Energy Consumption Measurements using AHAM HRF-1 and ISO 8561

David A. Yashar
National Institute of Standards and Technology
100 Bureau Drive, MS 8631

Gaithersburg, MD 20899-8631
USA

Telephone: 301-975-5868
Fax: 301-975-8973
E-Mail: dyashar@nist.gov

This investigation compares the energy consumption ratings obtained for refrigerators using the Association of Home Appliance Manufacturers (AHAM) HRF-1 test procedure, as adopted by the United States Department of Energy (DOE), and the International Organization for Standardization (ISO) equivalent test procedure, ISO 8561. Tests were performed on three different units according to both test procedures. These units included two household kitchen-type, automatic defrost refrigerator-freezers, one of each body style that is prevalent in the US (one with a top mounted freezer compartment and the other unit with the refrigerator and freezer compartments in a side-by-side configuration). An automatic defrost refrigerator which employs many novel energy saving devices and techniques was also tested. The results showed that the energy consumption ratings found for these refrigerators under the DOE tests were 25.0 % to 29.4 % higher than the results obtained with the ISO tests. The results were then compared to the findings of a previous study conducted at the University of Auckland.

As appliance manufacturers expand their businesses into a global market, it becomes more desirable to develop an international test procedure for the rating of their products. An international test procedure would allow manufacturers to reduce their use of valuable resources required to perform different tests for each appliance. Although the intent of each test procedure is the same for a given product, the differing needs and preferences have resulted in differences in the test procedures.

This study is concerned with the energy rating procedures for refrigerators. It is of particular interest to examine the energy performance ratings obtained for refrigerators when tested by the procedures accepted by the United States Department of Energy (DOE) and by the International Organization for Standardization (ISO). It is expected that these test procedures will produce very different results, due to the differences between the procedures. Namely, the main differences are as follows.

1) <u>Ambient temperature</u>. The ambient test conditions stipulated by the DOE procedure are much warmer than those required for the ISO test procedures. This is the most significant difference between the test procedures and will often result in higher measured energy consumption for the DOE test procedure.
2) <u>Freezer loading</u>. There are also differences in the loading of these units. For automatic defrost refrigerator-freezers, the freezer compartment is filled with loading packages for the ISO test procedure and is empty for the DOE test procedure.
3) <u>Target temperatures</u>. All energy consumption tests require that a certain temperature is held within the unit over a measurement period. Each test procedure outlines the required target temperatures according to the standards' classification of the

unit. Unfortunately, there are also differences regarding the classification of refrigerators, which sometimes make direct comparison of the performance rather difficult.

4) Temperature Measurements. The last major difference is the manner that the temperatures are recorded. The DOE test bases the results on the average of the measured temperatures in the compartment, whereas the ISO test procedures prefer to base the results on the maximum compartment temperature.

A study was conducted at the University of Auckland by Bansal and Krüger (1995), which compared the energy consumption of four different refrigerators as tested by five separate test procedures. Each of the units in their study used the phased out refrigerant CFC-12; however, their study offers the best basis of comparison to the current study. The results of their study showed that they were able to correlate, reasonably well, the energy consumption of a refrigerator as tested by different procedures. They accomplished this by curve fitting the data from their study as a function of two parameters. The first parameter was a theoretical Carnot Coefficient of Performance (COP) for each test procedure based on information from the temperatures outlined in the various procedures. The second parameter was a temperature difference parameter, based on the internal and external temperatures required by each test procedure. They then used these parameters to formulate multipliers that convert one test result to another.

The COP is defined as the ratio of the cooling power to the amount of work input to the compressor. It is equal to the ratio of the evaporating temperature of the refrigerant to the temperature difference between the condensing and evaporating temperatures, in absolute temperatures.

$$\mathrm{COP} = \frac{T_{evap}}{T_{cond} - T_{evap}}$$

Since the evaporating and condensing temperatures are unknown, Bansal and Krüger assumed a constant temperature difference between the evaporating temperature and the coldest compartment temperature, ΔT_{evap}, and also a constant temperature difference between the condensing temperature and the ambient temperature, ΔT_{cond}. This allowed them to estimate the COP as follows:

$$\mathrm{COP} = \frac{T_F - \Delta T_{evap}}{\left(T_{ambient} + \Delta T_{cond}\right) - \left(T_F - \Delta T_{evap}\right)}$$

For their study, they used values of 7 °C for ΔT_{cond} and ΔT_{evap}. Although these temperature differences may seem large, these values were selected because the units tested in their study do not employ forced convection to drive this heat transfer.

They also assigned a temperature difference parameter, ΔT, to each unit under a given standard; where this parameter is the difference between the ambient temperature and the compartment air. The curve that best fit their data was of the form:

$$W_A = \left(\frac{COP_B}{COP_A} \sqrt{\frac{\Delta T_A}{\Delta T_B}} \right) W_B$$

The subscripts A and B denote specific test procedures and the variable W denotes the energy consumption value.

Although the units used in the study at the University of Auckland are somewhat different from those used in this report, the principles applied to derive the parameters in their correlation are general to any vapor compression cycle. These parameters are inherent to the basic thermodynamic principles used in a refrigerator, and they provide a useful tool for comparison between different operating conditions. Therefore, this correlation was used as a basis for comparison to the data presented in this report.

The following sections present the experimental apparatus, the units tested, the experimental procedures, and the results of the energy consumption tests as measured in accordance with the procedures outlined by the DOE and the ISO.

EXPERIMENTAL SETUP

Two identical test cells were constructed in the laboratory in order to simultaneously measure the energy consumption of two refrigerators. Each test cell consisted of a non-thermally conductive platform upon which the refrigerator stood, a wall that stands adjacent to the rear of the refrigerator, and two sidewalls that partially enclosed the sides of the refrigerator. All faces of the test cells were painted dull black to minimize the radiant heat to and from the refrigerator during testing. Although similar, the dimensions of the test cell varied according to the test performed and the refrigerator being tested; therefore the cells were constructed so that the walls could be easily moved between tests.

The test cells were placed in an environmental chamber, which was large enough to house two test cells and all of the necessary data acquisition hardware. This environmental chamber is capable of providing fixed ambient conditions over long periods of time with little supervision, as was necessary due to the lengthy test periods associated with these standards.

Temperature data were gathered using a personal computer and a multiplexed data acquisition unit. Depending on the test type and the refrigerator, between 12 and 17 temperature locations per test cell were monitored using T-type thermocouples.

The electrical energy input was monitored using a separate personal computer dedicated to a digital power meter. All temperatures were sampled once every 30 s, and the power was sampled once per second. Table 1 lists the measured quantities and the uncertainty associated with 95 % confidence.

Table 1 Measurement Uncertainty

Measured Quantity	**Measurement Device**	**Uncertainty at 95 % confidence**
Temperature	Thermocouple	± 0.3 °C
Humidity	Chilled mirror hygrometer	± 2 °C dew point
Power	Watt-meter	± 0.3 %
Time	Personal Computer	± 1 s/d

UNITS TESTED

Three refrigerators were selected for participation in this study. All of these units are automatic defrost, "Refrigerator-Freezers" as classified by the US DOE classification system. Two of these refrigerators were domestically manufactured, the third unit selected for this study was purchased overseas, as it's unique, energy saving technologies and algorithms were of interest to this study. All refrigerators tested in this study used HFC-134a refrigerant.

The first refrigerator examined in this study is a side-by-side refrigerator-freezer. This refrigerator follows a periodic automatic defrost sequence to remove ice from its evaporator. It is equipped with an automatic icemaker and a through-the-door ice and water dispenser. This model was manufactured in the United States, for the intended sale in the United States.

The second refrigerator examined in this study is a top-mounted refrigerator-freezer. This model also follows a periodic automatic defrost sequence, and has an automatic icemaker. It was also manufactured in the United States, for the intended sale in the United States.

The third refrigerator examined in this study is a top-mounted, automatic defrost refrigerator-freezer. This unit was purchased from a manufacturer in New Zealand and shipped to the US, as its unique features are intriguing to this study. This model is typically manufactured for Asian and south pacific markets; therefore, it was specially built for this study with a compressor motor that operates on 115 V, 60 Hz electricity. There are three main features that are employed in this unit to allow more efficient use of its energy. These include:

A) <u>Intelligent Defrost Sequence</u>. For a typical defrost cycle, some measurement is taken and is used to trigger a sequence of events (this can include a number of devices used to measure the amount of frost that has accumulated on the evaporator or the amount of time that the compressor has operated). This event that triggers a defrost cycle usually occurs during a period of operation of the compressor. When the triggering mechanism is activated, the compressor is turned off and a heater is turned on. When the heater has completed its task, it is turned off and after a short delay the compressor begins to operate to return the evaporator and compartment to their operational temperatures. The sequence used in this model adds a period of non-operation after the defrost cycle is triggered, but before the heater turns on. This allows the evaporator to be warmed up by the air in the compartment, so that the heater does not have to operate for as long of a period of time. Domestic manufacturers have begun to adopt this defrost sequence.

B) <u>Pulse Amplitude Modulation (PAM)</u>. As a compressor motor first switches on, the initial draw of current is much higher than the steady draw seen during operation. In some cases, this initial draw can be 2 to 5 times the steady state operation current draw. Although it operates with this high current for only 1 s to 2 s, the energy used during this period can be significant compared to the per cycle energy. This model alleviates this through pulse amplitude modulation. At this time, domestic manufacturers have not began to incorporate this feature into their designs, however it is becoming popular in Japan and New Zealand and is likely to become a popular feature worldwide.

C) Variable Speed Fans and Ducts. In a typical household refrigerator, fans and ducts direct the airflow over the evaporator and deliver it to the compartments of the refrigerator. A feature that is unique to this refrigerator is that it has many ducts, each with its own dedicated fan. In addition, it also has a more complex system of temperature measurement and decision-making circuitry than typical refrigerators. This feature provides this unit with the ability to detect warmer spots in the cabinets and direct more cold air to those locations; conversely, a cold spot would realize a reduction in the supply of cold air. The purpose of this feature is to ultimately assure uniform temperatures throughout the refrigerated compartments.

EXPERIMENTAL PROCEDURE AND TEST CONDITIONS

For each measurement, the refrigerator was placed on the test cell platform and the walls were adjusted according to the procedure. If a thermal load was required for a particular test, load packages were loaded into the freezer and refrigerator compartment. Three thermocouples were placed on each side of the refrigerator in accordance with each test procedure to monitor the ambient conditions. Thermocouples were placed inside the refrigerator compartments (number and location to be in accordance with applicable test procedures). Automatic ice makers were turned off during all tests. Finally, the refrigerator’s electrical cord was plugged into the digital power meter so that its energy use could be recorded.

For all test situations and stabilization periods, the environmental chamber was maintained within 0.3 °C (0.5 °F) of the target dry bulb and 2.0 °C (3.6 °F) dew point temperatures. Since there were two test cells used in this laboratory, it was possible to record the data from one unit while the other would undergo its stabilization period.

U.S. Department of Energy Tests

The DOE follows the test procedure outlined by the Association of Home Appliance Manufacturers (AHAM HRF-1). According to this test procedure, the three automatic defrost refrigerators would all be classified as "Refrigerator-Freezers".

For the measurements on Refrigerator-Freezers, the freezer compartment is left empty, except for the thermocouples used to measure the compartment temperature. Three thermocouples were used for the top-mount units and five thermocouples were used in the side-by-side unit. Three thermocouples were also placed in the refrigerator compartments of each of these units.

The thermostat was set to the median setting for each compartment of the refrigerator-freezer, and it was operated in an environment held at a constant 32.2 °C (90 °F) until steady state operation was achieved. There is no specified humidity required for these tests, however it was held at a constant 20.0 °C (68 °F) dew point, which corresponds to 50 % relative humidity.

For the DOE test procedure, the recorded compartment temperature is the average of the measured temperature from each thermocouple; where the measured temperature is the time averaged temperature from a thermocouple over the duration of the test period.

The temperatures and electrical energy were then recorded over the duration of the test period. The test period encompasses one defrost sequence and the entire steady operation between two consecutive defrost sequences. Alternatively, if the defrost sequences are separated by more than 14 h of compressor run time; then the classification of this unit is termed "Long Time Automatic Defrost." For this type of refrigerator, the test period is broken into two parts, one part demonstrating steady operation and one part demonstrating the defrost sequence. The first part must be at least 3 h long and encompass a whole number of compressor on/off cycles, and the second part must record all of the events associated with the defrost sequence.

The target temperature for refrigerator-freezers is -15 °C (5 °F), measured in the freezer compartment. If the measured freezer compartment temperature for the first test is warmer than this, then the thermostats are set to the coldest setting for a second measurement. Conversely, if the measured temperature in the freezer compartment is colder than the target temperature, then the thermostats are set to the warmest setting for a second measurement.

After two measurements have been taken, a plot of energy consumption versus freezer temperatures is generated and a linear fit is produced. The energy consumption value is found from this curve fit as the energy required to produce a temperature of -15 °C (5 °F) in the freezer compartment. Although the relationship between the evaporating temperature and the energy consumption is not linear, this is a good approximation over this small range of operating conditions and is accepted as the industry standard.

ISO Tests

The three refrigerators were tested according to ISO 8561.

Under the ISO testing system, the freezer compartments of the refrigerators that are to be tested are sectioned and classified by a system that is indicative of the storage temperatures. Since none of the units tested in this study were manufactured for the European market, their freezer compartments were not classified by this system. The classification system separates the compartments into three classifications; t***, t**, and t* sections. The temperatures required to meet a certain classification are shown below in table 2. For the purposes of this study, the freezer compartments were treated as though they were all t** compartments, as some of these units were not designed to easily attain temperatures that would qualify them as t*** sections, and a consistent basis for comparison was needed.

Table 2 Required storage temperatures for ISO tests

Compartment Type	Required Storage Temperature (°C)
t***	≤-18
t**	≤-12
t*	≤-6

The ISO test requires that the refrigerator be tested in an environment of 25 °C (77 °F), with the relative humidity between 45 % and 75 %. For all of the ISO tests performed in this study, the dew point was held at a constant 16 °C (60.8 °F), which corresponds to a humidity level of 58 %.

For the measurements of the energy consumption, the ISO test procedures require that the freezer compartment be loaded. The load packages that are required are composed of the following recipe, designed to mimic the thermal properties of lean beef:

Per 1,000 grams:
230.0 g of oxyethylmethylcellulose
764.2 g of water
5.0 g of sodium chloride
0.8 g of 6-chloro-*m*-cresol

This matter is formed into packages of the following dimensions and mass specifications:

Table 3 Specifications for load packages required for ISO tests

Dimensions (mm)	Mass (g)
25 X 50 X 100	125
50 X 100 X 100	500
50 X 100 X 200	1000

Some of the 500 g packages are to have thermocouple probes in the center of the packages. These are termed measurement packages, or commonly "M" packages.

Finally, the ISO tests are a bit stricter than the DOE test procedure with their measurement technique. The reported temperature for a compartment is to be the maximum temperature seen from any thermocouple during the test. This maximum temperature must then satisfy the temperature requirements outlined in the procedures.

Packages were loaded into the freezer compartment in such a way that the compartment was essentially full, with the exception of minimum required spacing between stacks of packages. A number of "M" packages were distributed throughout the freezer load packages. Three "M" packages were placed in the main refrigerator compartment and another three "M" packages were placed in the cellar compartments.

The test period is to be a minimum of 24 h, and must be comprised of a whole number of operating cycles (i.e. from one point on a defrost sequence to the same point on another defrost sequence). If the defrost sequences are separated by more the 72 h of operation, then the test is terminated at 72 h and the defrost sequence is not taken into account.

The ISO test procedure does not instruct the settings of the thermostats, but rather provides a table of storage temperatures and states that “The energy consumption is that which is obtained when all the storage temperature conditions…are met simultaneously, and which gives the lowest energy consumption.” The required temperatures are those shown in Table 2.

The portion of ISO 8561 that provides information for the energy consumption test does not explicitly state that a two part interpolated test, such as the DOE test procedure, may be used. However, a later section of the same procedure refers to the energy consumption test result being found through interpolation of two tests. Therefore, these tests were carried out in the same manner as the DOE test procedure.

EXPERIMENTAL RESULTS

Side-By-Side Refrigerator-Freezer

Table 4 shows the data obtained from the energy consumption tests performed on the side-by-side refrigerator. As was expected, the energy consumption of this unit under the DOE test procedure was higher than the value obtained using the ISO procedure. This is mainly due to the fact that the DOE test procedure requires a larger temperature difference between the coldest cabinet and the ambient. What is interesting about these results is the relative increase in the amount of energy consumption. The energy consumption measured by the DOE test procedure was 29.4 % greater than that measured by the ISO test procedure. For the test data shown in Table 4, the temperature difference between the coldest compartment and the ambient temperature was 28.8 % greater for the DOE test procedure.

Table 4 Test results for side-by-side refrigerator-freezer

	DOE Test		ISO 8561	
	Median Setting	Warmest Setting	First Setting	Second Setting
Test period	117595 s	156551 s	163080 s	183000 s
Average Test Power	2.85 $\frac{kW \cdot h}{d}$	2.32 $\frac{kW \cdot h}{d}$	2.03 $\frac{kW \cdot h}{d}$	1.89 $\frac{kW \cdot h}{d}$
Freezer Temp	-18.00 (°C)	-12.99 (°C)	-12.99 (°C)	-11.06 (°C)
Ambient Temp	32.38 (°C)	32.32 (°C)	24.89 (°C)	24.90 (°C)
Final Result	**2.530** $\frac{\mathbf{kW \cdot h}}{\mathbf{d}}$ **at -15 °C (5 °F)**		**1.955** $\frac{\mathbf{kW \cdot h}}{\mathbf{d}}$ **at –12 °C (10.4 °F)**	

Using the algorithm outlined by Bansal and Krüger, these operating conditions would result in COP and ΔT of 4.09 and 47.35 °C for the DOE test procedure; and 4.99 and 36.89 °C for the ISO test procedure. The correlation derived in their study results in a calculated DOE result of 2.70 $\mathrm{kW \cdot h/d}$, based on the ISO test measurements, which is 6.8 % above the measured value. The values for ΔT_{cond} and ΔT_{evap} were fixed at 7 °C for this calculation, however this unit uses forced convection for the evaporator and condenser, which would decrease these temperature differences. Using smaller temperature differences would, however, result in a larger difference between the calculated value and the measured value.

Top Mounted Refrigerator-Freezer

Table 5 shows the data obtained from the energy consumption measurements performed on the top mounted, domestic, refrigerator-freezer.

The DOE test procedure resulted in an energy consumption value that was 26.6 % higher than the ISO test, while operating across a temperature difference that is 20.6 % larger. This is fairly similar to the results of the side-by-side refrigerator; however, there are a few other factors that need to be taken into consideration when examining the data for this unit.

Table 5 Test results for top mounted refrigerator-freezer

	DOE Test		ISO 8561	
	Median Setting	Warmest Setting	First Setting	Second Setting
Test period	2 part CT = 143.7 h	2 part CT = 181.6 h	260586 s	260430 s
Average Test Power	1.60 $\frac{kW \cdot h}{d}$	1.34 $\frac{kW \cdot h}{d}$	1.07 $\frac{kW \cdot h}{d}$	1.06 $\frac{kW \cdot h}{d}$
Freezer Temp	-21.02 (°C)	-17.87 (°C)	-16.86 (°C)	-16.54 (°C)
Ambient Temp	32.24 (°C)	32.33 (°C)	25.14 (°C)	25.11 (°C)
Final Result	**1.34 $\frac{kW \cdot h}{d}$ min at –17.9 °C (-0.2 °F)**		**1.06 $\frac{kW \cdot h}{d}$ min at –16.5 °C (2.3 °F)**	

First and foremost, this particular refrigerator was always too cold. The final result could not be interpolated to the target temperature for either test because, even at the warmest thermostat setting, the freezer compartment temperature was colder than the test target temperatures of -15 °C (5 °F) for the DOE procedure and -12 °C (10.4 °F) for the ISO procedure. According to the DOE and ISO 8561 procedures, if this occurs then the value obtained at the warmest setting and the corresponding temperatures are to be reported.

In addition, this unit displayed the "long-term automatic defrost" characteristics outlined in the DOE test procedure. The time between defrost sequences is denoted as CT for the DOE test results, and it is shown that this unit undergoes a defrost sequence approximately once per week. Therefore, the procedure that was used requires two separate measurements, one of the steady state performance and one of the defrost sequence, which draws approximately twice as much power as steady operation. These measurements are then combined to give a time weighted average of all amounts of energy used during operation.

Conversely, for the ISO test procedure, since no defrost sequence occurred over a 72 hour test period, the defrost sequence was not taken into account. By closer examination of the data from the DOE test, it is seen that accounting for the defrost energy adds only 0.6 % to the energy consumption for this unit. This is actually a bit low for the addition of the defrost power, but that is due to very large time between defrost cycles. In general, excluding the defrost power used on units that cycle less than once every 72 h results in less than 2 % savings in the energy consumption.

Comparing the results of this test to the study of Bansal and Krüger, these operating conditions would result in COP and ΔT of 3.87 and 50.19 °C for the DOE test procedure, and 4.89 and 41.62 °C for the ISO test procedure; assuming the same ΔT_{cond} and ΔT_{evap} as was used in their study. Their correlation agrees very well with the measured values for this test. The calculated DOE test result is 1.35 $\mathrm{kW \cdot h/d}$. This unit, however, uses forced convection to drive the heat transfer across its heat exchangers; therefore the values for ΔT_{cond} and ΔT_{evap} are a bit unrealistic for this refrigerator. Lowering the values of these parameters would again add disagreement between the calculated values and the measured values.

Top Mounted Refrigerator-Freezer with Energy Saving Technologies

The data from the energy consumption tests of the refrigerator with unique energy saving features is shown below in table 6.

Table 6 Test results for top mounted refrigerator with energy saving technologies

	DOE Test		ISO 8561	
	Median Setting	Warmest Setting	First Setting	Second Setting
Test period	2 part CT = 67.2 h	2 part CT = 75.1 h	259568 s	261088 s
Average Test Power	1.55 $\frac{\mathrm{kW \cdot h}}{\mathrm{d}}$	1.32 $\frac{\mathrm{kW \cdot h}}{\mathrm{d}}$	1.21 $\frac{\mathrm{kW \cdot h}}{\mathrm{d}}$	1.02 $\frac{\mathrm{kW \cdot h}}{\mathrm{d}}$
Freezer Temp	-16.93 (°C)	-12.80 (°C)	-13.02 (°C)	-9.84 (°C)
Ambient Temp	32.16 (°C)	32.30 (°C)	25.19 (°C)	25.11 (°C)
Final Result	**1.441** $\frac{\mathbf{kW \cdot h}}{\mathbf{d}}$ **at -15 °C (5 °F)**		**1.153** $\frac{\mathbf{kW \cdot h}}{\mathbf{d}}$ **at –12 °C (10.4 °F)**	

The energy consumption of this unit, as tested by the DOE test procedure resulted in a value that was 25.0 % higher than that under the ISO test, while operating across a temperature difference that was 27.1 % larger. This is in line with the results of the other refrigerators tested in this study. As was the case with the top mounted domestic unit, the defrost portion was not factored into the ISO test calculations. Including the energy for the DOE test procedure added 1.4 % to the energy consumption measurement.

Comparing these results to Bansal and Krüger, the COP and Δ*T* are 4.10 and 47.23 °C for the DOE test procedure; and 4.97 and 37.15 °C for the ISO test procedure. This resulted in an estimated energy consumption of 1.57 $\mathrm{kW \cdot h/d}$ for the DOE test procedure. This unit performed quite better, however, under the DOE test procedure.

This particular unit used forced air over the evaporator and natural convection over the condenser. Therefore the value for ΔT_{cond} may have been fairly suited, but the value for ΔT_{evap} would be too large, and lowering this value would add more disagreement between the correlation and the test data.

It was hypothesized that this unit would show a better relative performance under the ISO test procedure due to the variable speed fans and ductwork. The other unique features of this unit, the intelligent defrost sequence and PAM, should benefit the results of both the DOE and ISO test. The variable speed fans and ductwork function to eliminate temperature differences within a given compartment, which will ultimately result in the measured maximum temperature being closer to the average compartment temperature. The DOE test procedure states that the average freezer temperature be used as the basis for interpolation; whereas the ISO test procedure states that the maximum temperature seen at any location during the measurement period should be the basis for interpolation. Under this set of test conditions and procedures, this feature would present itself as a benefit during the ISO tests, but may not influence the results of the DOE tests.

However, this did not seem to be the case. This unit used 25.0 % more energy under the DOE test procedure than under the ISO test procedure, which is the smallest increase seen for any of the refrigerators tested in this study. Had the variable speed fans and ducts showed a favorable benefit towards the ISO test procedure, this unit would have shown the largest increase.

Overall Results

A summary of the results obtained during these tests is depicted in Figure 1. In all cases, the results of the tests showed that the refrigerators used considerably more energy under the DOE tests than under the ISO tests. For the three refrigerators, the DOE test measured the energy consumption to be 25.0 % to 29.4 % higher than the ISO test. Also shown on this figure are the predicted values of the energy consumption based on results of the ISO tests and the correlation developed at the University of Auckland.

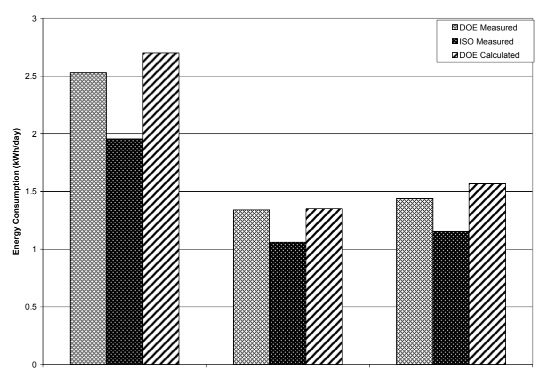

Figure 1 Summary of all test data measured during this study

For all three refrigerators, the predictions were 0.7 % to 9.0 % higher than the measured values. Since the correlation consistently predicted a value that was higher than the measured value, it seems that this correlation can be modified to better predict the performance of these refrigerators.

The parameters that are used in the Bansal-Krüger correlation are fundamentally important to the refrigeration cycle; however the dependence of each parameter may not be accurate due to the empirical method of determination. Although there is not enough data to develop a useful correction to the Bansal-Krüger correlation, it may be helpful to address the physics of this situation. For each unit, the COP is defined as the amount of cooling divided by the compressor work.

$$\mathrm{COP} = \frac{Q_{evap}}{W}$$

The amount of cooling power that is needed to maintain a certain temperature within the cabinet is the product of the overall heat transfer coefficient of the cabinet and the temperature difference between the ambient temperature and the internal cabinet temperature.

$$Q_{evap} = UA\Delta T$$

Therefore, a ratio of the compressor work under one test procedure to that under another procedure could then be expressed as:

$$\frac{W_A}{W_B} = \frac{\mathrm{COP_B}}{\mathrm{COP_A}}\frac{UA_A}{UA_B}\frac{\Delta T_A}{\Delta T_B} = \frac{\mathrm{COP_B}}{\mathrm{COP_A}}\frac{\Delta T_A}{\Delta T_B}$$

Although this seems rather straight forward in theory, this is not necessarily accurate in practice. This does, however, suggest that the dependence of a working correlation on the temperature difference parameter should be stronger than the square root relationship used in the Bansal-Krüger correlation.

Furthermore, the calculated values for the COP under each test were estimated using a 7 °C temperature difference between the evaporating temperature and the refrigerator's internal temperature. 7 °C was also used as the temperature difference between the ambient temperature and the condensing temperature. This value is too large for these units. Unfortunately, the actual ΔT_{evap} and ΔT_{cond} were not measured during these tests, nor would they be easily measured as the evaporator is generally not accessible to the user. Therefore, it may be difficult to introduce this parameter into a working correlation at all.

With data from only three refrigerators, it is premature to suggest a useful correction to the Bansal-Krüger correlation. For this reason, more test data should be taken on a variety of units in order to develop a better understanding of the influences involved with these two test procedures.

SUMMARY

The purpose of this investigation was to examine the differences between energy consumption ratings obtained by the United States Department of Energy test procedure and the analogous ISO test procedure. Three refrigerators were tested by each standard in this study.

During the tests, the results showed that the DOE test procedure consistently produced a larger value for the energy consumption. This was in line with the expectations due to the fact that the DOE test procedure requires that the units operate in a warmer environment during the test.

Overall, the correlation developed by Bansal and Krüger agreed with the data from this study to within 10 %. However, this correlation was developed empirically from data obtained from refrigerators which operated using a different refrigerant; and the predictions seemed to be consistently higher than the measured data for these units. This suggests that there may be other factors which can be included into this correlation to broaden its scope; which could then be used as a step towards an international test procedure. However, it would be necessary to examine more units to accurately compile a working correlation.

The relative ranking of the units tested were identical under both standards. This suggests that both the DOE and ISO test procedures are adequate tools that can be used to accomplish the same task. Some of the steps of the procedures differ in ways that complicate the testing, while other procedural steps that vary between the standards are somewhat arbitrary. In general, however, the test procedures are similar in nature.

REFERENCES

1. **Association of Home Appliance Manufacturers** *American National Standard, Household Refrigerators/Household Freezers*, ANSI/AHAM HRF-1-1988, Chicago (1988).
2. **Bansal P. K. and Krüger R.** Test standards for household refrigerators and freezers I: preliminary comparisons, *Int. J Refrigeration*, **18** (1), 4-20 (1995).
3. **International Organization for Standardization** *International Standard* **ISO 8561**, *Household frost-free refrigerating appliances – Refrigerators, refrigerator-freezers, frozen food storage cabinets and food freezers cooled by internal forced air circulation – Characteristics and test methods*, 1995.