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Uncertainty Study in Freezer/Refrigerator Consumption Tests

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ABSTRACT

Environmental effects caused by industrialized products have been one of the main reasons for advances and changeovers in recent technologies on refrigeration industry. The advent of new refrigeration gases non aggressive to atmosphere is a remarkable example of this trend. Another point is the great effort that has been done for efficiency improvement of household appliances providing a better use of the energy generated in the planet. The development of refrigerator-freezers usually relies on experimental confirmation, so the consumption test becomes a very important procedure concerning energy savings. This work will present a study of the influence of some parameters like thermal load packages, test duration and ambient temperature over the consumption test results taking especial care to the uncertainty. Statistical tools like Analysis of Variance (ANOVA) and Design of Experiments (DOE) were applied in this analysis reducing 69% the standard deviation of the final results.

1. INTRODUCTION

This work gave attention to the problem of the uncertainty associated to an experimental test under the influence of some parameters. The result of an experimental test must be regarded as a random variable; so it shall be given in terms of a number, an interval and an associated probability. The number is a reference of the interval within which the actual value has a probability to bee inside. If this interval is reduced its probability to contain the actual result diminishes due to a certain scatter, and vice versa. It is certainly very interesting to have a small interval for measurement dispersion, as close as possible to zero, with a high probability to contain the actual value, as close as possible to 100%. Unfortunately this condition demands expensive measurement equipments, a study of the variability and their respective sources could be done instead. Sometimes this is the only feasible way to reduce the variability of a certain measurement. The uncertainty of a measurement is due to all parameters that might do any influence on it. If the parameters with the major influence were identified and controlled, the variability of the measurement could be reduced just analyzing their effects and interrelation.

Here we dealt with the determination of the energy consumption of a household refrigerator-freezer, where some parameters were supposed to influence the result. The parameters were: thermostat position, ambient temperature, group of thermal load packages and test duration. Two of them have their influences previously known, at least, in qualitative terms; they are thermostat position and ambient temperature. The thermostat position was included as part of the test procedure, what will be described in details in section 2 (Experimental Procedure – Consumption Test). It controls the internal refrigerator temperature, which indirectly leads to the energy consumed. Lower temperatures inside the refrigerator demand higher energy consumptions, and vice versa. The influence caused by the ambient temperature on energy consumption is also known; higher ambient temperatures require higher energy consumption for the same temperature inside the refrigerator. Even being controlled by the chamber test system the ambient temperature floated slightly around the settled point (25°C in this case) promoting a trend on the energy consumed. This effect could be determined and used as a correction to reduce the variability of the final result. It is important to point out that when we say ambient temperature, it shall be understood as the average of the ambient temperature along the consumption test.

The packages used as thermal load in the food freezer compartment are made of a mixture of components trying to simulate thermal food characteristics. Certain variability, on their thermal conductivity for example, is expected and may cause some influence on the energy consumption result. When the refrigerator is loaded these packages define a group that has a certain thermal behavior. Discharging and reloading the refrigerator with different packages may provide some influence on the energy consumed. If this influence was verified the packages change should be avoided, otherwise the energy consumption result will be penalized with higher variability. The standard determines

a test period of at least 24 hours after stabilization. In cases where the refrigerator on-off cycle is smaller than 24 hours the energy consumption test duration could be reduced and the outcome might present similar result. In this work we decided to check this aspect doing experiments with 24 and 3 hours duration, as the on-off cycles varied from 70 to 130 minutes.

The four parameters described above were chosen mainly based on experience; another researcher could suggest other ones. The statistical analysis is capable to show which of them are significant or not to the consumption, so the important ones could be controlled in order to have a more precise result. The statistical tools employed in the data analysis were the Design of Experiment (DOE) associated to the Analysis of Variance (ANOVA); they suit quite well to the sort of problem presented here. They work based on a system or process that has a response variable, subject of study, which is expected to be affected by independent variables. In this work the energy consumption result is the response variable and the parameters mentioned above are the independent variables. The matter here is verifying which and how much these parameters influence the energy consumption result of the appliance analyzed. Determining these parameters and their effects on the energy consumption result could access it more accurately. The statistical methodologies demand predefined levels for the independent variables to permit the analysis; Montgomery (1991) and Box (1978) describe these statistical methodologies in deep details.

2. EXPERIMENTAL PROCEDURE – CONSUMPTION TEST

The experimental procedure applied in the determination of the energy consumption was based on the Standard ISO 15502, which describes the characteristics and test methods for household refrigeration appliances. The cabinet used here was provided with a single electro mechanical thermostat for regulating simultaneously the temperature of fresh food storage and food freezer compartments (single control: classified as Type I). The temperatures were measured by means of thermocouples positioned according to the standard. Cylinders made of brass were used to evolve the thermocouples and measure the temperatures in the fresh food storage compartment (three positions, top, medium and button) and ambient temperature; "M" packages (six packages provided with temperature sensor) were used in the food freezer compartment (these cylinders and packages are fully described in the standard). The ambient temperature applied was 25 ± 0.5°C and the cabinet was classified as a three star, so the maximum temperature of the warmest package (MTWP) in the food-freezer compartment, or target temperature, was –18°C. As it is difficult to adjust this temperature to fall exactly at –18°C, two tests are necessary, one warmer and another colder with a difference below 4 K between them. These results are interpolated in order to determine the test result at the target temperature. Simultaneously the average of the temperatures ("T_{ma}" column on Table 2) measured inside the fresh-food storage compartment must be kept below 5°C.

It is important to describe the difference between measured energy consumption and energy consumption result, or simply test. The second one is the final result of a consumption test and is obtained from the interpolation of two measured energy consumption experiments, as mentioned above. The measured energy consumption is the result of a direct measurement relative to a thermostat position; two of them are necessary to the interpolation procedure and consequent determination of energy consumption result.

3. STRATEGY ADOPTED

As mentioned above the employed statistical tools demand a special care concerning the levels of the independent variables settled for each test, so they have to be kept at some pre defined values, as stated on Table 1. According to these levels the tests were done and Table 2 presents the results.

Table 1: Variables and their respective codes and levels.

Variables	Code	Level 1	Level 2
Thermostat Position (TPO)	x_1	3,5	4
Group of Packages (G-Pack)	x_2	I	II
Test Duration (TD)	x_3	3h	24h
Ambient Temperature (T_{amb})	x_4	-	-
Codified Level	-	-1	+1

As can be seen on Table 1, the ambient temperature has no defined level, in spite to be settled at 25°C on the chamber test control system; in fact it slightly floated around that value (observe T_{amb} column on Table 2). This parameter was regarded as a covariable (according to statistical vocabulary), what means that it is supposed to be significant, but was not accurately controlled. It works, in practical terms, as if the parameter had been settled at many levels. The strategy adopted was conducting the analysis with the other three parameters (Table 4) determining the significant effects and subtracting them from the measured data to obtain the residual (or error). Plotting this residual as a function of the ambient temperature revealed its effect, shown in Figure 2. It was used to correct the measured energy consumption eliminating the ambient temperature influence, the values after correction can be seen in Table 2 in the column "Corrected Consumption". The next step was the interpolation of the two thermostat positions establishing the energy consumption at exactly –18°C.

The interpolation was done in the order they appear in Table 2, test number 1 was interpolated with test number 2, number 3 with number 4, and so on. At this point the ambient temperature and thermostat position don't need to be considered any more as their effects on the energy consumption were already incorporated. The energy consumption results could be analyzed under the influence of the two remaining parameters, group of thermal load packages and test duration. They were rearranged according to Table 3 and analyzed according to Tables 5, 6 and 7.

4. EXPERIMENTAL RESULTS

The test conditions and results are presented in Table 2. From the left, the first column brings the test number from 1 to 16; the next columns are thermostat position (TPO), group of thermal load packages (G-pack) and Test Duration, they establish the levels of these parameters for each test. The next column is the "Measured Energy Consumption" of each test. "T_{amb}" column shows the average of ambient temperature registered every minute along the test. The "Corrected Consumption" column is the measured energy consumption corrected from ambient temperature effect. The last two columns are the maximum temperature of the warmest package (MTWP) in the freezer-food compartment and the average temperature inside the fresh-food compartment (T_{ma}).

Table 2: Tests conditions and their respective results.

Test	TPO	G-Pack	Test Duration	[Wh/day] Measured Energy Consumption	[°C] T_{amb}	[Wh/day] Corrected Consumption	[°C] MTWP	[°C] T_{ma}
1	3.5	I	3h	985	24,9	993	-16.7	1.7
2	4	I	3h	1201	25,9	1127	-18.6	0.2
3	3.5	II	3h	941	25,0	941	-16.4	2.5
4	4	II	3h	1070	25,0	1074	-19.1	0.6
5	3.5	I	24h	953	25,2	936	-16.0	2.3
6	4	I	24h	1089	24,9	1097	-18.8	0.1
7	3.5	II	24h	916	24,8	936	-16.7	2.5
8	4	II	24h	1071	24,8	1088	-19.3	0.4
9	3.5	I	3h	999	25,5	958	-16.0	2.4
10	4	I	3h	1052	24,7	1077	-18.2	0.8
11	3.5	II	3h	940	25,0	938	-16.3	2.6
12	4	II	3h	1036	25,0	1033	-18.2	1.0
13	3.5	I	24h	926	24,9	934	-15.8	2.5
14	4	I	24h	1115	25,4	1082	-18.7	0.4
15	3.5	II	24h	931	25,0	931	-16.3	2.5
16	4	II	24h	1039	25,0	1040	-18.2	0.8

Interpolating the measured energy consumption from Table 2, the energy consumption results were calculated and are shown on Table 3. Two kinds of energy consumptions are presented in this table, one with no correction from ambient temperature influence obtained just through interpolation procedure (Energy Consumption column) and the other corrected by this effect (Corrected Energy Consumption column). This correction is described later.

Table 3: Energy consumption results after interpolation with and without ambient temperature correction

G-Pack	Test Duration	[Wh/day] Energy Consumption	[Wh/day] Corrected Energy Consumption
I	3h	1133	1084
II	3h	1018	1020
I	24h	1050	1051
II	24h	994	1012
I	3h	1047	1066
II	3h	1026	1023
I	24h	1069	1046
II	24h	1028	1028

5. DATA ANALYSIS AND DISCUSSION

The analysis of variance of the tests is presented in Table 4, based on the experimental design established in Table 1. The first column in Table 4 lists the "Sources of Variation", which in other words are the parameters checked to exert any influence over the energy consumption. The terms x_1x_2, x_1x_3 and x_2x_3 are called interaction and they are also possible sources of variation. Interaction is the effect of a certain parameter when it depends on the level of another parameter. The effect is the value added to the Response Variable when the parameter goes from level 1 to level 2. The column "Sum of Square" is the variance provided by each effect. "Degrees of Freedom" means the number of independent elements associated to the sum of square. "Mean Square" is the division of "Sum of Square" by the "Degrees of Freedom". F is the statistics that describes the probability distribution of the division of the effect variability by error variability.

Table 4: Analysis of Variance of the Measured Energy Consumption.

Sources of Variation	Effect	Sum of Square	Degrees of Freedom	Mean Square	F	p-value
Mean	1017					
(PTO) x_1	135.2	73110	1	73110	50.1	0.000058
(G-Pack) x_2	-46.9	8815	1	8815	6.0	0.036
(Test Duration) x_3	-23.1	2126	1	2126	1.5	0.26
x_1x_2	-13.3	708	1	708	0.5	0.50
x_1x_3	11.8	558	1	558	0.4	0.55
x_2x_3	15.4	954	1	954	0.7	0.44
Error		13124	9	1458		
Total		99395	15			

Depending on how much the variability, or mean square, of the effect is bigger than the error, it can be considered significant or not. The affirmative that certain effect is significant is supported by the value on column "p-value", which gives the probability of this affirmative be wrong. Low "p-value" means that the effect has a great chance to be significant. This can be observed for the effects of x_1 and x_2, whose p-values are 0.0058% and 3.6%, respectively. In other words, thermostat position and group of thermal load packages are parameters that have significant influence on the measured energy consumption, as these assertions have a very low probability to be wrong according to their p-values. Otherwise the effect of x_3 presented no significant effect, as its p-value is 0.26. In other words, the statement that the test duration has a significant effect on the measured energy consumption has a probability of 26% to be false. So, as its chance to be wrong is too high the statement was rejected and considered not significant.

The ambient temperature effect was evaluated based on Equation 1. "Y" represents the measured energy consumption and the two significant parameters are performed by x_1 and x_2, which in coded mode assume values of –1 and +1, according to Table 1. The coefficients are half of the significant effects from Table 4, and the constant is

the average of all measurements. Appling the equation to every test the residual, or ε, could be calculated as all the other values are known. The results obtained for ε are plotted in Figure 1 as a function of measured data.

$$Y = 1017 + \left(\frac{135.2}{2}\right)x_1 + \left(\frac{-46.9}{2}\right)x_2 + \varepsilon \tag{1}$$

It is important to highlight the fact that the ambient temperature effect is included in this residual. Plotting the same residual as a function of the ambient temperature revealed a certain trend, observed in Figure 2. Fitting these data to a linear equation, we found a coefficient, which means that at every 1°C of ambient temperature variation the measured energy consumption was affected in 82.7 Wh/day, in average. Discounting this effect from the measured consumption results obtained at ambient temperatures different from 25°C in proportional basis, this bias was eliminated. Following this procedure the column "Measured Energy Consumption", in Table 2, was corrected and the column entitled "Corrected Consumption" was generated free from ambient temperature influence. The test 2, in Table 2, exhibits an ambient temperature of 25.9°C, which is out of the limits (25 ± 0.5°C) defined by standard ISO 15502. In spite of this discrepancy the test was not discarded avoiding the need for another test and saving time.

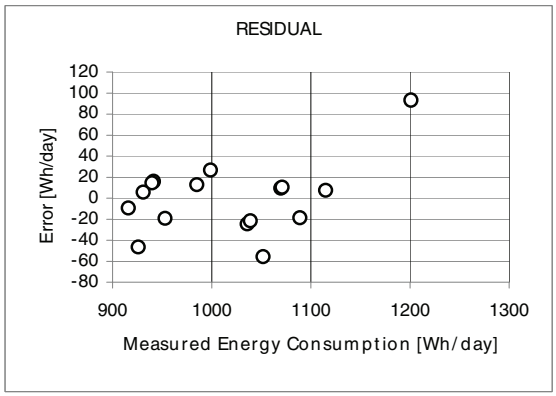

Figure 1: Residual as a function of measured data.

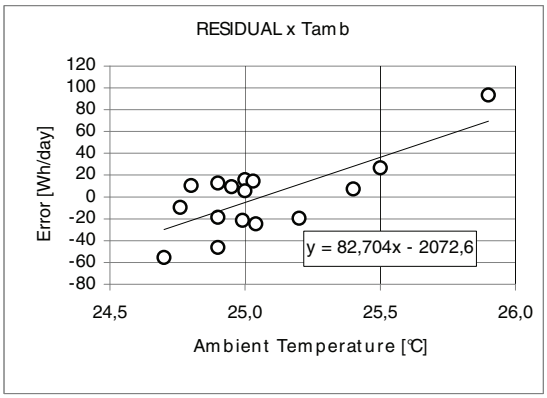

Figure 2: Residual as a function of the ambient temperature.

After, we could evaluate quantitatively its influence over the measured energy consumption. This aspect can be seen on Table 5 where the correspondent p-value is 1.1% endorsing the significant influence of this parameter. It is important to call the attention to the error sum of square from Table 4 to 5 showing that ambient temperature was responsible for a considerable part of that variability. The error was determined according to Equation 2, which incorporates the ambient temperature effect obtained from the fitted equation on Figure 2.

$$Y = 1017 + \left(\frac{135.2}{2}\right)x_1 + \left(\frac{-46.9}{2}\right)x_2 + [(82.7)T_{amb} - 2072.6] + \varepsilon \tag{2}$$

Table 5: Analysis of Variance of the measured energy consumption results considering the significant parameters including the covariable T_{amb}.

Sources of Variability	Sum of Square	Degrees of Freedom	Mean Square	F	p-value
TPO (x_1)	73110	1	73110	104	6.1E-07
G-Pack (x_2)	8815	1	8815	13	0.005
Tamb (x_4)	9739	2	4870	7	0.011
Error	7731	11	703		
Total	99395				

At this point the ambient temperature influence was already determined and discounted, the thermostat position was incorporated thorough the interpolation procedure, so energy consumption is free from these parameters. The results of the analysis of variance done with the corrected energy consumption (from Table 3) are presented in Table 6. The group of thermal load packages demonstrated once more to be significant (p-value of 0.29%) as the same result was found in the analysis of Tables 4 and 5, indicating agreement.

Taking a look at the test duration parameter we found a p-value of 9.5%, this is the probability to be wrong in considering this parameter significant. It is not a great probability, but taking into account the reference criteria of 5% this parameter was regarded not significant. It is important to say that it was considered not significant, but this point deserves deeper analysis as p-value is not so high and stabilization process may affect this conclusion. In other words, very well stabilized systems tend to be independent from test duration, but if stabilization was not carefully satisfied the conclusion could easily be different.

Table 6: Analysis of Variance of energy consumption results with ambient correction.

Sources of Variation	Effect	Sum of Square	Degrees of Freedom	Mean Square	F	p-value
Mean	1041.4					
(G-Pack) x_1	-41.3	3413	1	3413	41.8	0.0029
(Test Duration) x_2	-13.9	385	1	385	4.7	0.095
x_1x_2	12.5	315	1	315	3.8	0.12
Error		326	4	82		
Total		4439	7			

Table 7 presents a similar analysis as made on Table 6, but considering just G-Pack, which was the only parameter considered significant to the energy consumption. The total sum of square remained the same and the neglected parameters contributed to the error determination.

Table 7: Analysis of Variance of energy consumption results with ambient correction considering just the significant parameter.

Sources of Variation	Effect	Sum of Square	Degrees of Freedom	Mean Square	F	p-value
Mean	1041.4					
(G-Pack) x_1	-41.3	3413	1	3413	19.9	0.0042
Error		1026	6	171		
Total		4439	7			

The change of G-pack I to G-Pack II provided a reduction of 41.3 Wh/day, in average, on the energy consumption, expressed by the effect of this parameter in Table 7. It means that the results obtained with G-Pack I provided energy consumptions 41.3 Wh/day, in average, higher than those with G-Pack II. The experimental error could be determined based on the mean square of the error from Table 7. The square root of this variability is the standard deviation of the experimental error.

$$\sigma^2 = 171 \;\Rightarrow\; \sigma = 13 \text{ Wh/day} \tag{3}$$

Table 8 was done to compare the results before and after the analysis developed. The first line, designated "Before Analysis", was obtained as if no analysis had been done, it was determined just calculating the average and standard deviation from the original data ("Energy Consumption" column from Table 3). The last two lines present the energy consumption result for G-Pack I and G-Pack II, their averages were calculated subtracting and summing half of the effect from the mean, Table 7. Equation 3 determined their standard deviation. Superior and inferior limits of a 95% confidence interval ($\pm 2\,\sigma$) were also established for all results. The same data is depicted in Figure 3 where the confidence intervals are represented by bars and their respective averages by circumferences.

Table 8: Summary of the Energy Consumption Results before and after the analysis.

	Average	Standard Deviation (σ)	95% Confidence Interval	
			Inferior Limit	Superior Limit
Before Analysis	1046	42	961	1130
Pack I	1062	13	1036	1088
Pack II	1021	13	995	1047

The confidence interval obtained before the analysis is the wider one, enough to evolve the other two. The smaller intervals represent the results related to G-Pack I and G-Pack II. Their averages are statistically different, in spite of the partially overlapped confidence intervals.

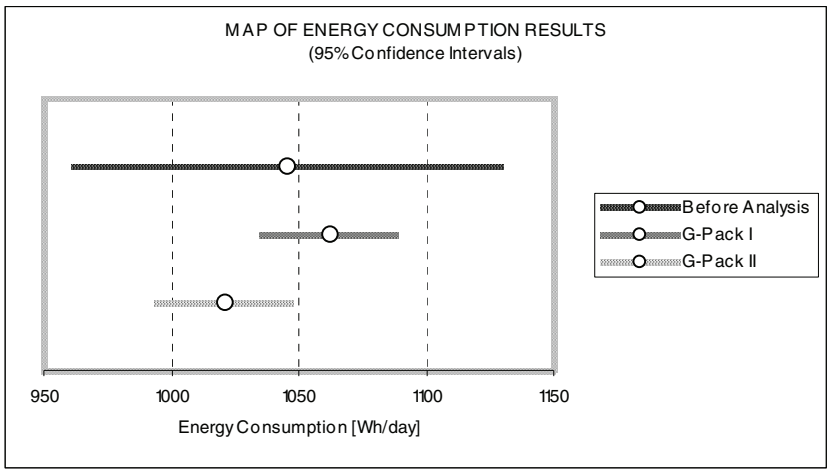

Figure 3: Confidence Intervals for Energy Consumption Results before and after the Analysis.

6. CONCLUSIONS

Ambient temperature and group of thermal load packages showed to be significant to the energy consumption test of the household refrigerator-freezer studied. The test duration parameter was considered not influent, but this conclusion demands more studies concerning stabilization aspects. Thermostat position was considered significant, as expected, and was used to determine the energy consumption according to standard procedure. The ambient temperature demonstrated an effect of 82.7 Wh/day on the energy consumption per degree Celsius of variation. The group of thermal load packages (G-Pack) was found to provide a systematic difference among the tests. The energy consumption results obtained with G-Pack I and G-Pack II were 1062 ± 26 Wh/day and 1021 ± 26 Wh/day, respectively, showing a mean difference of 41.3 Wh/day. On the other hand if no analysis had been done and all the tests were considered the consumption would be 1046 ± 84 Wh/day. The standard deviation was reduced from 42 Wh/day to 13 Wh/day, a decrease of 69% due to the statistical analysis. The statistical tools have shown to be very appropriate to the kind of problem faced in this work properly reducing the measurement uncertainty.

NOMENCLATURE

T	temperature	(°C)
σ	standard deviation	
x	parameter in codified mode	
ε	residual or error	
F	F distribution	
Y	response variable	

Subscripts

amb	ambient
ma	fresh food storage compartment

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