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Reliability Design of Mechanical System-Like Water-Dispensing System in Refrigerator Subjected to Repetitive Impact Loading

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Abstract

Based on field data and parametric accelerated life tests (ALT), the mechanical system-like water-dispensing system in a bottom-mounted freezer (BMF) was redesigned to find out the missing design parameter in the design phase. To carry out parametric ALTs using a force/momentum balance, the simple mechanical loads of the water-dispensing system were analyzed. At the first ALT, the hinge and front corner of dispenser lever were fractured. The failure shapes found experimentally were similar to those of the failed samples in field. Dispenser lever in water-dispensing system was modified as having its fillets and ribs. At the second ALT, the modified dispenser lever also was fractured because of not having enough strength for impact loading at its front corner. The missing design parameters of the dispenser lever were not enough to have corner fillet rounding and rib thickness. After parameter ALTs with corrective action plans, reliability of the newly designed water-dispensing system is assured to have B1 life 10 years with a failure rate of 0.1%/year.

Keywords: reliability design, water-dispensing system, parametric accelerated life testing, missing design parameter

1. Introduction

As customers want to have water-dispensing function, **Figure 1** shows the bottom-mounted freezer (BMF) refrigerator with the newly designed water-dispensing system. As shown in **Figure 1(b)**, it consists of the dispenser cover, spring, and dispenser lever. To dispense water for a product lifetime, the dispenser system needs to be designed to withstand the operating conditions subjected to it by the consumers who use the BMF refrigerator. Dispensing water in the BMF refrigerator has several operating steps: (1) press the lever and (2) dispense water.

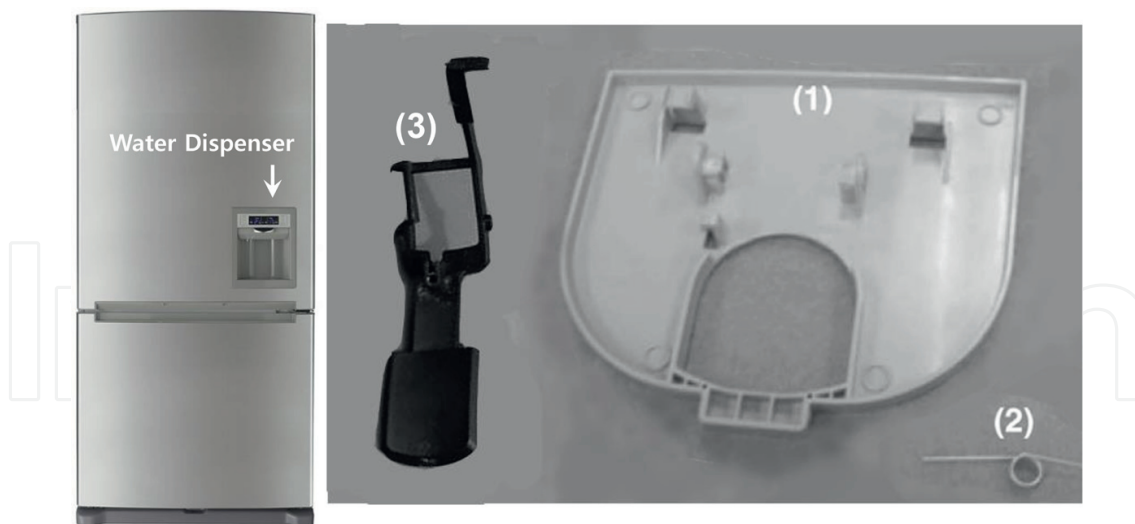


Figure 1. BMF refrigerator with the newly designed water-dispensing system. (a) BMF refrigerator. (b) mechanical parts of dispenser: (1) dispenser cover, (2) spring, and (3) dispenser lever.

He will push the dispenser lever if customer want to drink the cooling water. Consequently, the water-dispenser system will have a variety of repetitive mechanical loads when the consumer uses it, though depending on the consumer usage conditions.

The water-dispensing system in field had been fracturing, causing end-users to replace their product. When subjected to repetitive stresses in operating refrigerator, the failed water-dispensing system came from the design flaws. Market data also showed that the returned products had critical design flaws in structure, including stress risers—sharp corner angles and thin ribs—in the water-dispensing system. The design flaws that could not withstand the repetitive impact loads on the water-dispensing system could cause a crack to occur. Thus, the reliability design of the new water-dispensing system is required to robustly withstand repetitive loads under customer usage conditions (**Figure 2**).

A typical pattern of repeated load or overloading may cause structural failure in product lifetime under the customer usage conditions. Many engineers think such possibility can be assessed: (1) mathematical modeling like Newtonian method, (2) the time response of system simulation for (random) dynamic loads, (3) the rain-flow counting method, and (4) miner's rule that the system damage can be estimated [1–3]. However, because there are a lot of assumptions, this analytic methodology is exact but complex to reproduce the product failures due to the design flaws in field.

Robust design skills like Taguchi methods and statistical design experiments (SDE) [4–9] were studied by engineers and statisticians many years ago. Especially, Taguchi's robust design method utilizes parameter design to place it in a location where random noise factors do not cause effects and determines the optimal design parameters and their levels. As utilizing interactions between control factors and noise factors, the purpose of parameter design is to find the proper control factors that make the system's performance robust in relation to changes in the noise factors. In the robust design process, the noise factors are assigned to an outer array, and the control factors are assigned to an inner array in a complex matrix (**Figure 3**).

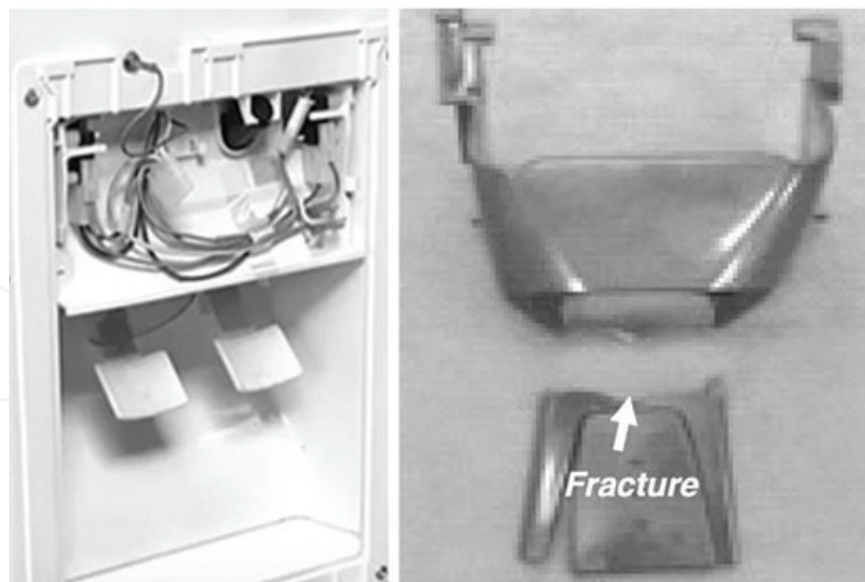


Figure 2. A damaged product after use.

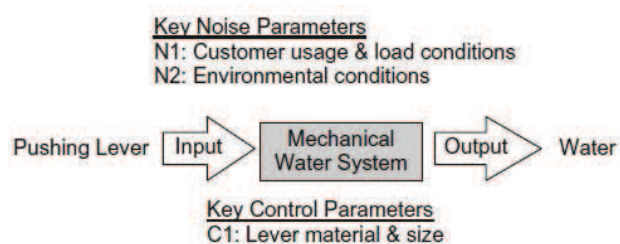


Figure 3. Parameter diagram of water-dispensing system.

However, as the noise array is calculated repeatedly for every row in the control array repetitive, experimental iterations in the Taguchi product array would require a lot of computing time. Because a mechanical structure has complex shape, Taguchi method would require infinite iterations. It is not easy to search out solutions in the robust design process, though a mechanical structure is simple. Newly designed refrigerators with the missing design parameters may result in reliability disasters and pay the huge quality costs.

In this study, we suggest a new parametric accelerated life testing (ALT) method that can enhance the reliability design of newly designed water-dispensing system. To confirm the design parameters, parametric ALT will utilize load analysis, new sample size equations with accelerated factor, and the modifications of dispenser system. It will benefit to confirm the final design of new product. Another case study of this new reliability testing methodology [10–23] will be suggested.

2. Load analysis

As seen in **Figure 4**, the mechanical dispensing system works like the functional design concept. To properly operate the water-dispensing system, its mechanical lever assembly consists of many mechanical structural parts. When a cup touches on the lever to release the

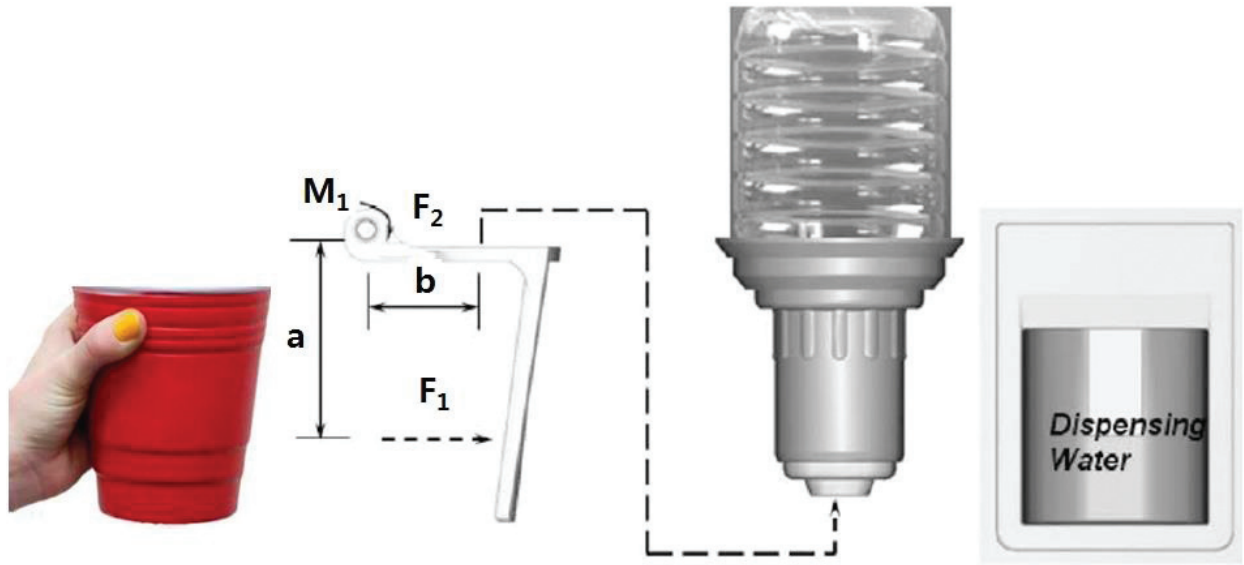


Figure 4. Functional design concept of the mechanical dispensing system.

water, water will dispense. Depending on the end-user usage conditions, the lever assembly goes through repetitive impact loads in the water-dispensing process. The concentrated stress of the pressing cup reveals sharp corner angles. As a result, the impact force applies on the hinge of lever. When designing the mechanical dispensing system, it is a critical design step to withstand these repetitive stresses. In the United States, the typical consumer claims the refrigerator to release water from 4 to 20 times a day.

From the free-body diagram of the simple lever system, the force and momentum at hinge can be represented as

$$F = F_1 \quad (1)$$

$$M = aF_1. \quad (2)$$

Because the stress of the dispenser lever depends on the applied force of cup, the life-stress model (LS model) [24] can be represented as

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

The acceleration factor (AF) can be derived as

$$AF = \left(\frac{S_1}{S_0} \right)^n = \left(\frac{F_1}{F_0} \right)^\lambda. \quad (4)$$

3. Parametric accelerated life testing (ALT) in water-dispensing system

To derive the sample size equation and carry out parametric ALT, probability concepts in reliability engineering should be made out. First of all, the characteristic life η_{MLE} from the maximum likelihood estimation (MLE) can be derived as:

$$\eta_{MLE}^{\beta} = \sum_{i=1}^n \frac{t_i^{\beta}}{r}. \quad (5)$$

If the confidence level is $100(1 - \alpha)$ and the number of failure is $r \geq 1$, the characteristic life, $\eta_{\alpha r}$ would be estimated from Eq. (4)

$$\eta_{\alpha}^{\beta} = \frac{2r}{\chi_{\alpha}^2(2r+2)} \cdot \eta_{MLE}^{\beta} = \frac{2}{\chi_{\alpha}^2(2r+2)} \cdot \sum_{i=1}^n t_i^{\beta}, \quad \text{for } r \geq 1. \quad (6)$$

If there are no failures, p -value is α and $\ln(1/\alpha)$ is mathematically equivalent to chi-squared value, $\frac{\chi_{\alpha}^2(2)}{2}$. The characteristic life, $\eta_{\alpha r}$ would be expressed as:

$$\eta_{\alpha}^{\beta} = \frac{2}{\chi_{\alpha}^2(2)} \cdot \sum_{i=1}^n t_i^{\beta} = \frac{1}{\ln \frac{1}{\alpha}} \cdot \sum_{i=1}^n t_i^{\beta}, \quad \text{for } r = 0. \quad (7)$$

Because Eq. (6) is established for all cases $r \geq 0$, it can be redefined as:

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

From the Weibull reliability function, we can find out that the characteristic life can be converted into L_B life as:

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

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

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

If the estimated characteristic life of p -value α , $\eta_{\alpha r}$ in Eq. (8), is substituted into Eq. (10), we obtain the BX life equation:

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

For a 60% confidence level, the first term $\frac{\chi_{\alpha}^2(2r+2)}{2}$ in Eq. (11) can be approximated to $(r+1)$ [25]. By Taylor expansion, if the cumulative failure rate, x , is below 20%, the second term $\ln \frac{1}{1-x}$ approaches to x , and it can be represented as:

$$L_{BX}^{\beta} = \frac{x}{r+1} \cdot \sum_{i=1}^n t_i^{\beta}. \quad (12)$$

Most lifetime testing has insufficient samples. The allowed number of failures would not have as much as that of the sample size.

$$\sum_{i=1}^n t_i^\beta = \sum_{i=1}^r t_i^\beta + (n-r)h^\beta \geq (n-r)h^\beta. \quad (13)$$

If Eq. (13) is substituted into Eq. (12), the BX life equation can be modified as follows:

$$L_{BX}^\beta \geq \frac{x}{r+1} \cdot (n-r)h^\beta \geq L_{BX}^{*\beta}. \quad (14)$$

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

$$n \geq (r+1) \cdot \frac{1}{x} \cdot \left(\frac{L_{BX}^*}{h} \right)^\beta + r. \quad (15)$$

From the sample size Eq. (15), we can go on parametric ALT testing under any failure condition ($r \geq 0$). Consequently, it also confirms whether the failure mechanism and the test method are proper.

If the acceleration factors in Eq. (4) are replaced with the planned testing time h , Eq. (15) will be modified as:

$$n \geq (r+1) \cdot \frac{1}{x} \cdot \left(\frac{L_{BX}^*}{AF \cdot h_a} \right)^\beta + r. \quad (16)$$

Reliability target of the new water-dispensing system is over B1 life 10 years. The operating conditions and cycles of the dispenser system were examined, based on the customer usage conditions. Under B1 life 10 years, if the objective number of life cycles L_{BX} and AF are given, the actual required test cycles h_a can be obtained from Eq. (16). ALT equipment can then be conducted in accordance with the operation procedure of the dispenser system. In parameter ALT, we can obtain the missing design parameters.

4. Laboratory experiments

For the water-dispensing system in BMF refrigerator, the working conditions of customer are about 0–43°C with a relative humidity ranging from 0 to 95% and 0.2–0.24 g's of acceleration. The water dispensing happens approximately 4–20 times per day. With a product life cycle design point for 10 years, water-dispensing system approximately happens for 73,000 usage cycles.

The maximum force expected by the consumer in dispensing water was 19.6 N. For accelerated testing, the applied force makes from double to 39.2 N. With a quotient, λ , of 2, the total AF was approximately 4.0 using Eq. (4). To find out missing design parameter of the newly designed water-dispensing system, reliability target can be set to more than the B1 life 10 years. Presumed the shape parameter β was 2.0 and x was 0.01, the actual test cycles calculated in Eq. (16) were 65,000 cycles for sample size 8 units. If parametric ALT for water-dispensing system fails less than once during 65,000 cycles, it will be guaranteed to have a B1 life 10 years with about a 60% level of confidence (**Figures 5 and 6**).

Figure 7(a) and **(b)** shows the failed product from the field and the first accelerated life testing, respectively. The failure sites in the field and the first ALT occurred at the hinge and front corner of dispenser levers as a result of high-impact stress. **Figure 8** represents a graphical analysis if

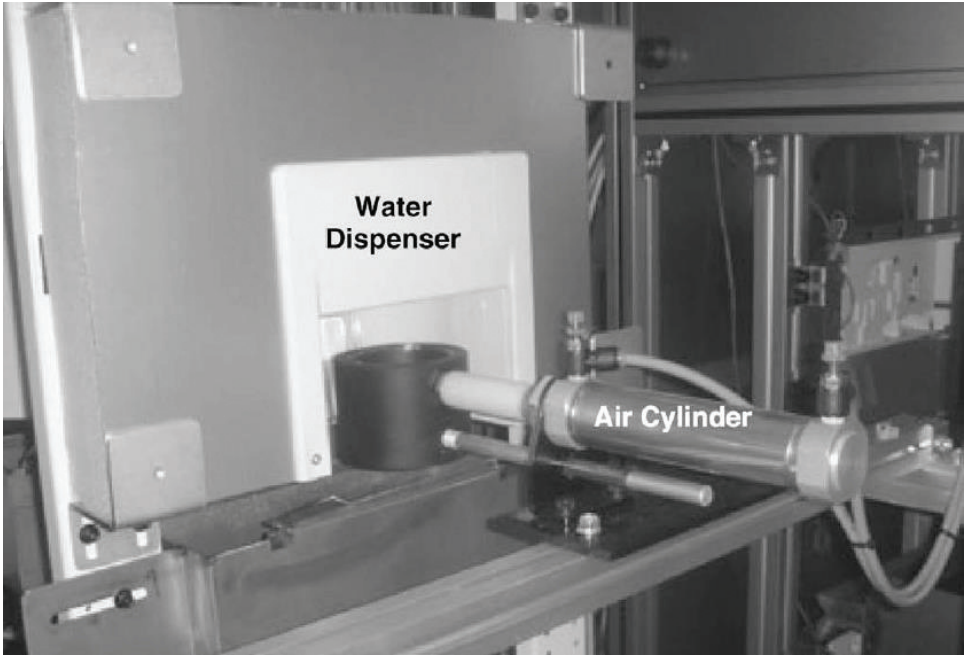


Figure 5. Equipment used in accelerated life testing.

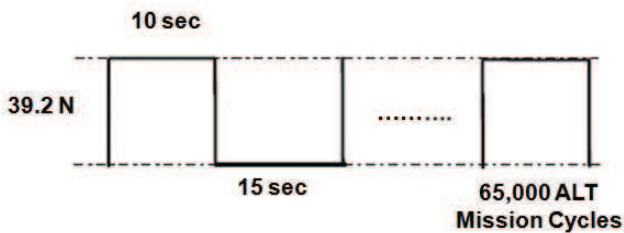


Figure 6. Duty cycles of repetitive impact load F on the water-dispensing system.

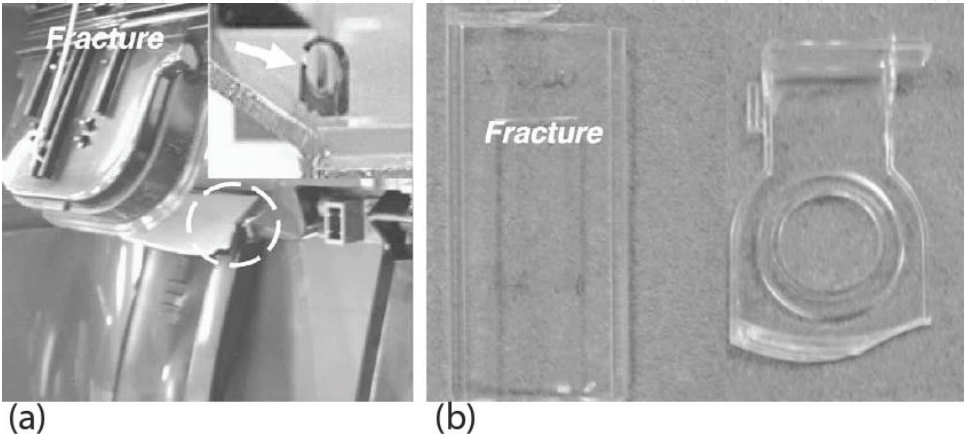


Figure 7. Failed products in field and crack after first ALT. (a) Failed products in field. (b) Crack after first ALT.

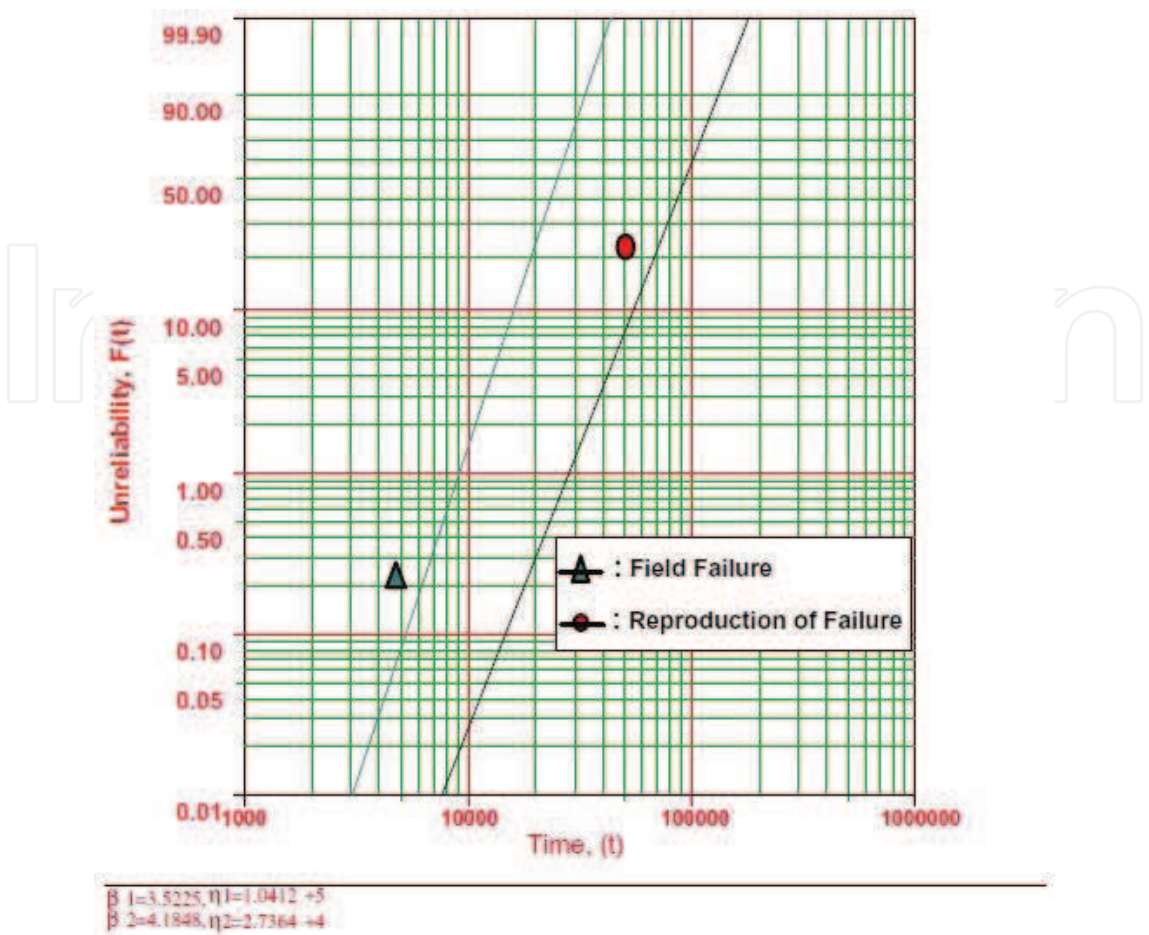


Figure 8. Field data and first ALT on Weibull chart.

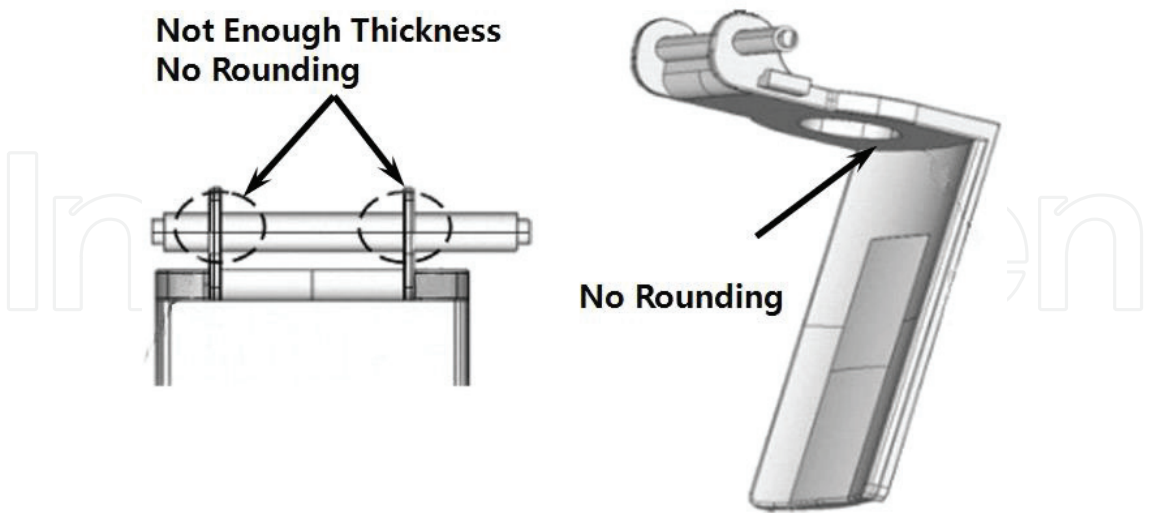


Figure 9. Structure of failing dispenser lever in field.

the ALT results and field data are plotted on Weibull distributions. For the shape parameter, the estimated value on the chart was 2.0. For the final design, the shape parameter was determined to be 3.5. The reduction factor R was 0.01 from the experiment data—product lifetime L_B ,

acceleration factor AF , actual mission cycles h_a , and shape parameter β . It means that R is β power of product lifetime versus testing cycle. Consequently, we know that this parameter ALT is effective to decrease the sample size because reduction factor is less than 0.1 from Eq. (16).

As seen in **Figures 7(b)** and **9**, the fracture of the dispenser lever in the first and second ALTs occurred in its hinge and front corner. As shown in **Table 1**, the missing design parameters of the dispenser lever can be listed. If dispenser lever is subjected to the repetitive impact load, we can conclude that its design flaws can result in a fracture.

To withstand the fracture of dispenser lever due to the repetitive food stresses, the dispenser lever was redesigned as follows: (1) increasing the rib rounding of hinge, C1, from R0 to R2.0 mm; (2) increasing the front corner rounding, C2, from R0 to R1.5 mm; (3) increasing the rib

CTQ	Parameters			Unit
Crack	KNP	N1	Impact loading	N
		C1	Hinge rib rounding, fillet1	mm
		C2	Front corner rounding, fillet2	mm
	KCP	C3	Hinge rib thickness, rib1	mm
		C4	Front side rounding, fillet3	mm
		C5	Front lever thickness, rib2	mm

Table 1. Vital parameters based on ALTs.

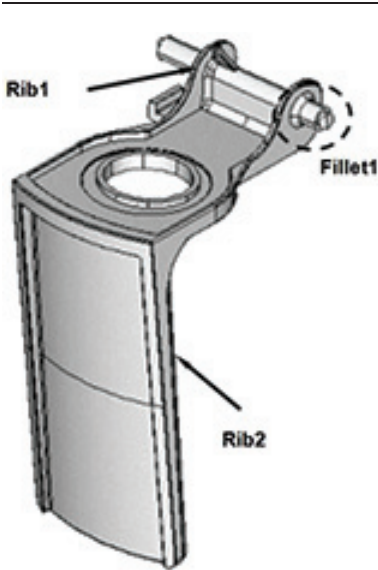
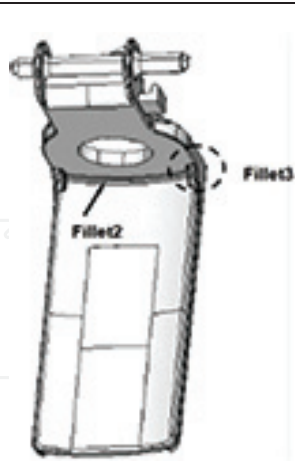
	
C1: Fillet1 R0 → R1.5 (1st ALT) → R2.0 (2nd ALT)	C2: Fillet2 R0 → R1.5 (1st ALT)
C3: Rib1 T1 → T1.8 (1st ALT)	C4: Fillet3 R0 → R8 (1st ALT) → R11 (2nd ALT)
C5: Rib2 T3 → T4 (3rd ALT)	

Table 2. Redesigned dispenser lever.

thickness of hinge, C3, from T1 to T1.8; (4) increasing the front side rounding, C4, from R0 to R11 mm; and (5) thickening the front lever, C5, from T3 to T4 mm (**Table 2**).

As the design flaws make better, the parameter design criterion of the newly designed samples was secured to have more than the reliability target—B1 life 10 years. The confirmed value, β , on the Weibull chart was 3.5. For the second ALT with sample size 8 units, the actual test cycles in Eq. (16) were 38,000. In the third ALT, there were no design problems of the water-dispensing system until the test was carried out to 68,000 cycles. We therefore concluded that the modified design parameters found from first and second ALT were effective.

Table 3 summarizes the ALT results. **Figure 10** also shows the results of the first ALT and third ALT plotted in the Weibull distribution. With the modified design parameters, final samples of the water-dispensing system were guaranteed to reliability target—B1 life 10 years.


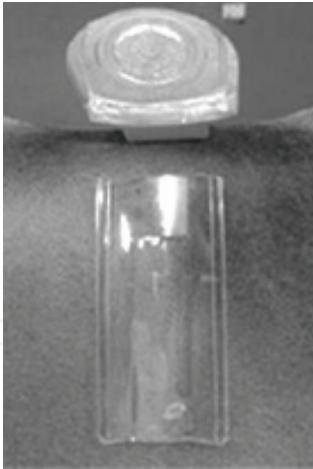
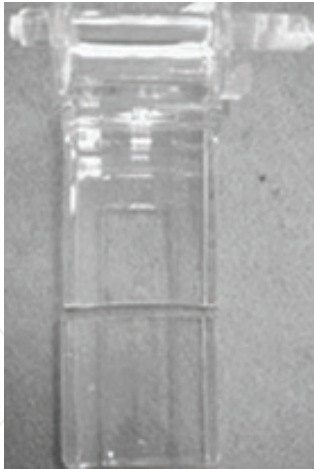
	1st ALT	2nd ALT	3rd ALT
	Initial design	Second design	Final design
In 38,000 cycles, lever has no crack	25,000 cycles: 2/8 fracture	32,000 cycles: 1/8 fracture	38,000 cycles: 8/8 OK 56,000 cycles: 8/8 OK 68,000 cycles: 1/8 fracture
Freezer Drawer Structure			
Material and specification	C1: Fillet 1 R0 → R1.5 C2: Fillet2 R0 → R1.5 C3: Rib1 T1 → T1.8 C4: Fillet3 R0 → R8	C1: Fillet 1 R1.5 → R2.0 C2: Fillet 2 R8.0 → R11.0	C3: Rib2 T3.0 → T4.0

Table 3. Results of ALTs.

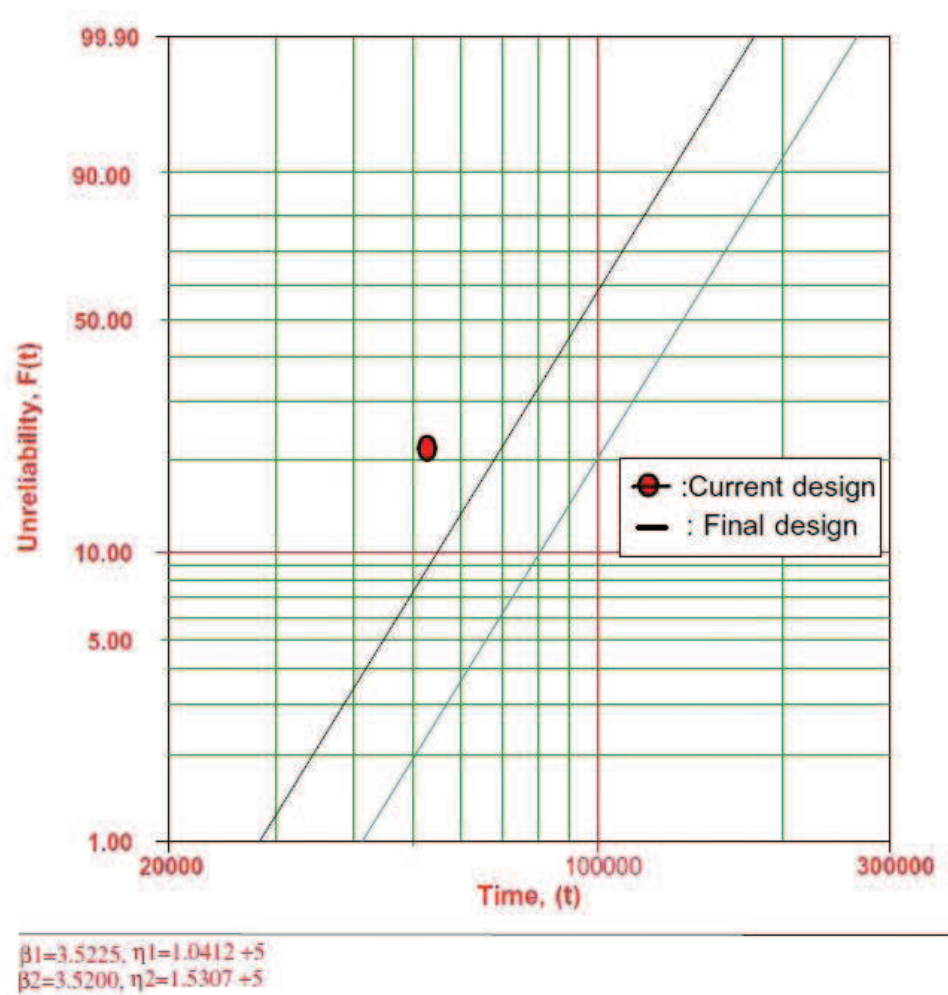


Figure 10. Results of ALT plotted in Weibull chart.

5. Conclusions

We suggested a new reliability design method for newly designed water-dispensing system in BMF refrigerators. The missing design parameters for the water-dispensing system were identified through parameter ALTs. At that time, the reliability target was B1 life 10 years.

As previously seen in the first ALT, the hinge and front corner of dispenser lever were fracturing because of design flaws due to repetitive impacting stress. As increasing the fillets and ribs of the dispenser lever, the water-dispensing lever system was corrected. During the second ALT, the front corner of dispenser lever also fractured because they did not have enough strength to withstand the repetitive impact loads. As additional reinforced ribs of dispenser lever were provided, we knew that the design of water-dispensing system was improved robustly.

As a result of these modified design parameters, there were no problems in the third ALT. Consequently, the modified design parameters were guaranteed to have the reliability requirement of water-dispensing system—B1 life 10 years. Through the inspection of returned products in field, load analysis, and parametric ALTs, we knew that the study of the missing design parameters of the water-dispensing system in the design phase was very effective in redesigning more reliable parts with significantly longer life.

Nomenclature

AF	Acceleration factor
BX	Durability index
$C1$	Hinge rib rounding, fillet1, mm
$C2$	Front corner rounding, fillet2, mm
$C3$	Hinge rib thickness, rib1, mm
$C4$	Front side rounding, fillet3, mm
$C5$	Front lever thickness, rib2, mm
$F(t)$	Unreliability
F	Force, N
$F1$	Pushing force under accelerated stress conditions, N
$F0$	Pushing 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
$N1$	Consumer pushing force, N
R	Reduction factor, $R = (L_B/AF \cdot h)^\beta \geq 1$
r	Failed numbers
S	Stress
S_1	Mechanical stress under accelerated stress conditions
S_0	Mechanical stress under normal conditions
t_i	Test time for each sample
TF	Time to failure
X	Accumulated failure rate, %
x	$x = 0.01 \cdot X$, on condition that $x \leq 0.2$
Greek symbols	
η	Characteristic life

λ	Cumulative damage exponent
μ	Friction coefficient
<i>Superscripts</i>	
β	Shape parameter in a Weibull distribution
n	Stress dependence, $n = - \left[\frac{\partial \ln(T_f)}{\partial \ln(S)} \right]_T$
<i>Subscripts</i>	
0	Normal stress conditions
1	Accelerated stress conditions

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