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Reliability Design of Residential-Sized Refrigerators Subjected to Repetitive Random Vibration Loads during Transportation

Seong-woo Woo[1], Michael Pecht[2]

[1]Director and Chief Researcher, Reliability Association of Korea, 146-102 Sunyoo-ro, Yeongdeungpo-gu, Seoul 150-103, Korea
[2]Center for Advanced Life Cycle Engineering (CALCE), University of Maryland, College Park, MD, USA

Abstract— *New designed residential-sized refrigerators subjected to repetitive random vibrations can be damaged during transportation. The damage consists of fracturing of the tubes between the compressor and condenser and tearing of the compressor rubber mounts. As the reliability quantitative (RQ) test specifications, parametric accelerated life testing (ALT) through sample inspections and corrective action plans was used to identify the key control parameters for the connecting tubes and compressor rubber mounts. The shape of failures in refrigerators found experimentally was identical to those of the failed samples in field. The connecting tube fractures resulted from the problematic shape of the compressor rubber mount. To correct these problems, the mounts and connecting tubes were redesigned. The refrigerators with targeted B1 life were expected to survive without failure during rail transport. Parametric ALTs were effective in identifying the missing design parameters of mechanical systems such as refrigerators during the design phase. The reliability design method presented in this paper should be applicable to other mechanical systems during transportation.*

***Keywords*— Refrigerators, noise parameter, Transportation, ALT.**

I. INTRODUCTION

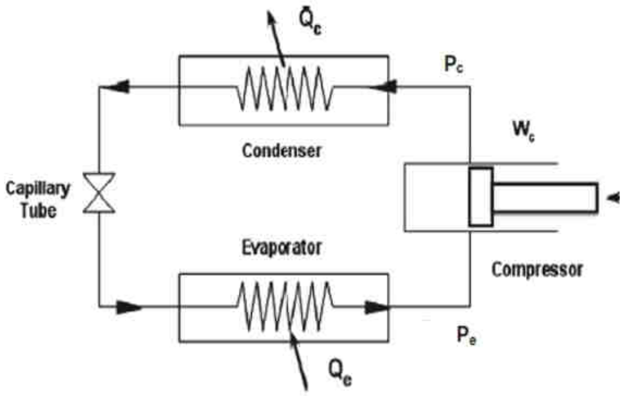


Fig.1: Vapor-compression refrigeration cycle

As seen in Figure 1, a vapor-compression refrigeration cycle consists of a compressor, a condenser, a capillary tube, and an evaporator. The compressor receives refrigerant from the low-side (evaporator) and then compresses and transfers the refrigerant to the high-side (condenser) of the system. The capillary tube controls the flow in a refrigeration system and drops the high pressure of the refrigerant in the condenser to the low pressure in the evaporator.

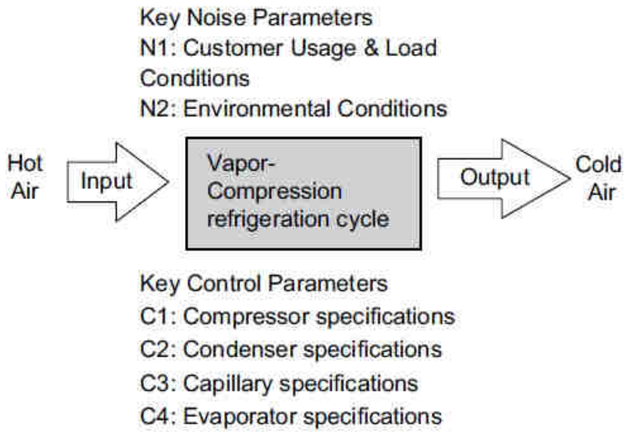


Fig.2: Robust design schematic of refrigeration system

These components can be put together as a subassembly and have an input and output for a vapor compressor cycle that is designed to produce cold air. For robust design techniques, a robust design schematic of refrigeration system employs two arrays: one for the control array (design) and the other for the noise array (loads). As minimizing a signal (output)-to-noise (load) ratio over the control factors, the control parameters in an optimal design can be determined (see Figure 2).

Fig.3: Typical side-by-side residential-sized refrigerator

As a residential-sized refrigerator transfers heat from the inside of the fridge to its external environment, its function is to store fresh or frozen food (Figure 3). After producing in factory, refrigerator is transported from one location to another. Modes of transport may include air, rail, road, and water. When residential refrigerators are moved by rail or automobile, they are subjected to random vibration loads. These vibrations are continually transmitted to the mechanical compartment of the refrigerators during transportation. If improperly designed, refrigerators might lose their functions. Consequently, the refrigerators are designed to survive the damage that can occur during transport by using compressor rubber mounts (Figure 4).

Fig.4: Mechanical compartment: (1) compressor, (2) rubber, (3) connecting tubes, and (4) fan and condenser

Robust design techniques, including statistical design of experiment (SDE) and the Taguchi methods [1], have been developed to help improve the reliability of product designs. Taguchi's robust design method uses parameter design to place the design in a position where random "noise" does not cause failure and is used to determine the proper design parameters and their levels [2-6].

The basic idea of parameter design is to identify, through exploiting interactions between control factors and noise factors, appropriate settings for the control factors that make the system's performance robust in relation to changes in the noise factors. Thus, the control factors are assigned to an inner array in an orthogonal array, and the noise factors are assigned to an outer array.

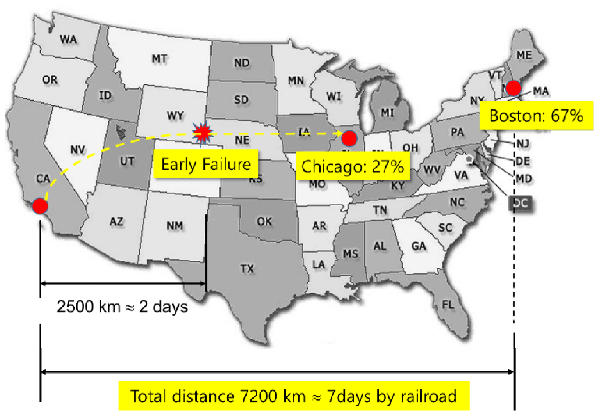
However, a large number of experimental trials using the Taguchi product array may be required because the noise array is repeated for every row in the control array. For a simple mechanical structure, a lot of design parameters should be considered in the Taguchi method's robust design process. Missing or improper minor design parameters may result in product recalls and loss of brand name value.

In this study, the reliability design of residential refrigerators subjected to random vibration during rail transportation was investigated. The method includes 1) setting overall parametric ALT plan for the product, 2) analyzing the failure modes of the returned product from the field, and 3) improving the designs of residential refrigerators using tailored parametric ALTs with a sample size equation.

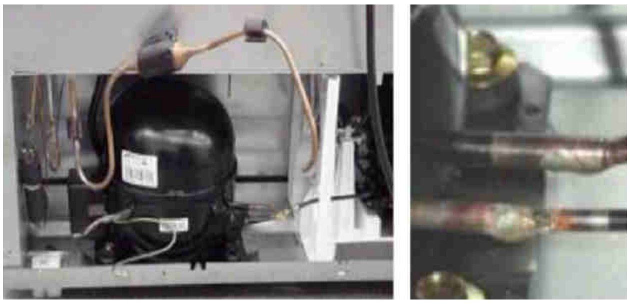
II. LOAD ANALYSIS AND *BX* LIFE

According to the investigation of company, the transportation distance of first failure was roughly 2500 km in 2 days. In Chicago the 27% among total transported product were approximately failed. After the refrigerator moved 7200km from Los Angles to Boston, the 67% of product were failed (Figure 5(a)).

In the field, the connecting tubes and the compressor rubber mounts in the mechanical compartments of side-by-side refrigerators were fracturing and tearing under unknown field conditions (see Figure 5(b)). Because the tubes were fracturing, refrigerant was leaking out of the tubes, which resulted in loss of refrigerating capacity. Field data indicated that the damaged products might have had structural design flaws that prevented protection from repetitive random vibration loads during transportation. These design flaws combined with the repetitive random vibration loads during shipping could cause a crack to occur, and thus result in failure.



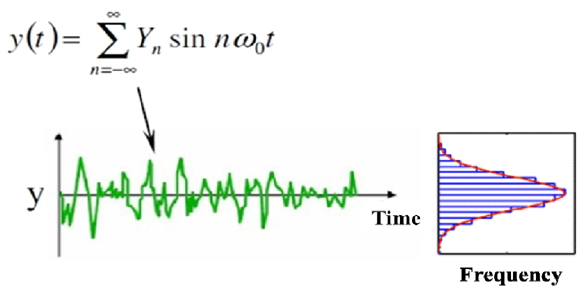
(a) Failed locations in the field



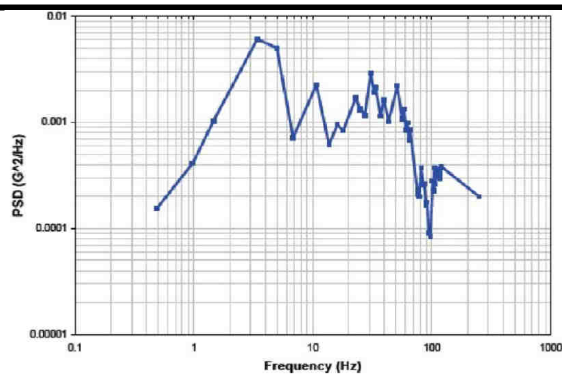
(b) Failed connecting tubes in the mechanical compartment

Fig.5: Fracture of the refrigerator connecting tubes in the field.

During transportation, the mechanical compartment (and the components in it) in the rear of the refrigerator is subjected to repetitive random vibration loads. To isolate and protect the components during transportation, refrigerator a compressor rubber mount is usually installed. If the system for vibration isolation is improperly designed, refrigerator subjected to the random vibration will be fractured. Refrigerators might loss the function that they supply cold air to the freezer and refrigerator compartments (see Figure 5 and 6).



(a) A refrigerator subjected to base random vibrations



(b) Typical intermodal random vibration in the United States

Fig.6: Refrigerators subjected to base random vibrations and their power spectral density.

A random vibration in refrigeration system is motion which is non-deterministic. Refrigerator is subjected to ride on a rough road or rail, wave height on the water. A measurement of the acceleration spectral density is the usual way to specify random vibration. As seen in Figure 6, a refrigerator subjected to base is random vibrations and their power spectral density.

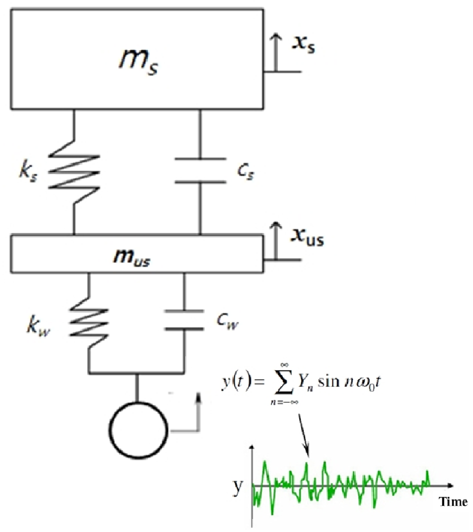


Fig.7: Two-Degree-of-Freedom Vehicle Model subjected to base random vibrations

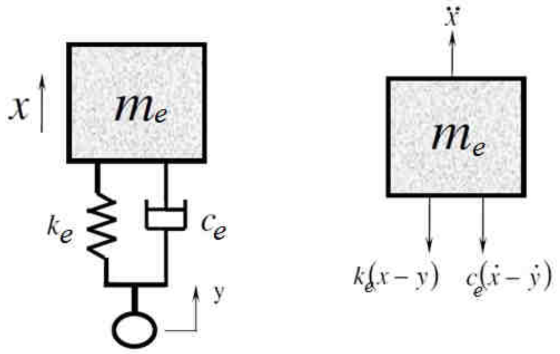


Fig.8: A simplified One-Degree-of-Freedom Vehicle Model

A refrigerator subjected to random vibration during transportation can be modeled using the two-degree-of-freedom vehicle model (see Figure 7). As seen in Figure 8, the equivalent model of refrigerator is simplified as:

$$m_e\ddot{x}+c_e\dot{x}+k_e x=k_e y+c_e\dot{y} \tag{1}$$

The force transmitted to the refrigerator can be expressed as force transmissibility Q [7]. That is,

$$Q=\frac{F_T}{kY}=r^2\left[\frac{1+(2\zeta r)^2}{(1-r^2)^2+(2\zeta r)^2}\right] \tag{2}$$

Because the stress of the refrigerator due to random vibrations during transportation depends on the transmitted vibration load (F_T) from the basis, the life-stress model (LS model) [8] can be modified as:

$$TF = A(S)^{-n} = A(F)^{-\lambda} \tag{3}$$

The acceleration factor (*AF*) can be expressed as the product of the amplitude ratio of acceleration *R* and force transmissibility *Q*. That is,

$$AF=\left(\frac{S_1}{S_0}\right)^n=\left(\frac{F_1}{F_0}\right)^\lambda=\left(\frac{a_1}{a_0}\frac{F_T}{kY}\right)^\lambda=(R\times Q)^\lambda \tag{4}$$

The characteristic life η_{MLE} from the maximum likelihood estimation (MLE) can be derived as:

$$\eta_{MLE}^\beta=\sum_{i=1}^n\frac{t_i^\beta}{r} \tag{5}$$

If the confidence level is 100(1 – α) and the number of failures is $r \geq 1$, the characteristic life, η_α, would be estimated from equation (5),

$$\eta_\alpha^\beta=\frac{2r}{\chi_\alpha^2(2r+2)}\cdot\eta_{MLE}^\beta=\frac{2}{\chi_\alpha^2(2r+2)}\cdot\sum_{i=1}^n t_i^\beta$$

for $r \geq 1$ (6)

Presuming there are no failures, *p*-value is α and In(1/α) is mathematically equivalent to chi-squared value, $\frac{\chi_\alpha^2(2)}{2}$. The characteristic life η_α, would be represented as:

$$\eta_\alpha^\beta==\frac{2}{\chi_\alpha^2(2)}\cdot\sum_{i=1}^n t_i^\beta=\frac{1}{\ln\frac{1}{\alpha}}\cdot\sum_{i=1}^n t_i^\beta$$

for $r = 0$ (7)

Equation (6) is established for all cases $r \geq 0$ and can be redefined as follows:

$$\eta_\alpha^\beta=\frac{2}{\chi_\alpha^2(2r+2)}\cdot\sum_{i=1}^n t_i^\beta \qquad \text{for } r\geq 0 \tag{8}$$

To evaluate the Weibull reliability function, the characteristic life can be converted into L_B life as follows:

$$R(t)=e^{-\left(\frac{L_{BX}}{\eta}\right)^\beta}=1-x \tag{9}$$

After logarithmic transformation, equation (9) can be expressed as:

$$L_{BX}^\beta=\left(\ln\frac{1}{1-x}\right)\cdot\eta^\beta \tag{10}$$

If the estimated characteristic life of *p*-value α, η_α, in equation (8), is substituted into equation (10), we obtain the B_X life equation:

$$L_{BX}^\beta=\frac{2}{\chi_\alpha^2(2r+2)}\cdot\left(\ln\frac{1}{1-x}\right)\cdot\sum_{i=1}^n t_i^\beta \tag{11}$$

If the sample size is large enough, the planned testing time will proceed as:

$$\sum_{i=1}^n t_i^\beta\cong n\cdot h^\beta \tag{12}$$

The estimated lifetime (L_{BX}) in test should be longer than the targeted lifetime (L^*_{BX}):

$$L_{BX}^\beta\cong\frac{2}{\chi_\alpha^2(2r+2)}\cdot\left(\ln\frac{1}{1-x}\right)\cdot n h^\beta\geq L_{BX}^{*\beta} \tag{13}$$

Then the sample size equation is expressed as:

$$n \geq \frac{\chi^2_{\alpha}(2r+2)}{2} \cdot \frac{1}{\left(\ln \frac{1}{1-x}\right)} \cdot \left(\frac{L^*_{BX}}{h}\right)^{\beta} \qquad (14)$$

However, most lifetime testing uses insufficient samples. The allowed number of failures would not be as much as that of the sample size.

$$\sum_{i=1}^{n} t_i^{\beta} = \sum_{i=1}^{r} t_i^{\beta} + (n-r)h^{\beta} \geq (n-r)h^{\beta} \qquad (15)$$

If equation (15) is substituted into equation (13), the B_X life equation can be modified as follows:

$$L_{BX}^{\beta} \geq \frac{2}{\chi^2_{\alpha}(2r+2)} \cdot \left(\ln \frac{1}{1-x}\right) \cdot (n-r)h^{\beta} \geq L_{BX}^{*\beta} \qquad (16)$$

Then, sample size equation with the number of failure can also be modified as:

$$n \geq \frac{\chi^2_{\alpha}(2r+2)}{2} \cdot \frac{1}{\left(\ln \frac{1}{1-x}\right)} \cdot \left(\frac{L^*_{BX}}{h}\right)^{\beta} + r \qquad (17)$$

From the generalized sample size equation (17), lifetime testing (or parametric ALT testing) can proceed under any failure conditions ($r \geq 0$). The equation also confirms whether the failure mechanism and the test method are proper.

For a 60% confidence level, the first term $\frac{\chi^2_{\alpha(2r+2)}}{2}$ in equation (17) can be approximated to (r + 1) [9]. If the cumulative failure rate, x, is below about 20%, the denominator of the second term $\frac{1}{1-X}$ approximates to x by Taylor expansion. Then the general sample size equation can be approximated as follows:

$$n \geq (r+1) \cdot \frac{1}{x} \cdot \left(\frac{L^*_{BX}}{h}\right)^{\beta} + r \qquad (18)$$

If the acceleration factors in equation (4) are added into the planned testing time, equation (18) will be modified as:

$$n \geq (r+1) \cdot \frac{1}{x} \cdot \left(\frac{L^*_{BX}}{AF \cdot h_a}\right)^{\beta} + r \qquad (19)$$

The reliability of three sample refrigerator was targeted to be 10 years over B_1. Based on the customer usage conditions, the operating conditions and cycles of the product (or parts) could be calculated for 10 years. Under the worst case, the objective number of cycles and the number of required test cycles can be obtained from equation (19). ALT can then be conducted on the basis of load analysis. In parameter ALT, the missing parameters in the design phase can be identified.

III. LABORATORY EXPERIMENTS

The operating conditions for three sample refrigerator were approximately 0–43 °C with a relative humidity ranging from 0% to 95%, and 0.2–0.24 g's of acceleration. Based on the field data, the rail transportation was expected to move a refrigerator 2,500 km in 2 days. For a total elapsed transportation time of 7 days, the refrigerator moved 7,200 km from Los Angeles to Boston.

(a) Horizontal vibration (Left ↔ Right)

(b) Vertical vibration (Up ↔ Down)

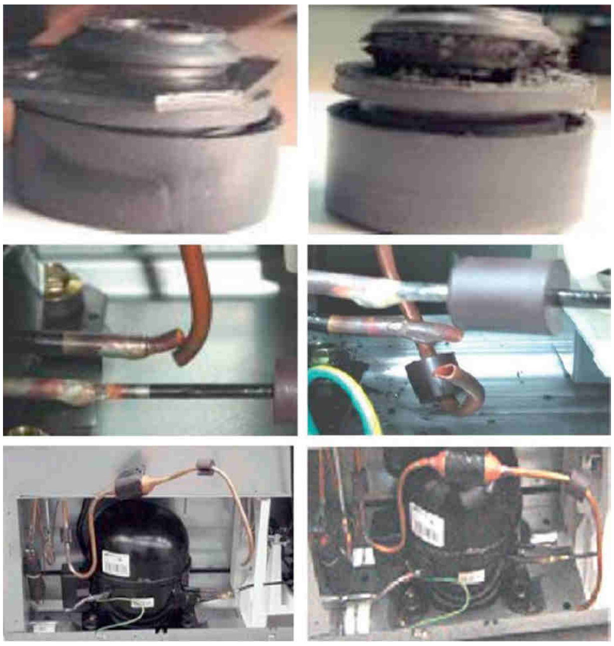
Fig.9: Vibration test equipment for the accelerated life tests

Table 1. ALT Conditions for accelerated testing of the refrigerator

System Conditions	Worst Case	ALT	AF
Transmissibility, Q (r = 1.0, ζ = 0.1)	-	5.1 (From eq. 2)	5.1 ①
Amplitude ratio of acceleration, R (a_1/a_0)	0.24 g	1 g	4.17 ②
Total *AF* (=(①×②)^2)			452

When the refrigerator was subjected to an acceleration of 1 g on a shaker table, the natural frequencies of horizontal vibration (left ↔ right) and vertical vibration (up ↔ down) were 5 Hz and 9 Hz in the package test (Figure 9). For natural frequency (r = 1.0) and small damping ratio (ζ = 0.1), the force transmissibility had a value of approximately 5.1 from equation (2). The amplitude ratio of acceleration was 4.17 (Table 1). Using a cumulative damage exponent of 2.0, the acceleration factor in equation (4) was found to be approximately 452.0. The shape parameter in the Weibull chart was 6.41, and the required target x for the B1 life was 0.01.

The test time and the number of samples used in the ALT calculated from equation (19) were approximately 40 min and 3 units without failure, respectively. Parametric ALT was designed to ensure a B1 of 10 years life with about a 60% level of confidence that the refrigerator would fail less than once during 40 min that makes up the reliability quantitative (RQ) test specifications.



(a) Field *(b) 1st ALT Results*

Fig.10: Failure of refrigerator tubes in the field and 1st ALT result.

All refrigerators in the parametric ALTs were fractured from horizontal vibration. Figures 10 (a) and (b) show the failed products from the field and the fractured samples from the ALT, respectively. The photos show that the shapes and locations of the failures in the ALT were similar to those seen in the field.

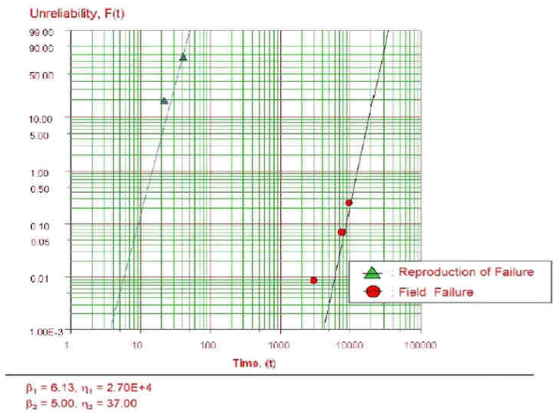


Fig.11:Field data and results of parametric ALT on a Weibull chart.

A graphical analysis of the ALT results and field data on a Weibull plot were shown in Figure11. Parametric ALT was valid in pinpointing the design weaknesses that were responsible for the failures in the field. From the Weibull plot, the shape parameter was confirmed to be 6.13.

The design flaws of the refrigerator that experienced fractured tubes between the compressor and condenser areas could be corrected by modifying the shape of the compressor rubber mount and the connecting tube design. The design improvements corresponded to the missing key control parameters (KCPs), as listed in Table 2.

Table 2. Confirmed key parameters based on the parameter ALTs

Failure Mechanism	Parameters			Unit
Fracturing	KNP	N1	Random vibration force	N
	KCP	C1	Shape of the compressor rubber	-
		C2	Connecting tube design	-

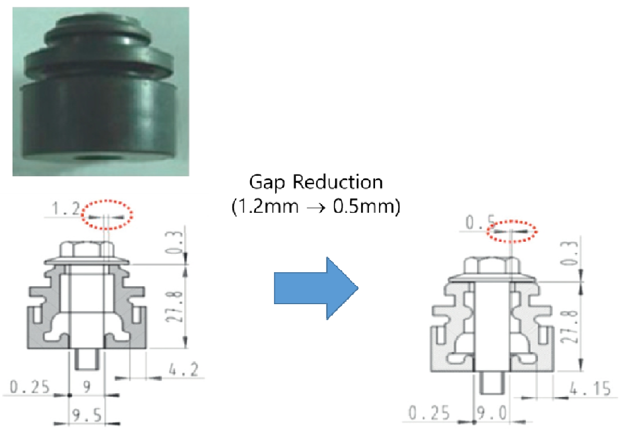


Fig.12. Shape of compressor rubber (polymer) mount

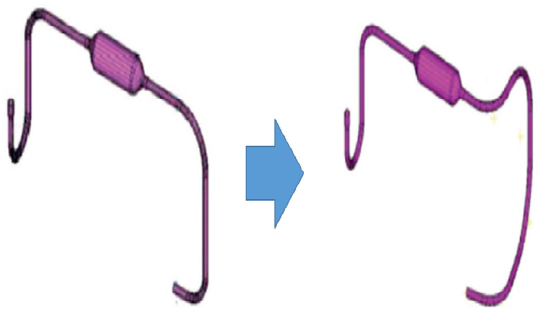


Fig.13. Shape of the connecting tube design

Figure 12 and 13 shows the redesigned refrigerator that has 1) a redesigned compressor rubber mount shape (C1); and 2) a redesigned connecting tube (C2). With these modified parameters, second ALTs were carried out. The design targets of the newly designed samples were more than the target life of a B1 of 10 years. The confirmed values of *AF* and β in Table 1 and Figure 11 were 452.0 and 6.41, respectively. The recalculated test time and sample size in equation (10) were 40 min and 3 EA, respectively. In the second ALT, the refrigerators were not fractured.

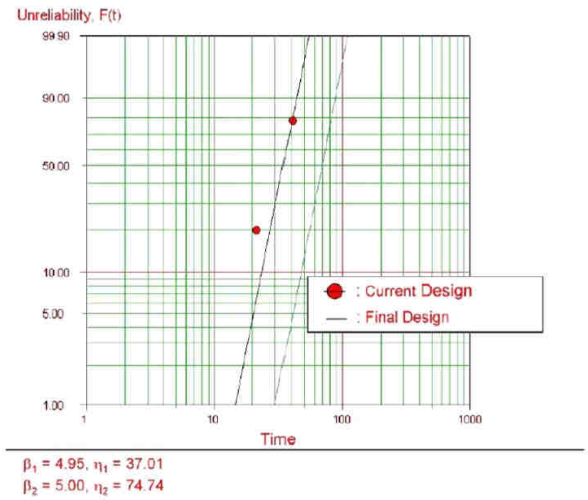


Fig.14. Field data and results of accelerated life test on Weibull chart.

Figure 14 and Table 3 show the graphical results of an ALT plotted in a Weibull chart and a summary of the results of the ALTs, respectively. Over the course of the two ALTs, refrigerators with the targeted B1 life were expected to survive without failure during rail transport.

Table 3 Results of ALTs

	1st ALT	2nd ALT
	Initial Design	Final Design
In 40 min, fracture of the connecting tube in refrigerator is less than 1	20 min: 1/3 fracture 40 min: 1/3 fracture	40 min: 3/3 OK 60 min: 3/3 OK
Machine room in refrigerator		
Material and specification	C1: Shape of the compressor rubber C2: Connecting tube design	

IV. CONCLUSIONS

Robust methodologies were used to improve the reliability of residential-sized refrigerators subjected to repetitive random vibration loads during transportation. These methodologies included setting an overall parametric ALT plan for the product, identifying the failure modes and mechanisms of fractured refrigerators in the field, conducting a series of ALTs, and redesigning the refrigerators based on the ALTs. Based on the products that failed both in the field and in the ALTs, the primary failure of the refrigerators occurred due to fracturing of the tubes between the compressor and condenser. The missing design parameters in the design phase of the refrigerator were the shape of compressor rubber mount and the connecting tube. The corrective action plans included revising the shape of the compressor rubber mount and the connecting tube. Based on the second set of ALTs, cracking occurred in residential-sized refrigerators subjected to repetitive random vibration loads during transportation. After a sequence of ALTs, the proper values for the design parameters were determined to meet the life cycle requirements—B1 of 10 years, respectively. Inspection of the failed product, load analysis, and two rounds of ALTs indicated that the newly designed residential refrigerator was greatly improved using the new robust design methodologies. Case studies on the design flaws also were suggested in references 11 through 21.

Nomenclature

a_0 Random acceleration under normal conditions, m/sec

a_1 Random acceleration under accelerated stress conditions, m/sec^2

AF Acceleration factor

BX Durability index

C1 Shape of compressor rubber

C2 Connecting tube design

F(t) Unreliability

F Force, *kN*

F1 Transmitted vibration force under accelerated stress conditions, N

F0 Transmitted vibration force under normal conditions, N

h Testing cycles (or cycles)

h^* Non-dimensional testing cycles, $h^* = h/L_B \geq 1$

KCP key control parameter

KNP key noise parameter

L_B Target B_X life and x = 0.01X, on the condition that $x \leq 0.2$

n Number of test samples
$N1$ Transmitted random vibration force under customer usage pattern, kN
Q Force transmissibility, F/kY
R Amplitude ratio of acceleration, A_a/A
r Frequency ratio, ω/ω_n
r Failed numbers
S Stress
S_1 Mechanical stress under accelerated stress conditions
S_0 Mechanical stress under normal conditions
t_i Testing time for each sample
TF Time to failure, h
x $x = 0.01 \cdot X$, on condition that $x \le 0.2$.
Y Range of sinusoidal base excitations

Greek symbols
τ Period of oscillation (time), sec
ϕ Phase angle, rad
η Characteristic life
ω Frequency of oscillation, rad/s
ω_0 Fundamental frequency, $\omega_0 = 2\pi/s$
ω_n Natural frequency, rad/s

Superscripts
β Shape parameter in a Weibull distribution
n Stress dependence, $n = -\left[\dfrac{\partial \ln(T_f)}{\partial \ln(S)}\right]_T$
λ Power index or cumulative damage exponent

Subscripts
0 Normal stress conditions
1 Accelerated stress conditions
e equivalent

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