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International Compressor Engineering Conference

School of Mechanical Engineering

2018

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# Improving the reliability of a domestic refrigerator compressor subjected to repetitive pressure loading

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## ABSTRACT

To improve the reliability of compressor subjected to repetitive pressure loading, a reliability methodology for parametric accelerated life testing (ALT) was suggested. It consisted of a parametric ALT plan, a generalized life-stress failure model with a new effort concept, an acceleration factor, and a sample size equation. Based on failure analysis, this parametric ALT should help an engineer uncover the design parameters affecting reliability during the design process of a compressor. As a test case, a compressor with a newly designed crankshaft subjected to repetitive pressure loading was studied. Using a mass and energy balance analysis, the pressure loads of compressor were analyzed. In the first ALT and field, the failure mode was compressor locking due to crankshaft wear. The missing design parameter of the crankshaft was the improper lubrication structure in the crankshaft. As a corrective action plan, the crankshafts were redesigned. In the second ALT, wear in the compressor crankshaft occurred. The minimum clearance between the crankshaft and thrust washer was then modified. After another parametric ALT with corrective action plans, the reliability of the newly designed compressor was expected to have a life of 10 years with a failure rate of 0.1%/year

## 1. INTRODUCTION

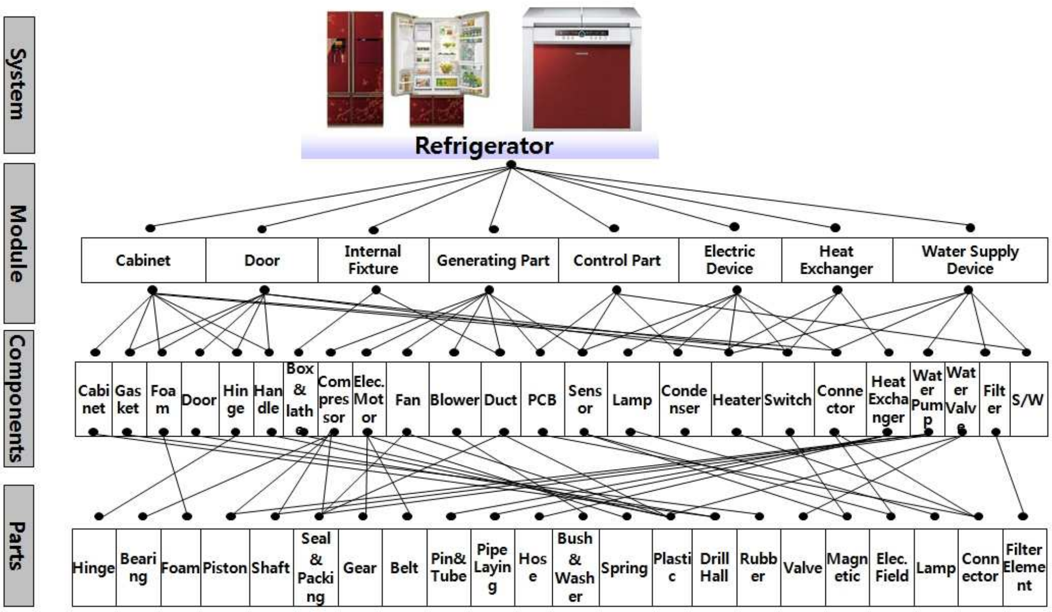



**Figure 1:** Breakdown of a refrigeration system with its modules, components, and parts

To store the fresh foods, a refrigerator provides cold air from the evaporator to the freezer and refrigerator compartments. A refrigerator includes the compressor and several different modules – cabinet, door, internal fixture (selves, draws), controls and instruments, generating parts (motor or compressor), heat exchanger, water supply device, and other miscellaneous parts (Figure 1).
Customers often want to have a refrigerator with low energy use and high reliability. For this (intended) function, the compressor can be redesigned to improve the overall energy efficiency of the refrigerator. The compressor needs to be designed to handle the operating conditions subjected to it by the consumers who purchase and use the refrigerator. To avoid the compressor failure in field, any defective configurations should be found and modified by experimental methods before launching the product. Based on failure analysis from returned product, compressor was locked because of the lubrication designs like oil shortage.
Repeated loads or overloading due to daily consumer usage may cause structural failure in the product and reduce its lifetime. Many engineers think such possibilities can be assessed by: 1) mathematical modeling using Newtonian methods, 2) assessing the time response of the system for dynamic loads, 3) utilizing the rain-flow counting method (Matsuishi, 1968), and 4) estimating system damage using the Palmgren-Miner's rule (1924). However, because there are many assumptions, this analytic methodology may be exact, but complex to reproduce the product failures due to the design flaws.
Robust design methods, including statistical design of experiments (DOE) and the Taguchi approach (1978) were developed to carry out optimal design for mechanical products. In particular, Taguchi's robust design method uses parametric design to place it in a position where random ''noise" does not affect the outcome. Thus, mechanical systems can be used to find out the proper design parameters and their levels. Through utilizing interactions between control factors and noise factors, the parametric design of a mechanical system can be used to determine the proper control factors that make the design robust regardless of the change of noise factors. In an orthogonal array, as the control factors are assigned to an inner array, the noise factors are assigned to an outer array.
However, because huge experimental computations in the Taguchi product array are required, a lot of design parameters for a mechanical structure should be considered. As new products are introduced with the missing design parameters in the mechanical structure, the product may result in recalls and loss of brand-name value.
Based on failure analysis, the purpose of this study was to present a reliability methodology for a compressor subjected to repetitive pressure loading in a commercially produced refrigerator. The reliability methodology included: 1) A parametric ALT plan, 2) a load analysis in field, 3) a tailored sample of parametric ALTs with the design modifications, and 4) the checking of the final design of the compressor to determine that it satisfied the reliability target.

## 2. Materials & Methods

### 2.1 Setting Overall Parametric ALT Plan

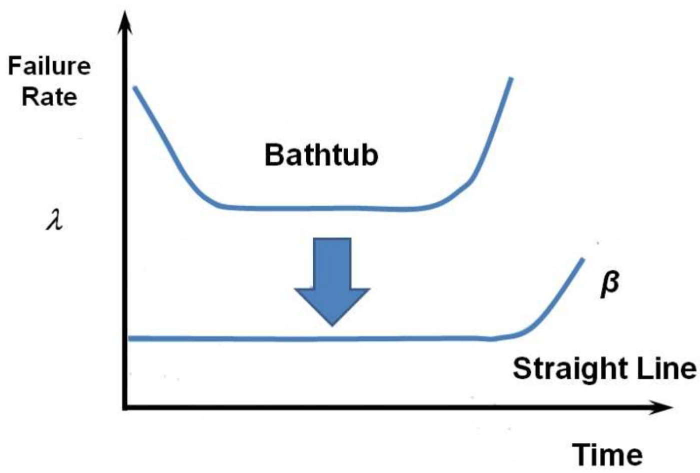



**Figure 2:** Bathtub curve and straight line with slope $\beta$

The reliability of compressor can be defined as the ability of a system or module to function under stated conditions for a specified period of time. It can be illustrated in a diagram called "the bathtub curve" that consists of three parts.

First, there is a decreasing failure rate early in the life of the product. Then, there is a constant failure rate. Finally, there is an increasing failure rate toward the end of the product's life. If a product follows the bathtub curve, it will have difficulties in succeeding in the market because of the large failures and short lifetime in the life of the product. Because of the faulty designs, the mechanical product will have higher failure rates in operation and incur financial losses for the company. The company will improve the design of product by setting reliability goals for new products to (1) reduce early failures, (2) decrease random failures during the product operating time, and (3) increase product lifetime. As the reliability of a mechanical product is improved, the failure rate of the product in the field should decline. For such a situation, the traditional bathtub curve with faulty design can be transformed to a straight line with the shape parameter β (Figure 2).
In the meantime, the mechanical product might be quantified from the product lifetime $L_B$ and failure rate $\lambda$ as follows:

$$R(L_B) = 1 - F(L_B) = e^{-\lambda L_B} \cong 1 - \lambda L_{BX} \tag{1}$$

This equation is applicable below about 20 percent of cumulative failures (Kreyszig, 2006). The reliability design of the mechanical system can be achieved by getting the targeted product lifetime $L_B$ and failure rate $\lambda$ after finding the missing control parameters and modifying the defective configuration of structures through parametric accelerated life testing (ALT).

**Table 1:** Overall parametric ALT plan of Refrigerator

| No | Modules | Market Data | | Design | Conversion | Expected | | Targeted | |
|---|---|---|---|---|---|---|---|---|---|
| | | Yearly Failure Rate, %/yr | $B_x$ Life, yr | | | Yearly Failure Rate, %/yr | $B_x$ Life, yr | Yearly Failure Rate, %/yr | $B_x$ Life, yr |
| 1 | Module A | 0.34 | 5.3 | New | x5 | 1.70 | 1.1 | 0.10 | 10 ($x$=1.0) |
| 2 | Module B | 0.35 | 5.1 | Given | x1 | 0.35 | 5.1 | 0.15 | 10 ($x$=1.5) |
| 3 | Module C | 0.25 | 4.8 | Modified | x2 | 0.50 | 2.4 | 0.10 | 10 ($x$=1.0) |
| 4 | Module D | 0.20 | 6.0 | Modified | x2 | 0.40 | 3.0 | 0.10 | 10 ($x$=1.0) |
| 5 | Module E | 0.15 | 8.0 | Given | x1 | 0.15 | 8.0 | 0.15 | 10 ($x$=1.5) |
| 6 | Others | 0.50 | 12.0 | Given | x1 | 0.50 | 12.0 | 0.40 | 10 ($x$=4.0) |
| Total | R-Set | 1.79 | 7.4 | - | - | 3.60 | 3.7 | 1.00 | 10 ($x$=10) |

In targeting the reliability of the refrigerator in a parametric ALT, there are three cases for modules: 1) a modified module, 2) new module, and 3) similar module to the prior design on the basis of market data. The compressor in a refrigerator is modified module added because customers want improved energy efficiency. Like module D listed in Table 1, compressors from the field data had yearly failure rates of 0.31 %/year and a lifetime, $L_{B1}$, of 3.2 years. To respond to customer claims, a new reliability target for the compressor was set to have a B1 lifetime of 10 years.

## 2.2 Parametric Accelerated Life Testing of the compressor

2.2.1 Acceleration Factor (AF)

For solid-state diffusion of impurities in silicon, the junction equation $J$ might be expressed as:

$$J = A\sinh(a\xi)\exp\left(-\frac{Q}{kT}\right) \tag{2}$$

On the other hand, a reaction process that is dependent to speed might be expressed as:

$$K = a\frac{kT}{h}e^{-\frac{\Delta E}{kT}}\sinh(\frac{aS}{kT}) \tag{3}$$

So the reaction rate, *K*, from equation (2) and (3) can be summarized as:

$$K = B\sinh(aS)\exp\left(-\frac{E_a}{kT}\right) \tag{4}$$

If the reaction rate in equation (4) takes an inverse number, the generalized stress model can be obtained as,

$$TF = A[\sinh(aS)]^{-1}\exp\left(\frac{E_a}{kT}\right) \tag{5}$$

The hyperbolic sine stress term of equation (5) in medium range is expressed as following:

$$TF = A(S)^{-n}\exp\left(\frac{E_a}{kT}\right) \tag{6}$$

The internal (or external) stress in a product is difficult to quantify and use in accelerated testing. Thus, stresses in mechanical systems may come from the efforts (or loads) like force, torque, and pressure. For a mechanical system, when replacing stress with effort, the time-to-failure can be modified as:

$$TF = A(S)^{-n}\exp\left(\frac{E_a}{kT}\right) = A(e)^{-\lambda}\exp\left(\frac{E_a}{kT}\right) \tag{7}$$

Design defects in product can be found by acting the larger efforts under the accelerated conditions. From the time-to-failure in equation (7), the acceleration factor can be defined as the ratio between the proper accelerated stress levels and typical operating conditions. The acceleration factor (AF) can be modified to include the effort concepts:

$$AF = \left(\frac{S_1}{S_0}\right)^n\left[\frac{E_a}{k}\left(\frac{1}{T_0}-\frac{1}{T_1}\right)\right] = \left(\frac{e_1}{e_0}\right)^\lambda\left[\frac{E_a}{k}\left(\frac{1}{T_0}-\frac{1}{T_1}\right)\right] \tag{8}$$

2.2.2 Sample Size Equation

To carry out a parametric ALT, the sample size equation with the acceleration factors in equation (8) might be expressed as (Woo *et al*., 2015):

$$n \geq (r+1)\cdot\frac{1}{x}\cdot\left(\frac{L_{BX}^*}{AF\cdot h_a}\right)^\beta + r \tag{9}$$

If the reliability of the mechanical system such as a compressor in refrigerator was targeted to be B1 life 10 years, then the number of required test cycles can be obtained for a given set of samples subjected to the accelerated conditions. In parametric ALTs, the missing parameters of mechanical system in the design phase can be identified to achieve the reliability target.

### 2.3 Case Study - Reliability design of the compressor with redesigned crankshaft

A simple refrigerator system consists of a compressor, a condenser, a capillary tube and an evaporator. The main function of the refrigerator is to provide cold air from the evaporator to the freezer and refrigerator compartments.

The compressor takes refrigerant from evaporator and then compresses it, which transfers it to condenser of the refrigerator. In the process, a reciprocating compressor increases the refrigerant pressure from that in the evaporator to that in the condenser in the refrigeration cycle. As customers demand refrigerators that use less energy, it is necessary to improve the overall energy efficiency of the refrigerator. One way to improve efficiency is to redesign the compressor in the refrigerator. The primary components in a compressor in a domestic refrigerator consist of crankshaft (1), piston assembly, stator and its frame, valve plate, and suction reed valve (Figure 3).

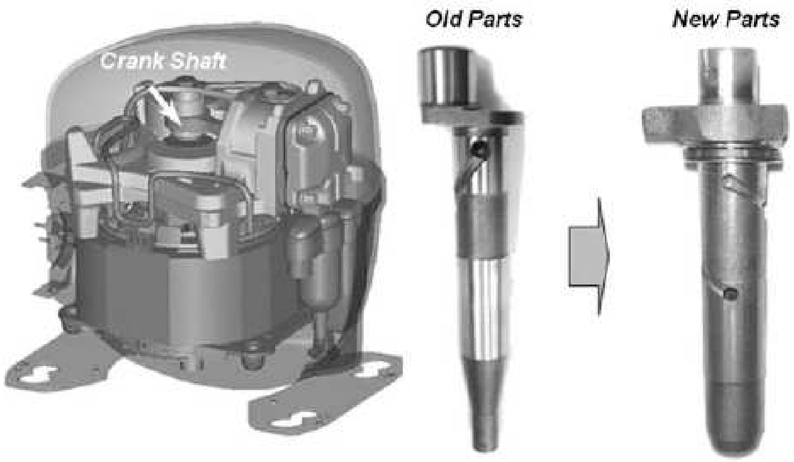
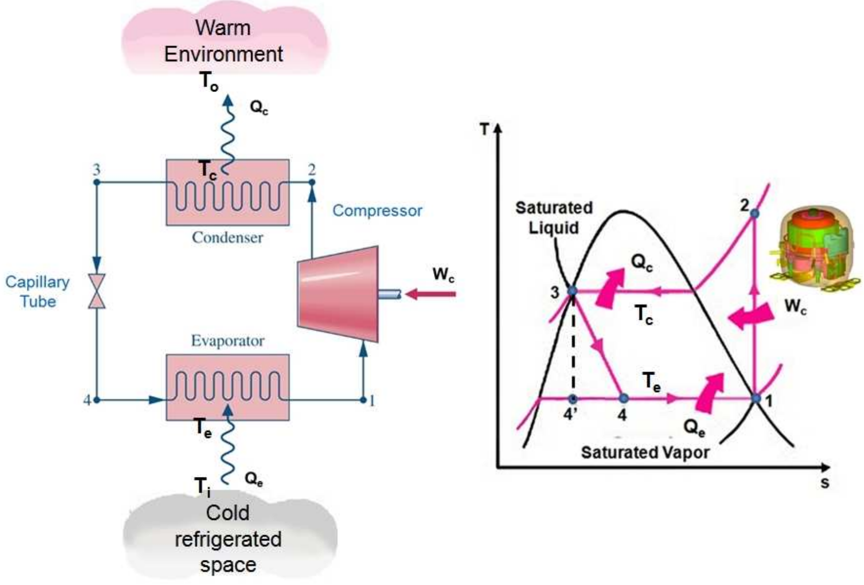



**Figure 3:** Redesigned compressor and crankshaft

Based on the failure analysis in field, compressors in the refrigerators had been locking, which was causing loss of the cooling function due to design failure. Based on the consumer usage conditions, compressors were subjected to repetitive pressure loads during the refrigerator operation (Figure 4).




(a) Refrigeration cycle (b) T-s diagram

**Figure 4:** Functional design concept of the compressor system in refrigeration cycle

In evaluating the design of a refrigeration cycle, it was necessary to determine both the condensing temperature, $T_c$ and evaporating temperature, $T_e$. The mass flow rate of refrigerant in a compressor can be modeled as

$$\dot{\mathrm{m}} = \mathrm{PD} \times \frac{\eta_{\mathrm{v}}}{v_{suc}} \tag{10}$$

The mass flow rate of refrigerant in a capillary tube can be modeled as (Whitesel, 1957)

$$\dot{\mathrm{m}}_{\mathrm{cap}} = A \left[ \frac{-\int_{P_3}^{P_4} \rho dP}{\frac{2}{D} f_m \Delta L + \ln\left(\frac{\rho_3}{\rho_4}\right)} \right]^{0.5} \tag{11}$$

By conservation of mass, the mass flow rate can be determined as:

$$\dot{\mathrm{m}} = \dot{\mathrm{m}}_{\mathrm{cap}} \tag{12}$$

The energy balance in the condenser can be described as

$$\mathrm{Q_c} = \dot{\mathrm{m}}\left(\mathrm{h}_2 - \mathrm{h}_3\right) = \left(T_c - T_o\right) / R_c \tag{13}$$

The energy balance in the evaporator can be described as

$$\mathrm{Q_e} = \dot{\mathrm{m}}\left(\mathrm{h}_1 - \mathrm{h}_4\right) = \left(T_i - T_e\right) / R_e \tag{14}$$

When nonlinear equations (12) through (14) are solved, the mass flow rate, $\dot{m}$, evaporator temperature, $T_e$, and condenser temperature, $T_c$ can be obtained. Because the saturation pressure, $P_{sat}$, is a function of temperature, the evaporator pressure, $P_e$ (or condenser pressure $P_c$), can be obtained as:

$$\mathrm{P_e} = f\left(\mathrm{T_e}\right) \; or \; \mathrm{P_c} = f\left(\mathrm{T_c}\right) \tag{15}$$

One source of stress in a compressor system may come from the pressure difference between suction pressure, $P_{suc}$, and discharge pressure, $P_{dis}$.

$$\Delta \mathrm{P} = P_{dis} - P_{suc} \cong P_c - P_e \tag{16}$$

For a compressor system, the time-to-failure in equation (7), TF, can be modified as

$$TF = A(S)^{-n} \exp\left(\frac{E_a}{kT}\right) = A(\Delta P)^{-\lambda} \exp\left(\frac{E_a}{kT}\right) \tag{17}$$

To find out the design defects in compressor, the higher pressure loads should be applied. The acceleration factor (AF) can be derived as

$$AF = \left(\frac{S_1}{S_0}\right)^n \left[\frac{E_a}{k}\left(\frac{1}{T_0} - \frac{1}{T_1}\right)\right] = \left(\frac{\Delta P_1}{\Delta P_0}\right)^\lambda \left[\frac{E_a}{k}\left(\frac{1}{T_0} - \frac{1}{T_1}\right)\right] \tag{18}$$

The operating conditions for the compressor in a refrigerator were approximately 0–43°C with a relative humidity ranging from 0% to 95%, and 0.2 – 0.24g's of acceleration. The number of compressor on-off operations was influenced by specific consumer usage conditions in the field. The reciprocating compressor has about 10–24 on-off cycles per day in the Korean domestic market. With a product life cycle design point for 10 years, the compressor had approximately 87,600 usage (on-off) cycles.
For this worst case, the pressure was 1.07MPa and the compressor dome temperature was 90°C. For the ALT, the pressure was assumed to be 1.96MPa and the dome temperature was 120°C to reveal the design faults in compressor under accelerated conditions. Using a cumulative damage exponent of 2.0 ($\lambda$), the acceleration factor from equation (18) was found to be approximately 13.2 (Table 2).

**Table 2:** Refrigerator ALT conditions in refrigeration cycle

| System Conditions | | Worst Case | ALT | AF |
|---|---|---|---|---|
| Pressure (MPa) | High-side | 1.07 | 1.96 | 3.36 ① |
| | Low-side | 0.0 | 0.0 | |
| | $\Delta$P | 1.07 | 1.96 | |
| Temperature (°C) | Dome | 90 | 120 | 3.92 ② |
| Total *AF* (=(①×②)$^2$) | | | | 13.2 |

For the reliability target – a B1 life 10 years, the test cycles for a sample thirty units calculated from equation (25) were 18,000 cycles if the shape parameter was supposed to be 2.0. This parametric ALT was designed to ensure a B1 life of 10 years with about a 60% level of confidence that it would fail less than once during 18,000 cycles. Figure 5 shows the experimental setup of the ALT with labeled equipment for the robust design of compressor. It consisted of an evaporator, compressor, condenser, and capillary tube in a simplified vapor-compression refrigeration system.

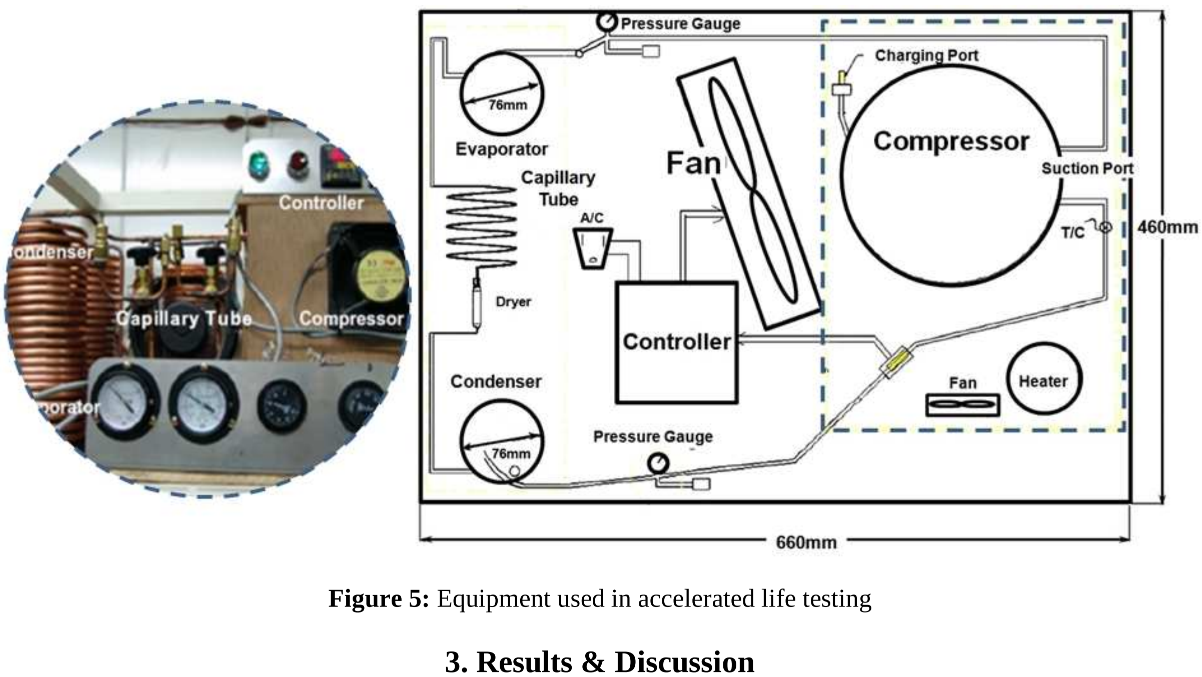
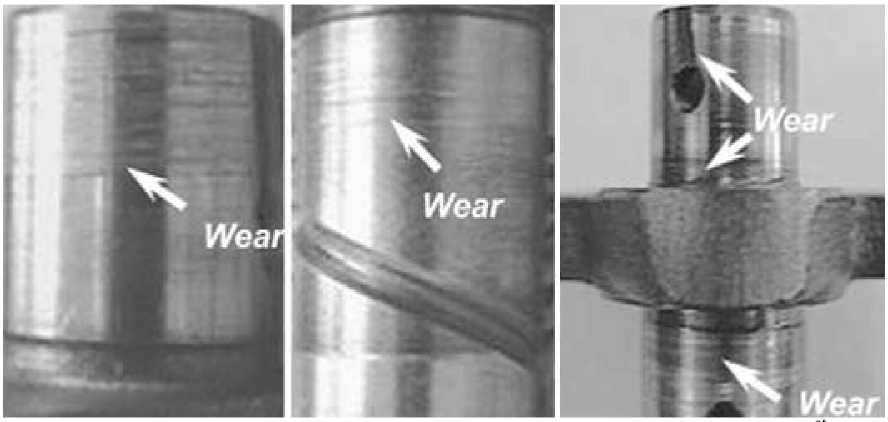



**Figure 5:** Equipment used in accelerated life testing

## 3. Results & Discussion

In a French door design refrigerator, it was found that compressors with the newly designed crankshafts were locking. Based on failure analysis, field data indicated that the damaged products may have had a design flaw – oil lubrication. Due to this design flaw, the repetitive pressure loads could create undue wear on the crankshaft and cause the compressor to lock. Figure 6 shows a photograph comparing the failed product from the field and that from the 1st accelerated life testing, respectively.

In the 1st ALT, the two compressors locked at 7,500 cycles and 10,000 cycles. When the locked compressors from the field and 1st ALT were cut apart, severe wear was found in some regions of the crankshaft where there was no lubrication – the moving area between shaft and connecting rod, and also the rotating area between crankshaft and block. As shown in the picture, the tests confirmed that the compressor was not well designed to ensure proper lubrication. The defective shape of the 1st ALT was very similar to that of the ones from the field.




(a) Failed products in field (b) Crack after 1st ALT

**Figure 6:** Failed products in field and 1st ALT

The root causes of the crankshaft wear came from the improper designs – 1) the lack of oil in areas that should have lubricated (Figure 7(a)), 2) low starting RPM ((Figure 7(b)), and 3) weak crankshaft material (FCD450). These compressor design flaws could cause the compressor to lock up suddenly when subjected to repetitive pressure loads.

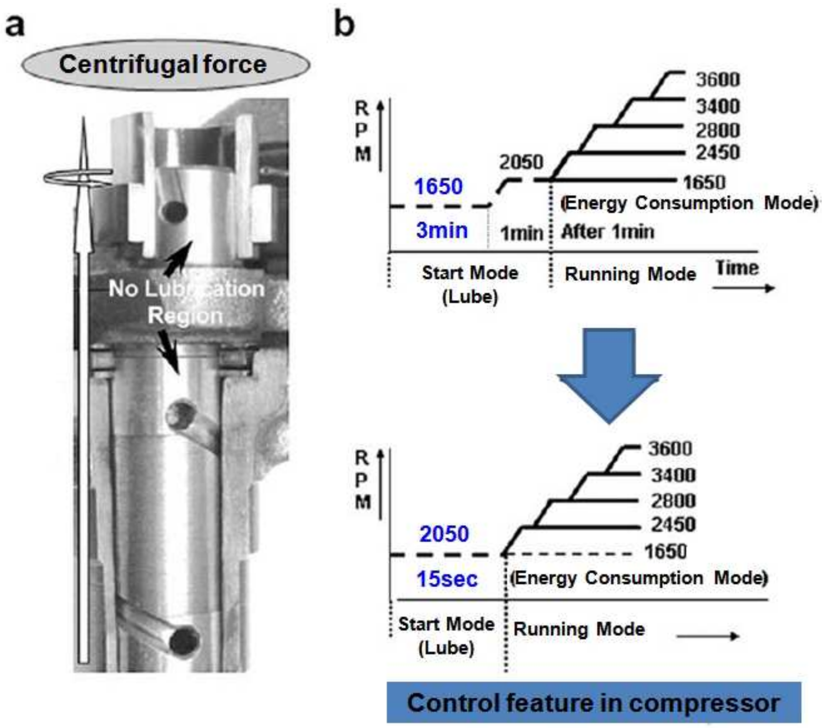



**Figure 7:** Failed products in field and 1st ALT

In the second ALT, the crankshaft wear due to interference between the crankshaft and a thrust washer was found at 18,000 cycles when the compressors were broken down (Figure 8).

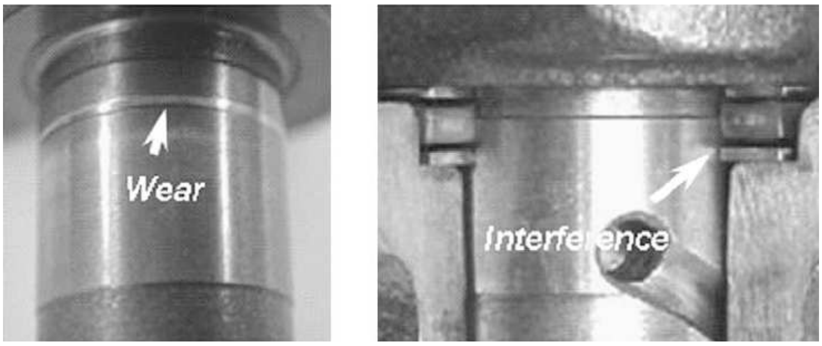



**Figure 8:** Failed products in 2nd ALT.

To withstand the design problems of crankshaft due to the repetitive pressure loads, it was redesigned as follows: (1) changing the starting RPM, C1, from 1650 RPM to 2050 RPM (Figure 7(b)); (2) relocating the lubrication holes and adding the new groove, C2 (Figure 9); (3) changing the crankshaft material, C3, from FCD450 to FCD500 (Figure 9); (4) increasing the minimum clearance between crankshaft and washer, C4, from 0.141 mm to 0.480 mm.

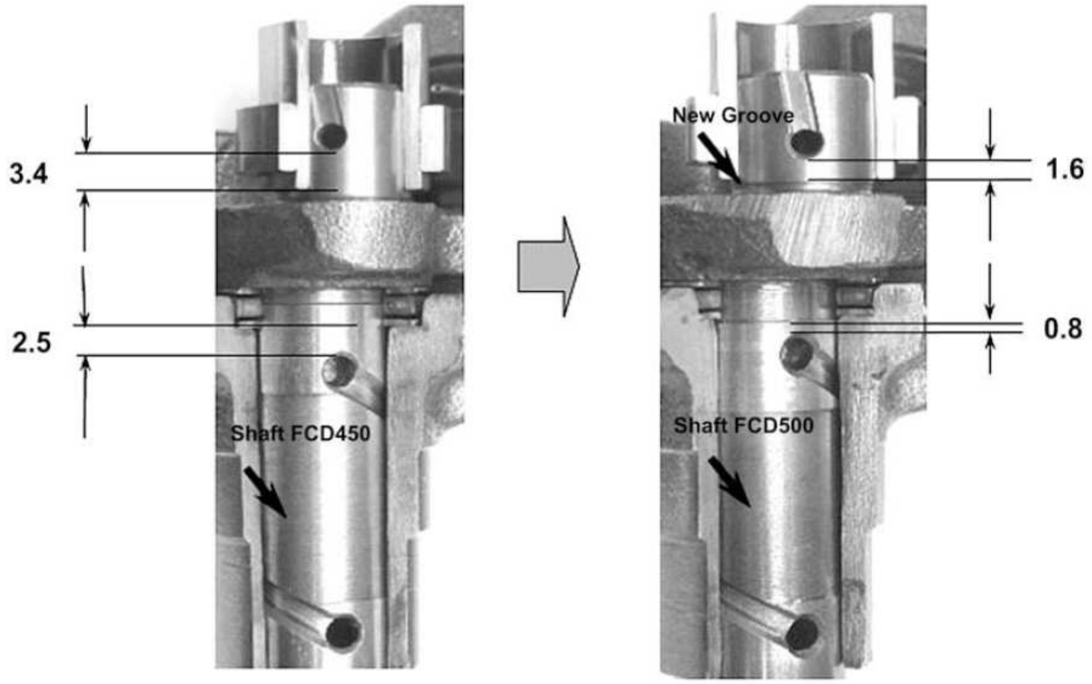



**Figure 9:** Redesigned crankshaft in first ALT.

With these design changes, the compressor with the newly designed crankshaft could operate smoothly over its product lifetime because there were no problems until 20,000 operation cycles. Over the course of three ALTs, the B1 life of the samples was improved to 10.0 years.

## 4. CONCLUSIONS

To improve the reliability of compressor in refrigerators, we have suggested the following reliability methodology – 1) Setting the overall parametric ALT plan, 2) Carrying out the parametric accelerated life testing with a corrective action plans, and 3) Checking if the final designs of the compressor satisfy the reliability target. As a case study, we used the design of a compressor with a newly designed crankshaft in French door refrigerators.

Based on failure analysis in the field and the 1st ALT, the compressor with a newly designed crankshaft locked (failed). The missing design parameters of the compressor in the design phase were the lubricating structure in crankshaft. The corrective action plans were (1) relocating the lubrication holes and adding the new groove, (2) changing the starting RPM from 1650 to 2050, and (3) changing the crankshaft material from FCD450 to FCD500.
Based on the 2nd ALT, the crankshaft wear due to interference between the crankshaft and a thrust washer occurred. The missing design parameter of the failed crankshaft was the minimum clearance between the crankshaft and the washer. As corrective action plans, the minimum clearance between the crankshaft and the washer was increased. In the 3rd ALT, there were no problems. After a sequence of ALT tests, the compressor with the proper values for the design parameters were determined to meet the reliability target – B1 life of 10 years.
When a generalized life-stress failure model with effort concepts, acceleration factor, and sample size equations are utilized, the reliability of a compressor system subjected to the repetitive pressure loads can improve. It also can quickly identify the faulty designs in the compressor system and determine if the reliability targets are achieved. This parametric ALT process should help engineers confirm the final design in the mechanical system and assess it.

## NOMENCLATURE

| | | |
|---|---|---|
| A | Cross-sectional area of the capillary tube | ($cm^2$) |
| e | effort | |
| $E_a$ | Activation energy | (eV) |
| h | Testing cycles (or cycles) | |
| $k$ | Boltzmann's constant | ($8.62\times10^{-5}$eV/K) |
| $\Delta L$ | Capillary length of the two-phase interval | |
| R | Thermal resistance | (°C/kW) |
| $L_B$ | Target BX life and $x$ = 0.01X, on the condition that $x \leq 0.2$ | |
| n | Number of test samples | |
| PD | Volume flow rate | ($m^3$/s) |
| $\Delta P$ | Pressure difference | (MPa) |
| r | Failed numbers | |
| S | Stress | |
| X | Accumulated failure rate, % | |
| $x$ | $x = 0.01 \cdot X$, on condition that $x \leq 0.2$ | |
| $\eta_v$ | Volumetric efficiency | |

**Subscript**

| | |
|---|---|
| 0 | normal stress conditions |
| 1 | accelerated stress conditions |
| a | actual |
| c | condenser |
| cap | capillary tube |
| e | evaporator |

## REFERENCES

Kreyszig, E. (2006). *Advanced Engineering Mathematics*, 9th edn, NJ:John Wiley and Son, p.683
Matsuishi, M. & Endo, T. (1968). Fatigue of metals subjected to varying stress, Japan Soc. Mech. Engineering.
Palmgren, AG. (1924). Die Lebensdauer von Kugellagern Zeitschrift des Vereines Deutscher Ingenieure, 68(14), 339–341.
Taguchi, G. (1978). Off-line and on-line quality control systems. In: Proceedings of the international conference on quality control, Tokyo, Japan.
Whitesel, W. (1957). Capillary two-phase flow Part II. *Refrigeration Engineering*, 65, 35.
Woo, S. & O'Neal, D. (2015). Reliability Design of Mechanical Systems Subject to Repetitive Stresses, *Recent Patents on Mechanical Engineering*, 8 (4), 222-234