply with the requirements of Table 2. A much more sensible definition of the defrost period (or rather the period where temperature deviations are allowed in Table 2) would be in line with the US 10CFR430 "Part 2" definition for variable defrost models which is the time from the initiation of a defrost to the second compressor "on" after the defrost heater has operated, or a period of 4 hours after the activation of the defrost heater, whichever is longer. This period is essentially the heating and then recovery period – note that the first compressor on after a defrost is usually very long as this pulls down the fresh food and freezer temperatures to the thermostat set points.
- Temperature rises in the freezer during a defrost under ISO with freezer test packs is typically about 3K; in contrast air temperature rises under AS/NZS are very large during a defrost (as there is no thermal mass in the air) (temperature rises of the order of 30K) so it is not possible to put temperature rise limits on the test where only air temperature sensors are used.
- The ISO test generally gives a higher than "expected" energy consumption for the same nominal fresh food and freezer temperatures – however investigations and comparative tests have shown that the ISO energy is perfectly consistent with AS/NZS test data if the average freezer and fresh food temperature is used rather than the warmest temperature of the warmest test pack.

General issues arising from the testing program

A range of issues arose from the outcomes of the testing program.

Test Temperatures: There is currently a large degree of "disharmony" with respect to refrigerator test procedures around the world, where ISO specifies 25^{o}C ambient (for temperate) or 32^{o}C (tropical), USA and AS/NZS specify around 32^{o}C ambient while Korea and Chinese Taipei specify 30^{o}C ambient. The Japanese Standard previously specified energy measurements at 30^{o}C and 15^{o}C with door openings and freezer test packs, but this standard was discontinued in favour of ISO and more recently the ISO version been amended to a single temperature 25^{o}C ambient with door openings but without test packs for forced air (test packs for natural convection). There are also differing internal temperature requirements for the various test procedures.

The nub of the problem is that a refrigerator is a thermodynamic appliance and has to operate under a range of ambient temperatures during normal use and its performance and energy consumption will vary under varying conditions. A static test at a single temperature without door openings (which is the basis for most current refrigerator tests) will not provide accurate data on how a refrigerator is likely to perform under a range of normal ambient conditions. The slope of the energy-ambient temperature performance profile for each refrigerator model will differ and it is not possible to estimate this function from a single static test point. In this respect, all existing refrigerator test procedures are inadequate, at least to some degree.

Energy test data used for regulatory purposes has two main functions. The first is to specify a minimum efficiency requirement for a product via a MEPS level. The second main use of energy test data for regulatory purposes is for energy labelling. The goal of an energy labelling program should be to encourage consumers to purchase the appliance that (1) uses the least energy during actual use and (2) meets their needs. It would be of little value (or even misleading) if an energy label ranked a number of models according to a test procedure but that their energy ranking in actual use was different (assuming the provision of comparable energy service). If a test procedure is used to specify requirements for energy labelling but it provides consumers with incorrect advice or information (say through incorrect ranking during actual use), then there should be serious questions regarding its use and validity. Similarly, if a model passes a MEPS level under the test procedure, but the performance and energy consumption in actual use is vastly different (or vice versa), then the test procedure is failing in its role in facilitating energy policy. There needs to be a strong nexus between test procedures, energy programs and actual use by consumers if policies are to be successfully implemented: all too often these important links are ignored by policy makers.

Much of the debate with respect to ambient test temperature centres around the issue of what is the "most" reflective of actual consumer use. This is a complex issue and the short answer is that no single temperature is really appropriate for everyone. Clearly, actual use in Thailand, Philippines or the Pacific Islands will be very different from Australia, Canada, France or Sweden. The internal-country variation is probably as large if not larger than the average between country variations in many cases. There is even some evidence from end use monitoring programs that refrigerator in use energy consumption in colder climates such as Canada and Sweden is higher than in more temperate climates because there is a much higher prevalence and degree of space heating during the very cold winter months. Test procedure ambient temperature conditions have generally been defined without having reliable in-situ temperature data on which to base these.

Control Positions: This is perhaps one of the most difficult areas that arose in the testing. AS/NZS allows several test points to be obtained from control positions selected by the user. The energy at the target fresh food and freezer temperature can then be estimated by linear interpolation or triangulation (a numerical approach for this is provided in the standard).

In contrast, the US test method dictates that both controls are adjusted together in a specified way, effectively meaning that the unit "appears" to have only a single control during testing. This is considered to be a rather archaic approach to refrigerator testing in 2001 and provides no credit to manufacturers that can provide flexible operation of the refrigerator through sophisticated temperature controls. The US positions for the determination of energy consumption (typically mid/mid and warm/warm) are often at very widely spaced temperature points, making the interpolation for energy at the target temperature potentially very inaccurate. The US test method encourages manufacturers to design the temperature balance of their models so that when the controls are moved together the temperature locus passes through -15^{o}C/+7.22^{o}C; this does not necessarily provide consumers with optimised performance in use. There is also an anomaly in the US test method regarding target temperatures: an all refrigerator has a fresh food target temperature of 3^{o}C while a refrigerator-freezer has -15^{o}C/+7.22^{o}C and a separate freezer has –17.8^{o}C.

ISO8561 only allows a single point that meets all of the target temperature requirements. This tends to mean that a "sub-optimal" energy consumption will be recorded by a test lab in order to save testing time. The new ISO draft under development is proposing limited interpolation between points above and below the target temperature, which will reduce testing time and improve accuracy.

Position of freezer thermocouples: For frost free models, it was possible to simultaneously measure freezer temperature positions for US and AS/NZS test methods. For most models, the US positions appeared colder than AS/NZS positions, although this varied from -0.8^{o}C (AS/NZS colder) to +1.5^{o}C (US colder) in the 9 units tested, with a weighted average difference of +0.5^{o}C. The energy impact of the thermocouple placements ranged from –0.7% (AS/NZS less energy) to +4.1% (AS/NZS more energy). The actual difference appears to some extent to depend on the compartment design and the location of the forced air vents in the freezer compartment. There is no doubt that the AS/NZS positions are more representative of the actual freezer temperature. It was not possible to directly compare these values with ISO measurements as freezer test packs are used for ISO tests.

Test Voltage Impact: The energy impact of the change in supply voltage from 240V to 230V as proposed in AS/NZS is relatively small and within the expected range. A consultancy was commissioned to explore this issue further (Bansal 2000a). The impact appears to be a 0% to 2% reduction in energy for 230V-240V rated compressors and a 4% to 5% reduction in energy for 220V-240V compressors. These tests were undertaken to measure the impact of moving towards a 230V test standard in Australia in line with the move to change the nation's grid voltage from 240 to 230 volts in 2003.

Ambient temperature difference: The ambient temperature for energy tests under AS/NZS is 32^{o}C while under US CFR430 it is 32.3^{o}C. The impact of this change is small in terms of tested energy and the EES model adequately accounts for this difference. ISO tests were conducted at 25^{o}C for temperate and 32^{o}C for tropical. The ISO results are broadly in line with expectations, with the main differences arising from differences in the method of compartment temperature determination. The loading or otherwise of the freezer during energy tests does not appear to have a large impact on the energy consumption per se.

Adaptive Defrost: Under the current rules of AS/NZS4474.1-1997, an adaptive defrost system is defined as "a form of automatic defrosting system where energy consumed in defrosting is reduced by an automatic process whereby the time intervals between successive defrosts are determined by an operating condition variable (or variables) other than, or in addition to, elapsed time or compressor run time." Under AS/NZS, if the time between defrosts is longer than 24 hours, the energy test is terminated after 24 hours. Under ISO, if the time between defrosts is longer than 72 hours, the energy test is terminated after 72 hours.

Under the US test method the test period is normally from defrost to defrost unless the unit is defined as long time defrost or variable defrost. Long time defrost models are uncommon (successive defrost cycles are separated by 14 hours or more of compressor-operating time). "Variable defrost control" in the US is where successive defrost cycles are determined by an operating condition variable or variables other than solely compressor operating time. Demand defrost is a type of variable defrost control. For most US demand defrost models the default values in the test method mean an assumed time between defrosts of 38.2 hours of compressor run time. The test method also assumes 50% compressor run time, so the default elapsed time between defrosts is 76.4 hours. The US method does not actually require the test to run for this long. Rather it emulates the result with a two part approach as described later in this paper.

Defining the operating cycle: AS/NZS, ISO and US test methods all define the operating cycle as defrost to defrost (the start of the defrost is usually defined as the initiation of the defrost heater). Some recent testing in Australia has identified an unusual mode of operation on an automatic defrost model from the US. The unit appeared to enter a pre-cool compressor run for a period of about 2 hours prior to the initiation of a defrost. Under the current requirements of ISO, US and AS/NZS test methods, it is not clear how to deal with this pre-cool period. The compressor normally cycled during equilibrium but this pre-cool was certainly not in equilibrium. As this pre-cool occurs before every defrost, it should probably be considered as part of the defrost cycle (rather than when the defrost heater commences operation). The revision of AS/NZS 4474.1 now being undertaken contains a proposal to address this problem.

Volume Measurements: The volume issue is a difficult one and arises from a lack of international harmonisation of test methods for its measurement. Essentially there are two international systems of refrigerator volume measurement - ISO and the AHAM/US. In Australia, the ISO system is used to define gross volume (with minor differences) and storage volume. ISO gross volume is only defined as a total value for a cabinet - there is no such thing as ISO gross volume at a compartment level. Due to the historical requirements of the energy labelling program in Australia, which has used gross volume to define the energy service, AS/NZS has had to contrive a gross volume definition at the compartment level, which is out of step with ISO definitions. It is hoped that this can eventually be addressed, although the new MEPS levels developed for 2004 will still be based on compartment gross volume.

The AHAM/US volumes generally lie between (but not always) ISO gross volume and ISO storage volume: things like fans and coil assemblies are excluded, but the volume outside baskets is included. The differences in freezer volumes are most pronounced, especially in frost free models and where baskets or drawers are present in vertical freezers or bottom mounted freezers.

From an energy policy and consumer perspective, it is most important that manufacturers optimise the storage volume available to consumers rather than the gross volume. Ideally all test methods should fully harmonise with the ISO volume measurements in the medium term.

Recommendations to improve refrigerator testing methods

The testing and analysis undertaken for this project has provided many insights into potential changes that could be introduced to improve current refrigerator test methods. Many of these are incremental, while some constitute major changes in the current paradigms. Gradual introduction of these changes will result in both more reliable, robust test methods and will lead to a gradual convergence of test procedures for refrigerators, which in turn will reduce testing costs and increase trade in the medium term. It is hoped that these can be considered carefully by policy makers and standard's committees.

- ***Harmonisation of internal test temperatures***: many of the major test procedures around the world specify different internal temperature requirements. Some of these anomalies are minor and arise from conversion from Fahrenheit to Celsius, while others are fundamentally different for historical reasons. Test methods in Taiwan, Korea, US (partly - separate freezers), JIS and ISO all use freezer temperatures of -18°C as their nominal target. Most test methods (apart from ISO) use 3°C (average) in the fresh food compartment (except US refrigerator/freezers but this is an anomaly). It would be an incremental change for many to eventually move to a target of 3°C and -18°C for fresh food and freezer compartments for energy consumption. (See also next point on how compartment temperatures are determined). The ISO temperature of 5°C is considered by many food technologists as too high for safe food storage.
- ***Method of temperature measurement***: The ISO method of defining the freezer temperature as the warmest temperature of the warmest test pack is out of step with most other refrigerator test methods and is not indicative of the average temperature of the compartment, which is the parameter that drives the operation, performance and energy consumption of a refrigerator. A small temperature excursion of a test pack will make temperature data completely non comparable between similar runs even on the same model and even where this occurs over a short period. The use of average data would overcome most of the superficial differences between ISO and other test methods and makes the data more useful and representative at an international level.
- ***Test packs for energy measurement***: While the ISO method of placing test packs into the freezer for energy consumption tests is widely used (mostly in Europe), it seems to raise a number of issues and problems, some of which are not easily resolved. Achieving adequate stability when testing with freezer test packs is very much slower than it is when testing

without and there seems to be some temperature stability issues with test packs that need to be addressed. The results with and without test packs are usually equivalent when the same ambient conditions and control settings are used, so the advantages of using test packs is dubious in many cases. The JIS test method has adopted ISO but has deleted test packs because of complications on forced air units with door openings.

- ***Volume measurement***: ISO probably provides the most consistent method of volume measurement. This should provide a long term option for harmonisation for many countries. However, the way that frost free models are dealt with under ISO in terms of gross volume needs to be refined in places.
- ***Ambient temperature***: As discussed above, all test procedures are currently inadequate in terms of ambient temperatures used for energy testing. A more generic test procedure that estimated energy consumption under a range of ambient test temperatures and under different defrosting loads and internal heat loads would be the most desirable approach. Although this is an attractive option in some respects, there are many uncertainties associated with it. This concept is developed more in Bansal (2000b).
- ***Treatment of defrost under ISO***: ISO requirements for allowable temperature excursion during defrosting as currently written are not practical or achievable and need refinement.
- ***Control settings and interpolation***: The US requirements to move both control settings together is completely arcane. ISO8561 as published only allows a single test point, but the revised version currently under development allows limited interpolation. The interpolation methods in AS/NZS are by far the most accurate and sophisticated for determination of energy consumption.
- ***Air temperature sensor placements***: Where air temperatures are measured in the freezer compartments, the AS/NZS positions (5) appear to be superior to the US positions (3). The ISO positions for fresh food temperature measurements are used almost universally and should be adopted wherever possible. Some updating of ISO diagrams and configurations would be helpful (eg clarification of box versus plate evaporators).
- ***Adaptive (variable) defrost and new technology***: Many major test procedures deal with adaptive defrost in some form, although the approach varies widely. As experience with these systems grows, it should be possible to develop a fair and consistent approach to their testing. Some analysts suggest that adaptive defrost appliances will dominate the market in 5 to 10 years. The introduction of other new technologies into refrigeration systems (especially electronics, fuzzy logic and controls and variable speed drives) will require continual review of test methods to keep them relevant.
- ***US Part 1 and Part method***: The US method for dealing with variable defrost models was found to be a very stable basis on which to compare energy data for models that vary their defrost period (or fuzzy logic machines, for example that are continuously changing). The Part 1 values (steady state) can be determined at any time after the compartments have attained stability after the defrost. Part 2 is includes the defrosting period plus the recovery compressor run after defrosting. Recommended as a new approach to energy measurements.
- ***Freezer test packs***: Where test packs are essential (eg for the ISO temperature operation test), those defined under ISO should be used. US requirements to use frozen spinach or sawdust for some refrigerator types are outdated.
- ***Temperature operation tests***: ISO temperature operation tests are considered to be a good measure of internal temperature control and it is recommended that this test be widely adopted as a performance measure. A wider range of ambient test temperatures than currently specified under a single climate class are required for some countries (eg Australia). Redefining stability requirements where it is not possible to disconnect the automatic defrost mechanism needs to be addressed.
- ***ISO tolerances***: The current method of specifying allowable tolerances on energy consumption in some ISO and IEC standards is poorly expressed and is considered unacceptable by some regulatory authorities. There needs to be a clarification that the stated tolerances are only applied to verification tests, not to tests used to make original claims. The 15% allowance for an initial test is also considered to be far too lenient.
- ***Special compartments***: ISO need to remain vigilant to ensure that special compartment types are adequately covered in the test procedure. Wine cellars with stratified temperature zones are a good example.

Other Improvements to Refrigerator Test Procedures

In terms of other options to improve refrigerator and freezer test procedures, the prospects are currently not very encouraging:

- there are a large number of test procedures in use around the world and many of these have fundamental differences which make it difficult, if not impossible to determine levels of equivalence between them (particularly given the way the data is currently recorded and the suite of tests required) - none of the current methods in use is clearly more superior to the others, which makes selection of one existing method over another somewhat arbitrary;
- test procedures are generally not very reflective of actual use and it is difficult to provide consumers with realistic and accurate advice on model selection using the current test results (it is possible that ranking may change substantially depending on actual conditions of use);
- there are currently no substantive algorithm or computer modelling options that are sufficiently well developed to take the place of current test procedures and to provide conversions between them - development of such options would be a substantial task but nevertheless is highly desirable - it may be necessary to test a model at 2 or more conditions so that conversions to any other set of test conditions can be synthesized with acceptable accuracy;
- a large number of countries regulate refrigerators and freezers for energy efficiency and as such there is substantial regulatory "baggage" or "inertia" built into the current test methods (changing the test method may mean complete revision of MEPS lines and/or energy labelling requirements, which is potentially disruptive and may be costly to both governments and industry).

Conclusions

This paper underlines the critical reliance of energy policies and programs on test procedures. All too often, governments pay too little attention to test procedures when developing energy policies that rely on them. For energy policies to be successful and credible, it is important that test procedures are both realistic in terms of the task measured and are able to reflect consumer behaviour – ensuring these objectives can be met while remaining repeatable, reproducible, cost effective and technically feasible is a challenge for standard's committees. With the advent of smart technologies and controls into appliances and equipment, it is becoming increasingly common and simple for test procedures to be thwarted, particularly those that are overly simple or unrealistic. While there is a large degree of "policy inertia" with regard to test procedures, especially for refrigerators, MEPS and energy labelling requirements are revised regularly, so there are opportunities to update test procedures at these times.

It is accepted that the objective of fully harmonised MEPS and energy labelling requirements for refrigerators and freezers is not practical or appropriate, and in any case the costs and benefits of these program elements would need to be demonstrated for each country. However, the options for further convergence regarding the test methods for refrigerators are likely to bring significant benefits to all countries both in terms of reduced testing costs, improved comparability of results and improved international trade. As new appliance technologies will inevitably necessitate the need to modify test methods to accommodate them, mechanisms should be established to ensure that such changes, as they occur, converge rather than diverge our test procedures. If governments and manufacturers – especially those supplying in several markets – see benefit in greater harmonisation, they should consider the changes in test method discussed in this paper.

Annex A – Brief Summary of three refrigerator test methods

This Annex contains the salient differences between AS/NZS, US and ISO test methods. A more detailed analysis of the differences can be found in APEC (1999), Technical Annex A.

AS/NZS4474

- Fresh food temperature thermocouple placements are equivalent in AS/NZS, US and ISO test methods;
- Freezers are always unloaded for energy tests;
- Test period is from defrost to defrost;
- Energy consumption is based on the energy over the test period (normalised to 24 hours) except where defrost time >24 hours.

- Energy consumption determined at target freezer temperature of -15°C and fresh food temperature of +3°C, triangulation interpolation allowed (multiple control positions around the target temperatures are allowed);
- Compartment temperatures are based on a numerical average over a whole number of compressor cycles that total ≥ 3 hours immediately prior to the initiation of a defrost;
- A total of 5 freezer temperature sensors are used; two high left (front and back), centroid and two low right(front and back), warmest 4 used for temperature calculations;
- Ambient temperature is 32°C with measurement at a single measurement point in front of the unit at a height of 1 metre. There are also limits on the allowable temperature gradient in the room.

US 10 CFR430 - Appendix A (USA)

- Fresh food temperature thermocouple placements are equivalent in AS/NZS, US and ISO test methods;
- Freezer compartments are unloaded for energy tests (except convectively cooled appliances and separate freezers which are loaded with packets of frozen spinach);
- Test period is from defrost to defrost;
- Energy consumption is based on the energy over the test period (normalised to 24 hours) except where the model is deemed to be Long Time or Variable defrost under the US regulations (variable defrost default period = 76 hours).
- Energy consumption is interpolated for a freezer temperature of -15°C, as long as the fresh food temperature is less than +7.22°C at this point. Otherwise the energy consumption is interpolated for a fresh food temperature of +7.22°C. Where there are two controls, these must be moved *together* when obtaining test points. Separate freezer target temperature is -17.8°C and an all refrigerator is +3°C.
- Compartment temperatures are based on a numerical average over a whole number of compressor cycles that total ≥ 3 hours immediately prior to the initiation of a defrost (same as AS/NZS).
- US freezer temperature sensors are located on the centre line of the unit (generally 3 (except for group 5S (side by side) which requires 5 locations); top-middle-back, centroid, bottom-middle-front;
- Long time defrost is defined as where the compressor run time is more than 14 hours over a test period.
- For Long Time and Variable defrost types, the US defines a two part measurement process for energy. Part 1 is the three hour period prior to a defrost (essentially the steady state part of the period) and Part 2 is the initiation of the defrost to the start of the ***second*** compressor on after the defrost (ie includes the long post defrost recovery compressor cycle). The Part 1 and Part 2 energy can be combined to "simulate" the energy consumption for any assumed time between defrosts.
- Ambient temperature is 32.3°C with two measurements required on the centre line of each side of the unit (high and low). There are also limits on the allowable temperature gradient in the room.

ISO8561

- Fresh food temperature thermocouple placements are equivalent in AS/NZS, US and ISO test methods (ISO uses suspended M packs rather than brass cylinders);
- Freezers are always loaded for energy tests with ISO test packs (these are loaded against the freezer wall, which can be problematic for forced air models);
- Test period is from defrost to defrost;
- Energy consumption is based on the energy over the test period (normalised to 24 hours) except where defrost time >72 hours; energy test terminated at 72 hours if a second defrost has not occurred;
- Energy consumption determined at target freezer temperature of -18°C and fresh food temperature of +5°C, single point measurement only is allowed (new ISO test method under development will allow limited interpolation for various control positions);
- Compartment temperatures are based on: fresh food is maximum value of the instantaneous averages of the 3 fresh food test packs; freezer is the warmest test pack temperature occurring over the whole operating cycle (except defrost period). Temperature excursions are allowed during the period when the defrost heater is on up to +7°C for fresh food and -15°C for freezer. Other requirements are that no fresh food position can move outside of the range 0°C to +10°C at any time.
- A total of 4 freezer temperature sensors are used (M packs);
- Ambient temperature is 32°C for tropical and 25°C for the other climate classes (most common) with measurement at a height of 1 metre on each side of the appliance. Note the EU energy test procedure uses 25°C for all climate classes including tropical. There are also limits on the allowable temperature gradient in the room.

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