STUDIES ON ALGORITHM DEVELOPMENT FOR ENERGY PERFORMANCE TESTING

STUDY 2 – STUDY OF ALGORITHMS FOR DOMESTIC REFRIGERATION APPLIANCES

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Executive Summary

This report explores a detailed investigation of the development and application of algorithms for domestic refrigeration appliances in APEC economies. There was very little information available in the literature on the topic. The report covers the following aspects of various test standards in APEC economies-

1. This report presents a comprehensive research study on the energy efficiency test procedures for household refrigerators and refrigerator-freezers. There are a number of test procedures currently operative in APEC economies. Some of the procedures that have been studied in the report include the International Standard (ISO), the Australian - New Zealand Standard (AS/NZS), the Japanese Industrial Standard (JIS), the Chinese Taipei National Standard (CNS), and the American National Standard (ANSI).

2. The report highlights the salient differences among these test procedures and identifies the main parameters that play an important role in the overall energy consumption of a refrigeration appliance. Most of the current procedures use closed door tests for reasons of repeatability but have highly inflated ambient air temperatures to compensate for lack of door openings. However, these procedures yield up to 25% more energy consumption than the real world in-field end use data.

3. The study examines the merits and demerits of current test standards and proposes new guidelines that should be considered in developing a new test procedure that could be accepted as a harmonized test procedure internationally. The new procedure should be simple, repeatable and reproducible, should represent realistic "*real world*" energy use, should encourage product innovation, should capture both the software and hardware developments and should facilitate 'free trade' among various economies. To achieve this, the report highlights areas where concerted efforts are required for carrying out requisite research and development work.

4. The report discusses the development of conversion algorithms for energy consumption of a cabinet from one test procedure to another. However, due to the complex nature of refrigerating appliances, a single test point provides insufficient information for this approach to be practically possible.

5. Instead, an innovative approach for modelling a refrigeration system has been proposed to measure energy consumption of an appliance to represent different climatic conditions (with varying kitchen temperatures and relative humidities) and "user behaviour" (i.e. frequency of door openings) conditions. The study discusses different scenarios and proposes guidelines for developing model(s) that could predict the energy consumption of a

refrigerator in different climatic conditions e.g. in Brisbane, Christchurch, Moscow, Singapore etc.

6. Such a modelling approach would be very useful in developing a harmonised test standard for all the economies and the resulting algorithms will provide a much better prediction of in-use energy consumption and performance. In particular, such algorithms will be helpful in translating energy consumption displayed on ‘energy labels’ from one test standard to another, enable in energy forecasting for policy makers, and identify the most energy efficient product in the market.

7. The report highlights issues and difficulties that need to be considered to develop such algorithms and proposes guidelines that would facilitate the development of such algorithms. However, collecting and generating data on various products from different manufacturers in various economies would be a surmounting task and expensive (exceeding US$1 million) and would need special attention.

8. Finally, the study concludes with a detailed description of the algorithms’ modelling approaches and makes recommendations for the future research work that should be carried out for these models to be suitably developed and satisfactorily applied.

Key Words: Refrigerator-freezers, Energy Consumption, International Procedures, AS/NZS, AHAM, ANSI, CNS, KS, GOST, ISO, JIS, conversion algorithms, test packages, modelling, test standards.

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Some arguments in the report are inherited from earlier reports by Lloyd Harrington (EES, Australia) and Paul Waide (UK).

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1. INTRODUCTION

Energy efficiency of household appliances, in particular refrigerators and freezers, is receiving increasing attention lately, and rightly so, as there is a huge potential for substantial energy savings in the domestic refrigeration sector. A refrigerator is one of the most popular household appliances and its ownership is already high in developed economies and increasing rapidly in the developing economies. In terms of appliance energy consumption, refrigerators are the largest single end users of electricity in the residential sector due to their widespread use and continuous operation. Therefore improved energy efficiency is of paramount importance.

It is difficult to compare the energy efficiency of different models of refrigerators/freezers due to their varying degree of features and utility and the differing technologies employed. Refrigerator manufacturers perform energy consumption tests on a random sample of their units and display the annual energy consumption on a label attached to the cabinets. The test procedure to specify the energy consumption on these labels depends on the test procedure relevant to the country where the cabinets are sold. However, the labelled energy consumption of a cabinet differs from the "in-field" data typically by 35% or more. Therefore, the current procedures neither help the consumer to make precise cost effective calculations and so decisions to purchase a product nor do they help the national policy makers in making accurate forecasts of electricity demand. There is, therefore, an increasing need for the harmonisation of trading conditions and testing among various economies.

It would be desirable to harmonise various test procedures into one procedure that can be accepted internationally for reasons of uniformity and trade. Therefore, it is crucial to quantify the effect of various performance variables on the energy consumption of refrigerators as the actual impact of each of these elements may vary significantly between different countries of use. A disaggregated test procedure will, therefore, enable the development of a general relationship to predict energy consumption under different operating conditions.

There are a number of test procedures being used around the world[1-8]. Most economies have introduced different regulations and test procedures and have simultaneously imposed regulations for refrigerators. The difference in testing procedures and procedure requirements are increasingly becoming a significant barrier to the trade in refrigerators among different economies around the world. The energy consumption results can differ significantly from one test procedure to another for the same cabinet. This occurs due to different test ambient temperatures and relative humidities, compartment internal temperatures, door openings and operational requirements away from the test conditions. *Earlier testing analyses by Bansal et al.*[9-13] *revealed that refrigerators perform best when tested to the procedure for which they were designed*. Testing of a cabinet to other procedures gives different energy consumption results. Due to the complexity of refrigeration systems, converting energy consumption from one test procedure to another is generally very difficult unless substantial additional information is collected during the tests.

For a fairer comparison, it is desirable to develop energy conversion algorithms, which will enable the energy consumption under one procedure to be estimated when the same cabinet is tested to a different procedure. A general relationship of this type would be of special interest to refrigerator manufacturers, governments, environmental groups, consumer organisations, utilities etc.

Another important issue with the current test procedures is that either they must be continually updated or they quite quickly become "out of date" and are unable to accommodate new product innovations. Modern refrigerators are increasingly controlled by microprocessors, which cause the unit to operate very differently from units with older, simpler controls. This report, therefore, examines the practical issues of having different test procedures and proposes new guidelines and approaches that should be looked into to improve the existing procedures for domestic refrigerator-freezers.

2. TERMS AND DEFINITIONS

Some of the frequently used terms and definitions that are relevant to the test standards are described in this section

2.1 Household Refrigerator

A household refrigerator is defined as a cabinet or any part of a cabinet which is designed for the refrigerated storage of food at temperatures above 0°C, has a source of refrigeration and is intended for household use. It may include a compartment for the (freezing and) storage of ice and/or for storage of food at temperatures below 0°C (typically at -15°C to -18°C). Household refrigerators can be divided into two classes:

2.1.1. All-Refrigerator

An all-refrigerator is a cabinet which does not include a compartment for the storage of food at temperatures below 0°C. It may include a compartment with a small volume for freezing and storage of ice.

2.1.2. Refrigerator-Freezer

A refrigerator-freezer (R/F) consists of two or more compartments, with at least one of the compartments designed for the refrigerated storage of food at temperatures (T_{FF}) above 0°C and with at least one of the compartments designed for the (freezing (T_{FR}) and) storage of frozen food. 3 star ISO cabinets (marked ✳✳✳) are designed for frozen food storage not for freezing food first. ISO 4 star cabinets (marked ✳✳✳✳) are designed to freeze and store food. (No such Australasian delineation).

2.2 Household Freezer

A household freezer is a cabinet designed for the extended storage of frozen food at an average temperature of -15°C or below. It has a source of refrigeration and is intended for household use.

2.3 Fresh-Food Compartment

A fresh-food compartment is intended for the storage of unfrozen food at an average temperature above 0°C, and may be subdivided into smaller zones or compartments allocated for the storage of particular types of product.

2.4 Freezer Compartment

A compartment is intended specifically for the freezing and/or storage of frozen food, and may include an ice-making zone or function. The classification of freezer compartments according to their storage temperatures is different in most of the test procedures. Thus, to have conformity between these procedures, the freezer compartments are classified in this study by using the International Standard's Organisation classification[2], as follows:

- "One-Star" Compartment (✳)
  Compartment with storage temperature not warmer than -6°C.
- "Two-Star" Compartment (✳✳)
  Compartment with storage temperature not warmer than -12°C.
- "Three-Star" Compartment (✳✳✳)
  Compartment with storage temperature not warmer than -18°C.
- "Food freezer"
  Refrigerating appliance having one or more compartments suitable for freezing foodstuffs down to a temperature of –18°C and which is also suitable for the storage of frozen food under "three star" storage conditions. (Note these are sometimes referred to as "four star" compartments — ✳✳✳✳.)

2.5 Control Cycle

A control cycle is the period between two successive starts or two successive stops of the compressor of a refrigerating system.

2.6 Defrost Cycle

A defrost cycle is the period between two successive starts or two successive stops of a defrost heater in a refrigerator-freezer having an automatic defrost system.

2.7 Test Packages

Most of the procedures typically use test packages in food storage tests while the ISO[2] requires loading of the freezer compartment with test packages for energy consumption tests. The packages are used to simulate food load in the freezer compartment. Their function is to provide thermal ballast and fill up space. The chemical composition of the packages[2] per 1000 g is:

- 764,2 g of water
- 230.0 g of oxyethylmethylcellulose
- 5.0 g of sodium chloride
- 0.8 g of parachlorometacresol.

The freezing point of this material is -1°C. The thermal characteristics of the packages correspond to those of lean beef[2].

2.8 Measurement Packages (M - Packs)

A measurement package (also called M-package) is a 500 g (50mm $\times$ 100mm $\times$ 100 mm) test package fitted at its geometric centre with a temperature sensor (e.g. thermocouple), which shall be in direct contact with the filling material.

2.9 Characteristic Temperature

This is the design temperature within the compartment of a cabinet that needs to be achieved during a test for the energy consumption measurement.

3. TEST PROCEDURES AND THEIR DIFFERENCES

There are a number of different test procedures operative in APEC economies (Harrington[14]) for the determination of energy consumption. The temperature and energy consumption requirements for various procedures are summarized in Tables A and B in the Appendix. Most test procedures measure energy consumption at the food compartment internal temperature of 3°C and the ambient temperature of either 32° or 30°C. The only exceptions are the ISO and ANSI that specify 5°C and 7.2°C respectively for the food compartment temperature. In addition, ISO specifies two different ambient temperatures (25/32°C) depending on the climate classification. However, the quoted energy consumption figures in ISO are usually based on the temperate climate classification of 25°C. Also, ISO is the only test procedure that specifies food loading in the freezer compartment of the frost-free refrigerator-freezers but with closed doors. The CNS[Ψ] requires the relative humidity of the ambient air to be 75%±5%, while the ISO recommends between 45 and 75%. AS/NZS, JIS and the ANSI do not prescribe any humidity requirements.

JIS was the only procedure that prescribed door openings of both the compartments (as shown in Table 1) but without loading of any food packs in either of the compartments. It required tests at a second test ambient of 15°C and weighted the two results assuming 100 days at 30°C (27%) and 265 days at 15°C (73%) to evaluate the annual energy consumption.

Table 1: Door Opening Requirement For the Japanese Industrial Procedure (Method A)

Type	**Compartment**	**Rate**	**Number of Openings**	**Opening Angle**	**Opening Time**
Refrigerator -Freezer	Fresh-Food	Every 12 Min	50	90°	10 s [#]
	Freezer	Every 40 Min	15	90°	10 s [#]

The door shall be fully opened for at least 5 s.

However, JIS has recently been revised (Banse[15]) to be compatible with ISO and is called JIS (Method C). The new procedure (Method C) prescribes the ambient temperature and food compartment temperatures to be 25°C and 5°C respectively and the frequency of door openings to be 25 times/ 25 minutes/day and 8 times/25 minutes/day for the food compartment and the freezer doors respectively. The frequency of door openings appears to have been reduced to half in the revised Method C.

Ψ Note that the Korean Standard is essentially identical to the Chinese Taipei National Procedure - both appear to be a JIS version of the procedure (at the warmer ambient) but without door openings.

The main differences of various test procedures may be summarized as below -

3.1 **Ambient Temperatures:** A large number of ambient temperatures are used including 15, 25, 30, 32 and 32.3°C. However, none of these temperatures reflect the actual prevailing temperatures in kitchens in various countries. It is evident from the performance monitoring programs that refrigerator "in use" energy consumption in colder climates (e.g. Canada or Sweden) is higher than in more temperate climates (e.g. Australia or New Zealand) due to space heating, leading to higher kitchen temperatures during the very cold winter months. The energy consumption increases with ambient temperatures and exhibits non-linear variation with ambient temperature (see Figures 1 and 2),

3.2 **Internal Compartment Temperatures:** The method and measurement of internal temperature vary considerably among the test standards as follows-

3.2.1 **Fresh food compartment temperatures:**

- 3°C for AS/NZS, CNS/KS, JIS
- 3.3°C for ANSI/Canada/Mexico (7.2°C for refrigerator-freezers)
- 5°C for ISO/GOST

3.2.2 **Freezer compartment temperature in refrigerator-freezers**

- - 15°C for AS/NZS, ANSI/Canada/Mexico,
- - 18°C for ISO/JIS and others

3.2.3 **Freezers**

- **-** 15°C for AS/NZS, -17.8°C for ANSI and - 18°C for ISO/JIS and others.

3.3 **Internal Volume:** Refrigerator performance requirements are normally given in terms of the refrigerator volume. AS/NZS is the only standard that uses gross volume, whereas all other standards specify 'net' or 'storage' volume.

3.4 **Door Openings:** JIS is the only test standard that requires door openings under controlled humidity conditions to (i) activate the defrost function (as a result of ice build up on evaporators) and to (ii) simulate heat load on the cabinet in 'real use' by introducing heat and humidity. However, door openings are seen as unrepeatable, unreproducible, hard to implement, expensive and arbitrary (in terms of frequency and duration of opening).

3.5 **Test Packages:** are intended to simulate the thermal mass in the freezer compartment of a cabinet under "real use" conditions. "M-packages" – test packages with a thermocouple incorporated, are used to perform temperature measurements. The material inside the test packs is different in ANSI from the one in ISO (though the Americans are presently debating changing their fill material to that in the ISO standard). Different standards have different requirements as given below, however, thermal stability of test packs during defrost cycles is seen as a major problem-

- AS/NZS, JIS (Method A), CNS/KS do not require any test packages for energy tests,
- ISO specify loading of test packs (in the freezer compartment of a cabinet) that must touch freezer walls,
- ANSI and JIS (Method C) specify test packs for natural convection units (but not frost-free units). The freezer compartment is about 75% filled with test packs.

4. PRACTICAL ISSUES WITH DIFFERENT TEST PROCEDURES AND PROPOSED SOLUTIONS

4.1 **Need For The Development Of Next Generation Test Procedures[16-17]:** Current test procedures are seen to be obsolete as they are unable to accommodate accurately the "smart" technological changes being introduced in the refrigerator industry e.g. microprocessor controllers, freezer frost detection sensors, and variable speed compressors. Microprocessors are usually programmed so that they demonstrate low energy use during testing, but the actual in-service performance may be better or worse than the test results. Before the introduction of the freezer frost detection sensor, the defrost operation was clock-controlled. This sensor reduces the energy consumption significantly in real use. With this device, the closed door testing will not activate the second defrost cycle and therefore, one needs the open door testing (or some other stratagem) to find the savings from a sensor defrost function. However, none of the existing procedures reward the adaptive defrosts system correctly. It is well known that variable speed compressors can save energy by more than 40% but their impact does not show up on conventional test results. In the future, microprocessors may enable automatic energy consumption planning for our appliances interacting with the Internet (and anticipating weather conditions). These processors may also command refrigerators to perform cooling mostly at night to avoid peak loads on the electricity supply system, to obtain a cheaper tariff and to take advantage of the more efficient operation at lower ambient temperatures.

➡ Therefore, there is a need for the continuing development of "New generation test procedures" that can accommodate all these concerns, features and advancements. The new procedures should capture both the hardware [e.g. response to use, loads, door-openings, Coefficient of Performance (COP) etc.] and software (i.e. Test of "intelligence" of the system) performance, encourage technological innovation in the product and allow harmonisation with other test procedures.

4.2 **Externalities:** Some marketing claims are made that appliances made-in the "European Union" are more efficient than those from local or other manufacturers. This may not be true. The confusion may arise due to the fact that the energy consumption of a refrigerator under ISO is generally about 20% less than AS/NZS or ANSI because both AS/NZS and ANSI have more stringent test ambient temperatures than the ISO (temperate conditions) test. Another important issue is the classification of the ambient temperature for testing these appliances and ensuring that they can work under extreme climatic conditions. For example, although ISO also specifies tropical test conditions (i.e. ambient temperature being 32°C), it does not give confidence to the end user in Darwin (Northern Territory of Australia) where an appliance would need to work satisfactorily under very hot (50°C) and humid conditions.

4.3 Harmonising Different Test Procedures: There is some discrepancy among different procedures concerning the fresh food compartment temperature, freezer compartment temperature and the test packs.

4.3.1 Compartment temperatures: Most test procedures specify 3°C as the fresh food compartment temperature except ISO (that uses 5°C), and -18°C for the freezer compartment temperature except AS/NZS and ANSI (that specify -15°C). There does not seem to be any strong reason for either of these discrepancies. The primary safety reason for refrigerators is to maintain the food quality by eliminating the growth of micro-organisms[18] (i.e. thermophiles, mesophiles and psychrophiles) and enzymes. Thermophiles cease to grow at temperatures below 45°C, mesophiles below 10°C and psychrophiles below - 7°C. Therefore, the reason to store food at as low as -18°C is unclear from a safety perspective. [Note that –18°C is a soft conversion of 0°F and this may be the source of this value. A freezer running at –18°C uses significantly more energy that one running at –15°C].

➨ Nevertheless it is suggested that temperatures of 3°C (for the food compartment) and -18°C (for the freezer compartment) should be universally used in all procedures for reasons of uniformity, consistency and comparability.

4.3.2 Test packs: Test packs in the freezer are intended to simulate ballast or food loads in the freezer compartment during the test. ISO is the only procedure that prescribes the loading of 'test packages' in the freezer compartment of a frost-free refrigerator-freezer for energy consumption tests. (ISO still calls up the stacking, where possible, of test packs against a freezer wall. This is not acceptable in a frost –free freezer.) A number of other contentious issues result from the use of these packages (Harrington[19]), including-

- Whether the test packs are present or not,
- The number and positions of measurement points,
- Whether measurements taken are an 'average' over time or taken at a particular instant (maximum/minimum),
- How often are the measurements recorded, and
- Whether it is the warmest M-package, the second warmest, or the average temperature that defines the compartment temperature.

All these differences may produce slightly different test results. During a defrost cycle, the test packs in the freezer can lead to thermal in-equilibrium for a short period in the freezer compartment, which can create stability and repeatability problems. The exact placement of the test packs relative to the defrost system can also be critical. Frost-free appliances largely dominate the market in USA, Australia, New Zealand, Korea, Chinese Taipei and Japan and the normal practice in these markets is to remove freezer test packages during an energy consumption test, at least for frost-free cabinets. *ISO specifies that the warmest food pack temperature should be equal or less than -18°C.* This means that the average temperature in the freezer compartment would be a lot colder (say around -22°C). Further, it has been experienced that it is very difficult to achieve stable conditions in the freezer compartment [Harrington[14, 19]], especially with frequent defrosts (say about 10 hours apart).

➡ Therefore, all test procedures should have consistently similar requirements. It is suggested that the freezer compartments should **not** be loaded with 'food packs' and freezer "average" temperature of -18°C should be universally used.

4.4 Static Test At A Single Ambient Temperature With 'Closed' Doors: Most test procedures specify a static test at a single ambient temperature with 'doors' being closed. Elevated ambient temperatures used in most procedures crudely simulate the heat loads from door openings and the introduction of warm food into the cabinet. This process fails to produce satisfactory results that could be representative of an *in-situ* 'real world' refrigerator performance under a range of ambient conditions and door openings (i.e. according to specific user requirements) for a number of reasons.

(a) Firstly, elevated temperatures do not really represent actual use and can under value cabinets with efficient refrigeration systems but poorer insulation compared with better-insulated cabinets having less efficient systems,

(b) Secondly, the manufacturers may optimise their cabinets around the specified static temperature, which does not necessarily imply that the cabinets will perform well under different ambient conditions,

(c) Thirdly, the energy consumption increases with ambient temperature (see Figure 1 and 2) but the slope of the curve differs for each type of refrigerator model and the manufacturer. For example, the slopes $\left\{ \Delta E / \Delta T \right\}$ for all-refrigerators[§] and refrigerator-freezers vary between 11 and 21 kWh/year/K. Therefore, current test procedures are inadequate to address this issue [Bansal[13]].

➡ A dual or triple temperature test may obviously address this issue better, although it may exhibit non-linear energy consumption outside the 20-30°C temperature domain. The energy consumption of a cabinet can then be related to ambient temperature through a polynomial of the type-

$$E = a_0.T + b_0.T^2 + c_0.T^3 + ... \quad (1)$$

§ Bansal[13] tested six cabinets each of all-refrigerators (two models each of C190, C275 and C370) and refrigerator-freezers (two models each of N169, N249 and N375). All-refrigerators had storage volume of 190, 270 and 370 litres respectively, while refrigerator-freezers had 46, 46 and 85 litres in the freezer and 108, 181 and 278 litres in the food compartments respectively.

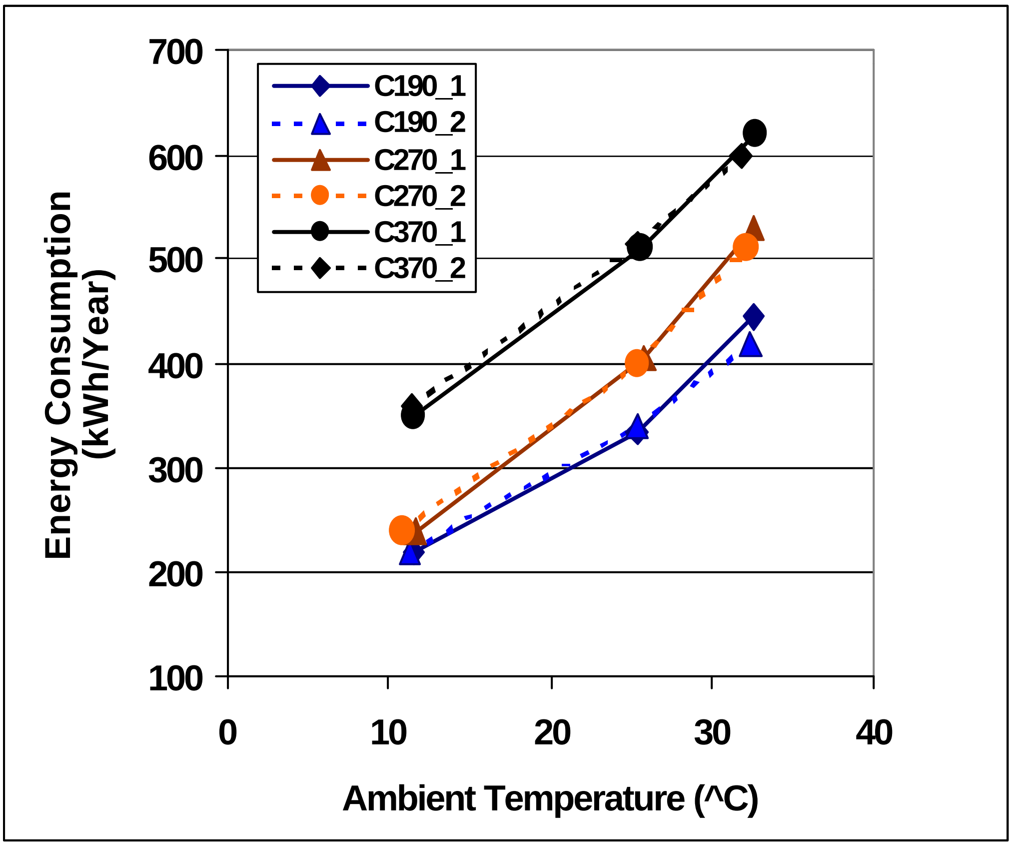

Figure 1: Annual energy consumption (kWh/year) with ambient temperature for AS/NZS for all-refrigerators (after Bansal[13]).

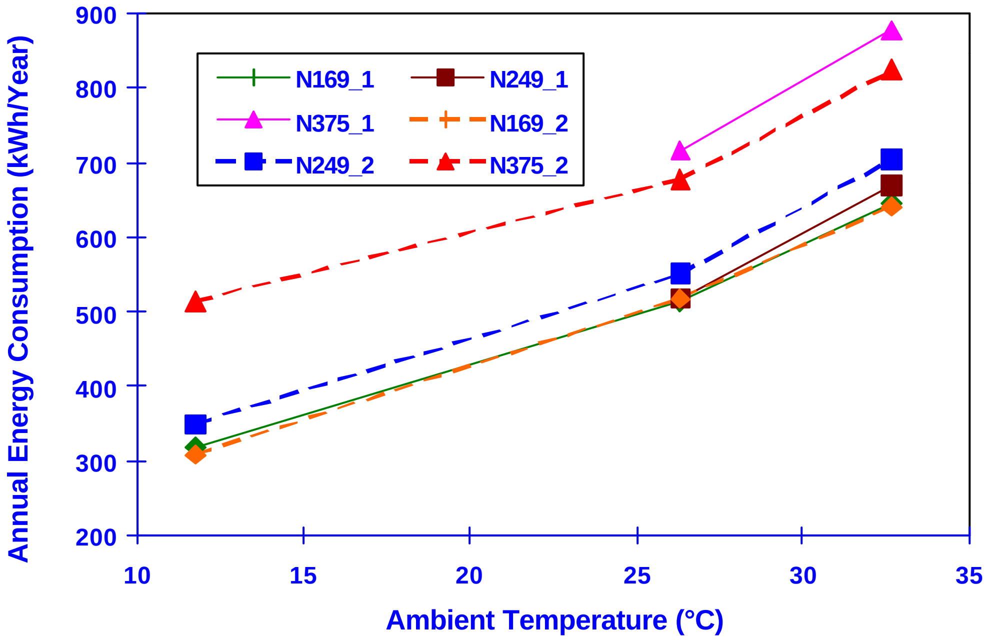

Figure 2: Annual energy consumption of different models of refrigerator-freezers with ambient air temperature - air relative humidity at 60% (after Bansal[13]).

5. DEVELOPMENT OF CONVERSION ALGORITHMS

5.1 Reasons for Developing Conversion Algorithms

5.1.1 Many countries require testing of a cabinet as per their standard and the energy consumption data to be shown on a label, attached to every cabinet on sale. However, there are so many different test standards currently operative around the world that it is impossible to know how a product (i.e. refrigerator, refrigerator-freezer or freezer) designed or optimised for a specific market (or, more precisely, for that market's standard) would perform in any other market (that uses a different test standard).

5.1.2 The development of conversion algorithms would be advantageous in a number of areas. These include-

(a) The ability to translate energy consumption of a cabinet from one test procedure to another, where the impact of usage, climatic, or local conditions is significantly different,

(b) Helping decrease repeated testing and approval costs to manufacturers,

(c) Providing good international comparison of product energy efficiency performance and their free movement in various economies,

(d) Facilitating free trade and availability of efficient appliances among various APEC economies,

(e) Helping the consumer to make cost effective decisions and enabling accurate forecasts of electricity demand.

5.1.3 There is, therefore, an urgent need to develop conversion algorithms that can be used to translate the energy consumption results of a cabinet from one test standard to another. These algorithms should be able to translate energy consumption under a range of ambient conditions (e.g. from 16°C to 32°C and relative humidities varying from the dry climate of Central Otago in New Zealand to the high humidity of Singapore).

5.2 Formulation of Conversion Algorithms

Energy consumption of a refrigerator is primarily a function of two factors, namely the cooling load on the cabinet and the efficiency of the cooling system. The cooling load on a cabinet occurs due to heat ingress (about 65%) through the cabinet walls, door seals and gaskets, followed by auxiliaries (about 20%). The secondary factors, however, include the door openings and food loading (about 15%); their proportional contribution to the cooling load increases with the increase in cabinet insulation.

5.3 Previous Research on Conversion Algorithms

5.3.1. There is very little information [9, 11, 18, 23-24] available on the topic in the literature. Bansal and Kruger[9] have compared the energy consumption of a refrigerator from one test standard to another using a simple conversion algorithm. They presented an analysis of test standards and performed tests on a number of cabinets (*all-refrigerators* and *refrigerator-freezers*) under the following test standards-

i) The International Standard (ISO),

ii) The Australian - New Zealand Standard (AS/NZS),

iii) The Japanese Industrial Standard (JIS) and

iv) The Korean Standard/Chinese Taipei National Standard (CNS).

v) The American National Standard (ANSI),

Their approach treated the energy consumption of a refrigerator as a function of the cooling system efficiency and the total cooling load on the system. The cooling load was considered to be proportional to the temperature difference between the ambient and the cabinet internal temperature. For cabinets having multiple compartments operating at different temperatures, the cooling load was treated as if it were proportional to the storage volume weighted internal/ambient temperature difference.

5.3.2. This simple model approximated the cooling system behaviour by an '*ideal*' reversed Carnot engine. This means that the coefficient of performance (COP) of the cooling system was considered to vary as a simple function of the evaporator and condenser temperatures. From laboratory measurements on a number of cabinets, various temperatures were chosen for the analysis. For example, the evaporator temperature T_{evap} was estimated to be 15°C lower than the design operating temperature of the compartment for all-refrigerators and 7ºC lower for the freezer compartments. The condenser temperature T_{cond} was taken to be 7ºC higher than the ambient temperature. However, sensitivity analysis revealed that by varying these temperatures within certain limits affected the overall result only marginally. The resulting formulation to predict the energy consumption of a cabinet from one procedure to the other may be written as–

$$E_A = \left(\frac{COP_B}{COP_A} \cdot \sqrt{\frac{\Delta T_A}{\Delta T_B}} \right) \cdot E_B \qquad (2)$$

where suffixes 'A' and 'B' represent any two procedures, E is the energy consumption, and ΔT is the temperature difference between the compartment and the ambient air. This correlation represented the experimental results reasonably well for most of the procedures except the JIS where the agreement was not that good, almost certainly because the effect of door openings was neglected.

5.4 Practicality of Conversion Algorithms

5.4.1. The energy consumption of a refrigerator is a function of a number of parameters. In order to develop an algorithm that could satisfactorily predict the energy consumption from one test standard to another, it is important that the influence of most of the other important parameters is considered in the formulation.

5.4.2. Parameters that affect energy performance include-

(a) Kitchen temperature (or ambient temperature),

(b) Compartment internal temperature,

(c) Refrigerant type and insulation efficiency,

(d) Adjusted volume and variation in insulation thickness on various compartments,

(e) Input voltage and frequency,

(f) Loading of Food Packages,

(g) Energy consumption measurement duration and procedure,

(h) Advanced features,

(i) Thermocouple locations,

(j) Door openings,

(k) Defrost mechanisms;

(l) Cooling load and cooling system efficiency.

5.4.3. Furthermore, the ambient and the compartment internal temperatures[18] are two semi-arbitrary aspects of current refrigerator energy test protocols that arguably drive the design of the product rather than respond to it. Both these factors influence the energy consumption of a refrigerator so much that the regional differences in their values make inter-regional comparisons of refrigerator energy performance very difficult.

5.4.4. Thus a refrigerator is a very dynamic thermodynamic appliance and its characteristics cannot be determined realistically from a single ambient temperature test. In effect, a single point does not define a line, let alone a curve.

5.4.5. A manufacturer, having knowledge about the coefficient of performance of the refrigerator cooling system, can use these data in conjunction with a test result to provide some idea of what performance would be like under other test conditions. However, the uncertainty and inaccuracy of this approach are such as to make it problematic whether the results would be acceptable to the energy efficiency regulators in importing economies.

6. MODELLING ALGORITHMS

In concept, a conversion algorithm takes the result of testing a cabinet to one standard and uses it to predict what the result would be if the same cabinet were tested to another standard. As an example, a first attempt for a conversion algorithm for a single compartment all-refrigerator might postulate that energy use is directly related to the temperature difference between ambient air and compartment internal temperature. This temperature difference is 25°C minus 5°C (= 20 K) for the ISO test, but 32°C minus 3°C (= 29 K) for the AS/NZS test. Therefore, a unit that uses 580 kWh per year when tested to the Australian/New Zealand Standard will use only 400 kWh per year (i.e. 580x20/29) if tested to the ISO test procedure. In practice, such a simple "conversion" algorithm ignores several significant factors and would be inaccurate.

In principle, a more complex algorithm may be devised to have a reasonable degree of accuracy. However, if a single test does not provide sufficient base data, it may be necessary to extend the test to include additional measurements. If these additional measurements become too great in number, or if an additional test point is required, then the conversion is no longer from one test standard to another, and the algorithm may more properly be described as a *modelling algorithm*.

A modelling algorithm can be used so that a unit could be tested only once (at a number of test points) and can then predict the behaviour under any set of conditions. Such a set of conditions could well be specified by a local mandatory standard or regulation. However, aligning some features of the existing standards could enhance the accuracy and applicability of the modelling algorithm.

6.1 The Concept of Modelling Algorithms

6.1.1. The results of a single test generally cannot be used to predict the results of testing at a different point or to a different procedure. However, a series of tests, possibly combined with measurements, can provide sufficient data to enable a mathematical model of the appliance to be constructed. A modelling algorithm is the set of formulae to which the test and measurement data are applied. If the figures that represent a set of operating conditions are fed into the algorithm, it produces a calculation of the associated energy performance.

6.1.2. The set of operating conditions could be the test conditions specified by an energy performance standard, or they could be a representation of in-service use. Several sets of operating conditions can be fed in to obtain an idea of how the appliance would perform under different seasonal conditions, in different locations, or when used in different ways.

6.1.3. Modelling algorithms are also more likely to be able to take account of the effects of new technology being incorporated into refrigerating appliances.

6.2 Advantages in Developing Modelling Algorithms

6.2.1. Currently the labelled energy consumption of a cabinet differs from the "in-field" data by typically 10%, 25% and 15% in Australia[19], New Zealand[21] and USA/Canada[22] respectively. The problem gets worse particularly when refrigerators are exported to other countries with entirely different climatic and 'usage' conditions. Therefore, the current procedures neither help the consumer to make concise cost effective decisions to purchase a product nor are they helpful in making accurate forecasts of electricity demand. There needs to be a certain mechanism in place for knowing a refrigerator's comparative performance under a range of conditions that could be determined with the use of algorithms.

6.2.2. The development of modelling algorithms would be advantageous in a number of areas, including-

(a) Enabling the performance of a cabinet to be predicted under various in-service conditions,

(b) The ability to predict the energy consumption of a cabinet under any given test procedure, where the impact of usage, climatic, or local conditions may be significantly different from the place of manufacture,

(c) Helping decrease repeated testing and approval costs to manufacturers,

(d) Providing good international comparison of product energy efficiency performance and their free movement in various economies,

(e) Facilitating free trade and the availability of efficient appliances among various APEC economies, and

(f) Helping the consumer to make cost effective decisions and enabling accurate forecasts of electricity demand.

However, some major development work backed up by comprehensive testing would be required to check the feasibility of this approach.

6.3 Issues Related to the Development of Modelling Algorithms

6.3.1. Harmonisation between regions would require reform of the testing protocols that have a strong influence on the refrigerator specifications. Apart from the cooling load on a cabinet and the efficiency of the cooling system, the energy consumption of a refrigerator is a function of a number of parameters. In order to develop an algorithm that could satisfactorily predict the energy consumption under a given set of conditions, it is important that the influence of most of the other important parameters is considered in the formulation. Substantial research and development efforts are required to develop such algorithms for energy conversion.

6.3.2. Energy Consumption of a cabinet is a function of many parameters, including the following-

(a) Kitchen temperature (or ambient temperature),

(b) Compartment internal temperature,

(c) Refrigerant type and insulation efficiency,
(d) Adjusted volume and variation in insulation thickness on various compartments,
(e) Input voltage and frequency,
(f) Loading of Food Packages,
(g) Energy consumption measurement duration and procedure,
(h) Advanced features,
(i) Thermocouple locations,
(j) Door openings,
(k) Defrost mechanisms;
(l) Cooling load and cooling system efficiency.

6.4 Effect of Different Parameters on Modelling Algorithms

The ambient and the compartment internal temperatures[18] are two semi-arbitrary aspects of current refrigerator energy test protocols that arguably drive the design of the product rather than respond to it. These factors, and others that determine energy performance are considered below.

6.4.1. **Ambient temperatures:** It has long been recognized that the average yearly kitchen temperatures are far lower than 25°C (ISO) or 32.2°C (ANSI) and the use of these inflated ambient temperatures always result in an overestimate of the refrigerator energy consumption compared to in-situ consumption. In the USA, the overestimate is sufficiently high for freezers (which are better insulated and are opened less frequently than other refrigerators) that DOE multiplies the measured energy consumption as per ANSI test conditions by 0.7 (for chest freezers) and 0.85 (for upright freezers) to be more representative of the *in situ* energy consumption.

Considering the example of Australia, it does not make sense to use a single ambient temperature to identify the diverse ambient conditions of two entirely different geographic locations such as Darwin and Hobart. The same arguments may apply to many countries including USA and Russia.

A refrigerator is a very dynamic thermodynamic appliance and its characteristics cannot be determined realistically from a single ambient temperature test. The refrigerator performance changes significantly with ambient temperature (see Figure 1 and 2).

➡ Therefore, for all these reasons, it is reasonable to use two or more ambient temperatures to define the slope of the energy consumption for different climates (representing sub-regions) and user behaviours. This would eliminate the re-testing of a cabinet when it is exported from one economy to another and within one economy to represent the actual energy consumption of the cabinet in a particular in-situ situation.

6.4.2. **Compartment Internal Temperature:** With regard to the choice of compartment temperatures, it is not clear why some of the regional differences exit in terms of food (3 or

5°C) or the freezer (-15 or -18°C) compartment temperatures. According to a hypothesis[18], ISO protocol arbitrarily chose 0°F (or –17.8°C) as the end point. From food preservation and safety perspective, there is no growth of non-hazardous food spoilage organisms below –12.2°C, while at a higher temperature the growth of hazardous organisms is retarded. Enzymes can continue to spoil the food at very low temperatures but the spoilage rate is reduced at colder temperatures.

➡ Therefore, there seems to be urgency to resolve the issues related to commonly acceptable dual test ambient as well as compartment temperatures. A temperature of 3°C and -18°C respectively for the food and the freezer compartments could be consistently applied for uniformity among all test procedures.

➡ This will enable the manufacturers to design their products with improved energy efficiency and to facilitate trade among different APEC economies. Due to the existing differences in test procedures among different economies, testing of a cabinet at multiple ambient temperatures would be desirable to establish a reliable computer simulation package for the modelling of energy consumption results for any test or usage conditions.

6.4.3. **Alternative Refrigerants:** It is claimed that hydrocarbon refrigerants (i.e. Iso-butane) are not necessarily better than HFC-134a at low evaporating temperatures but are considered being better at high evaporating temperatures. This means that a cabinet (using iso-butane as the refrigerant) may consistently perform better in ISO than AS/NZS or ANSI due to less heat load on the cabinet and therefore, high evaporating temperature in the cabinet.

➡ This means that the energy consumption is specific to the refrigerant used and algorithms would need to be adjusted to model energy consumption for different refrigerants.

6.4.4. **Adjusted Volume and Variation in Insulation Thickness on Various Compartments:** A refrigerator may have multiple compartments, operating at different temperatures. Assuming these compartments have similar insulation quality, their temperature variation can be compensated by defining a term ‘adjusted volume’ as-

$$V_{adj} = \sum_{i=1}^{n} V_{c,i} . \Phi_{c,i} \qquad (3)$$

where $$\Phi_{c,i} = \left[\frac{T_a - T_c}{T_a - T_f} \right] \qquad (4)$$

T_a is the ambient temperature, T_c is the compartment design temperature, T_f is the fresh food compartment temperature, n is the number of compartments with different operating temperatures in the appliance and $V_{c,i}$ is the storage volume of compartment i. For the fresh food compartment, $T_c = T_f$ and therefore, the factor Φ is unity.

However, since most standards have different requirements for ambient and the compartment temperatures and the insulation thickness is always more on the freezer walls than the food compartment walls, the heat flow into the cabinet varies according to the temperature difference across a refrigerator wall.

➡ The cooling load on the cabinet needs to be properly evaluated by adjusting the storage volumes of the compartments in view of multiple existing temperature differences and corresponding insulation thickness.

6.4.5. **Input Voltage and Frequency:** The data (Bansal[25]) for the same series compressors operating between 115V/60Hz and 220V/50Hz or 240V/50Hz suggest that compressors with 220 or 240 V tend to be about 3% more efficient than 115V/60Hz. However, the improvement disappears at higher capacities. Compressors that are optimised at 240V/50 Hz may result in an improvement of about 3% and 5% respectively when operated at 230V/50Hz or 220V/50Hz respectively. However, a refrigerator can consume up to 5% less energy when tested from 240V/50Hz to a lower voltage 230V/50Hz – this includes the overall effect of the compressor and all auxiliaries. This is primarily caused by the relative balance of iron losses to copper losses in high voltage and low voltage compressor motors. Most of the economies are likely to have either 115V/60 Hz (e.g. USA, Japan) or 230V/50Hz (e.g. Australia, Europe, New Zealand); it is reasonable to expect the future compressors to be optimised for 230V/50Hz rather than 240V/50Hz.

➡ The inclusion of voltage and frequency variation factors between various economies in developing modelling algorithms would be advantageous.

6.4.6. **Loading of Food Packages in the Freezer Compartment:** That loading of food packages in the freezer compartment of a refrigerator-freezer or a freezer is required in some of the test standards has been discussed in depth earlier. During the defrost cycle, the packages cause thermal inequilibrium in the compartment, resulting in stability and repeatability problems. In some cases (e.g. ISO), the average temperature in the freezer compartment is much colder than the specified -18°C.

➡ For consistency in different test standards, loading of test packages in the freezer compartments should be discontinued. If not, it would be desirable to collect additional data so that the impact of test packages on the energy consumption could be separately quantified by testing the cabinets with and without test packages. This information can then be helpful in developing modelling algorithms.

6.4.7. **Energy Consumption Duration and Procedure:** It may be seen from Tables A and B (in the Appendix) that both the energy measurement period (between 3 hours and 24 hours) and the procedure to measure energy consumption vary from one standard to another. This requires setting up of specific control strategies for each standard for automatic measurement of energy consumption during the experiments. However, it is quite complicated to address the effect due to this parameter in a simple mathematical model.

➡ It may be difficult to include the effect of this parameter directly in the development of modelling algorithms; however, its overall effect will show indirectly in the development of algorithms.

6.4.8. **Advanced Features:** It has been experienced that refrigerators perform quite differently depending upon their advanced features. For example,

(a) Number of evaporators,
(b) Number and type of compressors,
(c) Multiple compartments,
(d) Specific purpose compartments (e.g. a special compartment in some Japanese refrigerators to keep sushi),
(e) Ice maker, and
(f) New technology (e.g. microprocessors, vacuum insulation panels, variable speed drives).

Although these features are quite user friendly and satisfy the requirements of specific markets, their effect can influence the energy consumption substantially.

➡ It is difficult to incorporate the individual effect of these parameters in the measurement of energy consumption from one test standard to another. Therefore, considerable efforts would be required to design a scheme to incorporate their effect in the modelling algorithms.

6.4.9. **Temperature Sensor Locations:** Each standard specifies different locations[19] for the placement of sensors to measure temperatures. For example, for a freezer compartment, ANSI specify 3 locations on the centreline of the compartment (front/bottom, centroid, back/top) while AS/NZS specifies 5 positions (centroid, top left of front and back and bottom right of front and back) and uses the warmest 4 to determine freezer compartment temperature. The two standards have only one common position at the centroid. These effects lead to measurements of different temperatures and hence energy consumption. Moreover the difference between the values predicted by the different measurement points is inherently unknown. This prevents accurate modelling, and so alignment of this detail is particularly important.

➡ The test standards should harmonise these issues and should have common temperature measurements so that their effect on the modelling algorithms is minimal.

6.4.10. **Door Openings:** It has already been stated that door openings create instability in the operation of a refrigerator and the process becomes unrepeatable and unreproducible. The energy consumption of a refrigerator-freezer increases by up to 17% (Bansal[13]) with door openings.

➡ Bansal and Kruger[9] highlighted 'door openings' as the main factor for the disagreements between different standards while applying correlation (2) above for the energy conversion of energy consumption from one test standard to another. Either the effect of door openings should be included in the harmonised test standard by introducing water vapour into the cabinet or its effect should be carefully incorporated in the modelling algorithms.

6.4.11. **Defrost Mechanisms:** Most standards specify the energy consumption measurement during a test from defrost to defrost. However, many modern refrigerators are using ‘adaptive defrost’ mechanism and its usage at times delays the second defrost beyond the maximum measurement duration of the test. These variations could yield different results. This problem could be overcome by the introduction of water vapour into the compartment as proposed above.

- ➡ Although it may not be easy to incorporate the effect of adaptive or other defrost mechanisms in the algorithms, an approach to address their effect on energy consumption algorithms needs careful investigation.

6.4.12. **Cooling Load and System Efficiency:** All the above factors contribute to the overall cooling load on a refrigeration appliance. The efficiency of each of the service components (e.g. fans, compressor(s), heat exchangers, capillary tubes) in the appliance to remove this load from the cabinet determines the overall system efficiency. The component efficiencies are steadily improving and refrigerators are becoming more energy efficient. A simple form of the ideal reversed Carnot cycle principle can be applied to define this efficiency of the system (see Equation 3).

- ➡ With the exception of input voltage and frequency, there are no overriding technical reasons why all other factors should not be harmonised for all energy testing protocols. Developing an algorithm that could include the effect of all these factors and could universally be applied to the test standards in most APEC economies will be a daunting task. However, their normalized effect may be incorporated in an algorithm that could be applicable on a few standards or their variations.

7. A GENERIC APPROACH TO MODEL ENERGY CONSUMPTION[20]

7.1 Need of Modelling Algorithms: In ANSI or AS/NZS, high ambient temperatures are used to crudely compensate for the door opening heat loads. This compensation becomes less realistic as cabinet insulation is improved. Therefore, well-insulated cabinets that perform well in ANSI or AS/NZS would be less impressive in JIS (Method A) or “real” world door opening schemes. ISO is seen to underestimate the "real" world energy consumption of a refrigerator. It is also well known that tests with door openings have poor repeatability and are expensive. Moreover, it has been widely observed by the industry that major heat load on a cabinet is introduced due to the loading of warm food in the “real use” conditions rather than warm air due to door openings (which has low thermal mass). Therefore, current test procedures fail in accurately predicting the actual in-use energy consumption of a refrigerator. There is, therefore, a need for the modification of the test procedures.

7.2 Physics and Theory of Modelling Algorithms: Current test procedures need to be extended to ensure that some modelling of actual user behaviour and refrigerator/freezer performance has been exercised. This includes the impact of ambient temperature, the introduction of warm foods into the refrigerator compartment, the impact of door openings, and the introduction of humidity into the refrigerator compartments. Considering all these issues, the total energy consumption of a refrigerator (E, in kWh/year) can be defined [Bansal[20]] as the summation of the following four terms-

$$E = E_{ambient} + E_{processing} + E_{defrost} + E_{other} \qquad (5)$$

where the terms $E_{ambient}$, $E_{processing}$, $E_{defrost}$ and E_{other} respectively represent the energy consumption due to the heat loads of the ambient air (on a cabinet with doors closed), the air-infiltration and loading of warm food load into the cabinet (representing door openings), the defrost heater and other accessories such as condensation heaters (or anti-sweat heaters), lights, fans etc. Note that some of these terms may be incremental.

One way of achieving the best of both worlds is to perform a closed-door test at (say) 20°C (or different ambient) without any door openings or loading of ‘test packages’ in any of the compartments. However, an electrical heating load (say 10 or 20W or some value that is a function of compartment volume) may be placed inside the fresh food compartment of a refrigerator (or inside both the compartments of a refrigerator-freezer) to emulate the processing load due to door opening and/or introduced warm food. The compartment temperature should be maintained as per the specific test standard (e.g. 3°C for fresh food and -15°C for the freezer compartment as per AS/NZS). In the simplest form, the electrical load will be steady but better results may be obtained with a regime that varies with time. The refrigerator could undergo static tests (testing at specific ambient temperatures) with and without internal heat loads. These test points will provide data on the refrigerator's ability to remove introduced heat from the cabinet under a range of heat load conditions. Similarly, a controlled method of introducing relative humidity into the compartments could be developed to enable the defrost energy performance to be developed. One way of achieving this could be by introducing water vapour into the cabinet by heating water in an electric pan in the cabinet. These additional tests, combined with test measurements at two or more ambient temperatures, would yield data that could be explored to simulate refrigerator energy performance under a range of ambient and usage conditions.

Specific performance curves can be generated (similar to Figure 1 and 2) for each model by each manufacturer but for different product categories. This will enable the performance of a cabinet under a range of operating conditions, including different ambient temperatures and usage conditions.

From Figure 1 and 2, it is possible to deduce the closed-door energy consumption of a cabinet at typical kitchen temperature of about 20°C. From field surveys, it is possible to deduce the total energy consumption of an equivalent refrigerator in normal use in a kitchen. The difference between these two figures can be used to establish wattage required for processing load inside the refrigerators (and freezers).

This scheme would result in a simple, repeatable, reproducible and a harmonised test procedure that could be accepted internationally for the measurement of energy consumption of a refrigerator. The proposed scheme would be additionally advantageous, as it will enable the determination of energy consumption of a refrigerator under any set of conditions.

7.3 Approach for Developing Modelling Algorithms

The approach in developing the modelling algorithms may require a physical description of a refrigerator (i.e. dimensions, advanced features, performance attributes) together with some physical test data of the energy consumption of the cabinet under two or more sets of test conditions in question to calibrate the model. Such a model may need to be extended to model energy under a range of realistic usage conditions (e.g. ambient temperatures varying between 16°C and 32°C, and relative humidity between 50% and 90%). Introducing calibrated internal heat loads and defrost performance via the controlled introduction of relative humidity could include simulation of door openings.

The modelling process will require additional research using dual protocol testing of models from both markets under consideration. Some comprehensive testing would be necessary to check the validity of such an approach. These experiments may be quite extensive and may include the following aspects-

(a) Testing of various cabinet types (e.g. All-refrigerators, refrigerator-freezers or freezers) under the two protocols,
(b) Testing of all cabinet types from each product category,
(c) Testing of cabinets from various manufacturers and from different APEC economies with varying degrees of features, including specific usage conditions. This unified approach may eliminate the bias of the algorithm toward a specific manufacturer or climatic condition,
(d) Quantifying the effect of individual parameters (as illustrated in section 7.4 above) on the energy consumption,
(e) Developing specific conversion algorithms between any two standards, following initially the approach adopted by Bansal and Kruger[9],
(f) Improving the approach by Bansal and Kruger[9] by incorporating the effect of other important variables such as a load equivalent to door openings, range of ambient and usage conditions, advanced features etc.,
(g) Advancing the modelling approach to a general approach which could be applied to any test standard and any type of refrigerator, and
(h) Quantifying the uncertainties involved in the modelling approach.

This empirical data should be used to develop, calibrate and verify a general simulation model of refrigerator energy performance. This model can then be used conduct a wide ranging factor analysis producing protocol conversion formulae applicable to both current and future designs.

7.4 Caution With the Experimental Approach

Collecting and generating experimental data (e.g. different parameters, product categories, product types) from various manufacturers and economies will be a challenging but mammoth task. This type of research may be expensive (of the order of US$1 million) to conduct properly but should result in reliable software suitable for general conversion of results between testing protocols using basic refrigerator design specifications as the input. However, the scope of the project may be reduced at the cost of some accuracy to the modelling algorithms.

8. RESEARCH AND DEVELOPMENT REQUIRED TO FACILITATE THE ABOVE ISSUES

In order to address the above issues and achieve the desired objectives, concerted efforts are required to carry out necessary 'research and development' work. Amongst other things[17], these include the following:

(a) Future test procedures should capture both the 'hardware' and 'software' developments. In particular, they should include cost effective methods to measure the in-use impact of increasingly sophisticated "smart" refrigerator-freezer systems that would encourage further technological developments,

(b) There may be merit in devising a test with testing at dual ambient temperatures, although it may exhibit non-linear energy consumption outside the 20-30°C temperature domain,

(c) There is a room for greater alignment in the definition of a range of measurement issues, such as food packs and internal compartment temperatures,

(d) Current test methods should be modified to reflect the actual user behaviour such as the impact of ambient temperature, the introduction of warm food loads into the compartment, the impact of door openings and the introduction of humidity into the compartments. A generic approach of closed-door tests with additional heat loads (as suggested in this report) may be used as a guideline to address this issue, and

(e) There is an urgent need to develop modelling algorithms (with additional tests being performed on a variety of refrigerator-freezer cabinets and model types) to obtain the results of energy consumptions under different test conditions in various economies for consistent comparisons. Such algorithms will facilitate international 'free trade', decrease testing and approval costs to the manufacturers and promote diffusion of advanced energy saving technologies.

9. CONCLUSIONS AND RECOMMENDATIONS

This report presented a comprehensive research study on the comparison of various test standards in APEC economies on refrigerator-freezers. Most of the current procedures use closed door tests for reasons of repeatability but have highly inflated ambient air temperatures to compensate for lack of door openings. However, these procedures yield up to 25% more energy consumption than the real world in-field end use data.

There is an urgent need for considerable 'research and development' work to develop new test procedures that can capture both the 'software' and 'hardware' advancements in refrigerator technology. A generic approach has been proposed in the report to modify the current test procedures to enable some modelling of the actual user behaviour and refrigerator/freezer performance. The modelling parameters in this approach include the impact of ambient temperature, the introduction of warm food loads into the cabinet, the impact of door opening, and the introduction of humidity into the refrigerator compartments. This approach may be used as a guideline to develop future energy performance procedures for refrigerators/freezers.

Simple conversion algorithms are not possible, as a single test point provides insufficient data to be able to predict behaviour under any different set of test conditions.

Therefore modelling algorithms are needed to translate the energy consumption results of a cabinet from one test procedure to the other to facilitate 'free international trade' and avoid 'time consuming and costly' testing to the manufacturer. Such modelling algorithms will also provide a much better prediction of in-use energy consumption and performance. These algorithms need to meet the following objectives-

(a) Model the energy consumption under a range of ambient conditions (e.g. ambient temperatures varying between 16°C and 32°C, and relative humidity between 50% and 90%). This may require closed door testing of cabinets (with controlled addition of heat load and moisture in the cabinet) for two or more ambient temperatures,

(b) Help in translating the energy consumption displayed on ‘energy labels’ from one test standard to another,

(c) Enable in energy forecasting to policy makers, and

(d) Identifying the most energy efficient product in the market.

A number of differences in test procedure need to be aligned before a fully applicable modelling algorithm can be developed.

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Table A: General testing requirements for various test standards (Bansal and Kruger, 1995)

Cabinet Type or Parameters	Requirement	AS/NZS	ISO	ANSI[1]	JIS C[2]	CNS/KS	GOST
Testing	Ambient (T_A)	32±0.5 °C	25/32±0.5 °C	32.2±0.6 °C	25±1 °C	30 ±1 °C	25/32±0.5 °C
Parameters ➔	Relative Humidity	-	45 -75 %	-	75±5%	75±5%	-
All-Refrigerator	Fresh Food	3 ±0.5 °C	5°C	3.3 °C	3 ±0.5 °C	3 ±0.5 °C	5°C
Refrigerator - Freezers[3]	Fresh-Food	3 ±0.5 °C	5°C	7.2 °C	3 ±0.5 °C	-	5°C
	Freezer ✱	-9 ±0.5 °C	-6°C	-9.4 °C	-6 ±0.5 °C	-	-6°C
	Freezer ✱✱	-15±0.5 °C	-12 °C	-15 °C	-12 ±0.5 °C	-12/-15±0.5°C	-12°C
	Freezer ✱✱✱	-	-18 °C	-	-18 ±0.5 °C	-18 ±0.5 °C	-18°C
Separate Freezers	Freezer	-15±0.5 °C	-18 °C	-17.8 °C	-18 ±0.5 °C	-18 ±0.5 °C	-18°C
Freezer Compartment	Loading of Test Packages	Unloaded	Loaded[4]	Sometimes[5]	Sometimes[5]	Unloaded	?
All Compartments	Door Openings	No	No	No	Yes	No	?
All Compartments	Anti-sweat heaters	Always on	When needed	Average on and off	Always on	Always on	?
All Compartments	Volume for labels/MEPS[6]	Gross	Storage (for EU)	Storage	Storage	Storage	?
Energy Measurement Period		Lesser of 1 kWh or 16h operation[7]	≥ 24 h	3h< t <24h 2 or more cycles	= 24 h of testing	= 24 h of testing	?

[1] Mexico and Canadian requirements are equivalent to US DOE/AHAM.

[2] JIS C means Method C of JIS. Earlier in Method A, 73% of the consumption was weighted at an ambient of 15°C and 27% at 30°C.

[3] As per ISO- one, two and three star (✱,✱✱,✱✱✱) compartments are defined by their respective storage temperature being not higher than –6°C, -12°C and -18°C.

[4] The freezer temperature is defined by the warmest test package temperature that must be lower than – 18 °C.

[5] The freezer temperature is taken to be the air temperature (contrary to ISO). Freezer compartments that are frost free (forced air) are generally unloaded. However, separate freezers in ANSI are always loaded (to 75% of the available space) irrespective of defrost type.

[6] Minimum Energy Performance Standards

[7] Note that for cyclic products, the test period consists of a whole number of compressor cycles. For frost free models, the test period consists of a whole number of defrost cycles.

Table B: Energy Consumption Testing Requirements for Household Refrigerators

	AS/NZS	ISO	ANSI/AHAM	JIS (Method A)	CNS/KS
Installation of the refrigerator	such that any shielding on either side of the cabinet is 300 ±10 mm	on a wooden platform and next to a rear wall at the minimum allowable distance	such that the distance from the wall is ≥ 254mm	--	see manual
Stable Operating Conditions	$\Delta T_{FF} \leq 0.5°C/6h$ $\Delta T_{FR} \leq 0.5°C/6h$ Over more than two cycles	$\Delta T_{FF} \leq 0.5°C/24h$ $\Delta T_{FR} \leq 0.5°C/24h$	$\Delta T_{FF} \leq 0.023°C/h$ $\Delta T_{FR} \leq 0.023°C/h$	-	$\Delta T_{FF} \leq 1°C/24h$ $\Delta T_{FR} \leq 1.25°C/24h$
Humidity	Needs not to be controlled	45 % - 75 %	Needs not to be controlled	75 % ±5%	75 % ±5%
Ambient Temperature					
• **Maximum Vertical Temperature Gradient**	1°C/m from floor to 2m height	2°C/m from platform to 2m height	0.9°C/m from 51mm above the floor	3°C from 50mm above the floor to 2m height	3°C from 50mm above the floor to 2m height
• **Number of M$^{\$}$-Points**	1	3	2	1	1
• **Location of M-Points**	between 250mm and 350mm from the front mid-height position	350mm from the side/front walls	915mm above the floor and 254mm from the centre of the two sides	either side of refrigerator to get a mean value	see manual [12]
• **Calculation**	$T_A = \overline{T}(\overline{T}_{A1})^{\#}$	$T_A = \overline{T}(\overline{T}_{A1}, \overline{T}_{A2}, \overline{T}_{A3})^{\#}$	$T_A = \overline{T}(\overline{T}_{A1}, \overline{T}_{A2})^{\#}$	$T_A = \frac{1}{2}(T_{A\max} + T_{A\min})$	$T_A = \frac{1}{2}(T_{A\max} + T_{A\min})$
Fresh Food Compartment					
• **Number of M-points**	3	3	3	3	1
• **Compartment Temperature**	$T_{FF} = \overline{T}(\overline{T}_{FF1}, \overline{T}_{FF2}, \overline{T}_{FF3})$ ie. mean of the average of all measured temperatures at that point	$T_{FF} = \overline{T}(T_{FF1}, T_{FF2}, T_{FF3})$ with $T_{FF\,i} = \frac{1}{2}(T_{FF\,i\max} + T_{FF\,i\min})$ where i = 1, 2, 3	$T_{FF} = \overline{T}(\overline{T}_{FF1}, \overline{T}_{FF2}, \overline{T}_{FF3})$	$T_{FF} = \overline{T}(T_{FF1}, T_{FF2}, T_{FF3})$ with $T_{FF\,i} = \frac{1}{2}(T_{FF\,i\max} + T_{FF\,i\min})$ where i = 1, 2, 3	$T_{FF} = \frac{1}{2}(T_{FF\max} + T_{FF\min})$ ie. mean of the highest and the lowest recorded temperature
Freezer Compartment					
• **Test Load**	no	yes (100 %)	yes (75 %); no load in automatic defrost models	no	no

Table B contd.....

• **Number of M-Points**	5	4 - 6	3 - 12	1	1
• **Size of M-Packs**	-	50 × 100 × 100 mm	40 × 100 × 130 mm	-	-
• **Compartment Temperature**	$T_{FR} = \overline{T}(\overline{T}_{FRi})$, i = 1-5 without the coldest sensor ie. mean of all recorded temperatures	$T_{FR} = T_{FR\ max}$ ie. maximum temperature of the warmest M -package	$T_{Fr} = \overline{T}(\overline{T}_{Fri})$ mean of all the recorded temperatures	$T_{Fr} = \frac{1}{2}(T_{Fr\ max} + T_{Fr\ min})$ ie. mean of the highest and the lowest measured value	$T_{Fr} = \frac{1}{2}(T_{Fr\ max} + T_{Fr\ min})$ mean of the highest and the lowest measured value
Operation of Automatic Defrost	yes	yes	yes (manual defrost also)	yes (not manual defrost)	yes (not manual defrost)
Door Openings	-	-	-	during first 10 hours of test: a) FF every 12Min for 10s b) FR every 40min for 10s ** freezer door shall not be opened when it is inside the cabinet	-
Temperature Readings	at least every 30 Min for at least 3 hours		at least every 4 Min		
Test Period					
• **General**	≥ 16 h but only until 1 kWh of energy is consumed	≥ 24 h	≥ 3 h and ≤ 24 h; so that compressor completes two or more whole cycles	= 24 h	= 24 h
• **With Automatic Defrost**	from a point in one defrost cycle to a corresponding point in another cycle	complete defrost cycles (if no defrost cycle starts during 24 h, the test period shall be 48 h)	from one point during a defrost period to the same point during the next defrost period	a) if defrosting once a day, start after 14h after commencement of test b) others shall start after 5h	a) if defrosting once a day, it shall start after 14 h after commencement of the test b) others shall start after 5 h
• **Without Automatic Defrost**	between two compressor switch off cycles	whole number of control cycles	whole number of control cycles		

$ "M" stands for Measurement.

Mean of the average of all recorded temperatures.

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