

# Improving the Lifetime of a Reciprocating Compressor for Domestic Refrigerator

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**Abstract** — To enhance the lifetime of a newly designed reciprocating compressor in a refrigerator, parametric accelerated life testing (ALT) were developed using new definitions of the sample size equation and the B1 life index. In 1<sup>st</sup> ALT, compressor was locked due to the fracture of the suction reed valve. The failure modes and mechanisms of the suction reed valve in the accelerated tests were found to be similar to that of the failed product in the field. The root cause of the failure was the overlap between the suction reed valve and the valve plate in the suction port. The design faults in the design phase were modified by the trespan size, tumbling process, the material and thickness for the valve, a ball peening and brushing process for the valve plate. In 2<sup>nd</sup> ALT, compressor was locked due to the interference between the crank shaft and thrust washer. The corrective plan was to give heat treat the surface of crank shaft. During the third ALT, there were no problems. The B1 life of the compressor became more than 10.0 years.

**Keywords**—reciprocating compressor, lifetime design, load analysis, sample size equation, parametric accelerated life testing

## I. Introduction

Most global compressor companies are making every effort to develop more efficient domestic compressors. Simultaneously, they are required to reduce the cost of the product, which leads them to seek cheaper and more reliable products. As their attempts should supply a newly designed compressor to marketplace, lifetime needs to be evaluated by a proper testing method or parametric ALT.

Under customer usage (or environment) conditions, domestic compressor in refrigerator is critical for achieving consistent operation over a specified lifetime period. It can be designed to optimally choose the parts. When these factors are properly determined, they will make the compressor functions “robust”, which is insensitive to noise factors such customer usage (or environment) conditions. However, some factors in the design review have been missed. In the marketplace, the design flaws shorten the product lifetime (Fig.1)[1].

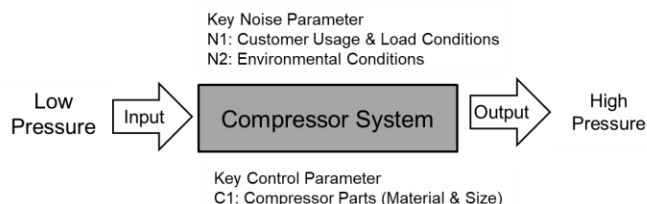


Figure 1 Parameter diagram of compressor system.

Rotary compressors in 1987 were abnormally failing from marketplace. That is, because oil sludge, formed in the refrigeration cycle, blocked the capillary tubes, the refrigerator no longer functioned. There were massive recalls of the compressor. Consequently, preventing a failure mode such as a blocking of the compressor was very important in the newly designed refrigerator.

Conventional methods such as product inspection without systematic reliability methodology rarely reproduce the reliability problems occurring in marketplace use. And designing for the maximum reliability requires extensive reliability testing at each development step. As a result, the cost of quality assurance and appraisal may increase significantly. However, reliability testing methods such as ALT were not used extensively at the time.

In reliability testing, product designers rely on the accelerated life testing (ALT). Because it carries out under severe conditions, this method can help shorten the product development cycles, costs less money, and clarify diverse design faults. However, any failures after ALT may not represent those occurring in market conditions. This problem arises because of the inconsistency of the direction and magnitude of the load, such as force, torque or pressure in system dynamics. Moreover, there are no definitions on the number of test samples and the test times. Parametric ALT need to develop the methodology that describes relationship between the sample size equation and test time. And ALT equipment should be designed to match product loads.

In this paper, the reliability design of a compressor is investigated with new reliability methodologies such as parametric ALT. It has the following procedures: (1) a parametric ALT plan based on product BX lifetime, (2) a load analysis for accelerated life time test, (3) a tailored sample of parametric ALTs with the design modifications, and (4) an evaluation of whether the final design(s) of the product achieves the target BX lifetime. As a test case, reciprocating compressors in refrigerators returned from the field were studied.

## II. Theoretical background

### A. Field Application problems

Unknown specific customer usage conditions and patterns, the suction reed valves of domestic refrigerator compressors used in the field were cracking and fracturing, leading to failure of the compressor. Because the function of refrigerator including the compressor was lost, customers would ask to have the refrigerator replaced. To solve the problem, it was

very important to reproduce the field failure mode of the suction reed valve in the laboratory. Apparently, the failed compressor in the market place might have had two structural design flaws: (1) Suction reed valve had an overlap with the valve plate; and (2) The valve plate had a sharp edge. As the suction reed valve impacts the valve plate, it will fracture (Fig. 2).

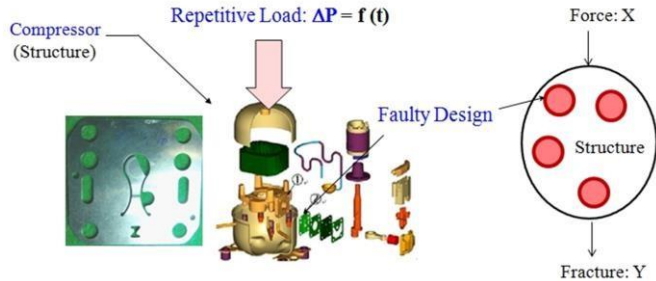


Figure 2 Failure of the compressor structure caused by repetitive pressure load and its design defects.

### B. Load analysis of compressor

To store the food fresh, the main function of the refrigerator is to provide cold air from the evaporator to the freezer and refrigerator compartments. A refrigerator consists of a compressor, a condenser, a capillary tube and an evaporator. The vapor compression refrigeration cycle receives work from the compressor and transfers heat from the evaporator to the condenser. A capillary tube controls flow and drops the high pressure of the refrigerant in the condenser to the low pressure in the evaporator. A compressor increases the pressure of the refrigerant (Fig. 3).

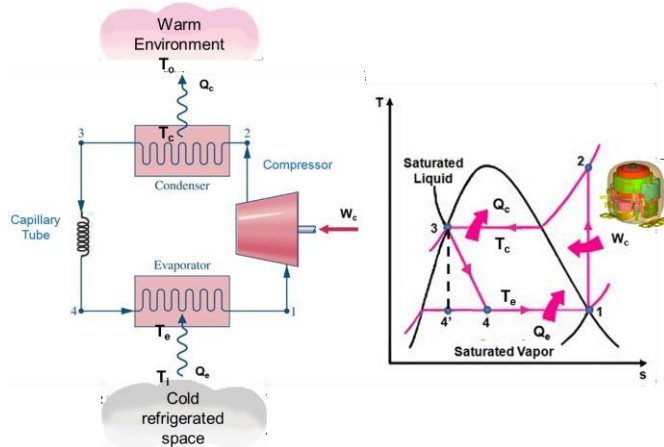


Figure 3 Compressor system in the refrigeration cycle.

In the process compressor systems are subjected to repetitive stress due to pressure loads. If there is a void (design fault) in the structure that causes an inadequacy of strength when the loads are applied, the compressor may abruptly fail during its expected lifetime. After identifying the product failure by experiments such as parametric ALT, an engineer can optimally design the compressor shape and select a

material type so the compressor can sustain repetitive loads and its lifetime can be extended.

In a refrigeration cycle design, it is necessary to determine both the condensing pressure,  $P_c$ , and evaporating pressure,  $P_e$ , when load analysis is carried out. These pressures depend on ambient conditions, customer usage conditions, and heat exchanger capacity in the initial design stage.

The internal stress of the compressor depends on the pressure difference suction pressure,  $P_{suc}$ , and discharge pressure,  $P_{dis}$ . That is,

$$\Delta P = P_{dis} - P_{suc} \cong P_c - P_e \quad (1)$$

By repeating the on and off cycles, the compressor receives the dominant stress. Under accelerated stress conditions, the life-stress model (LS model) can be modified as [2]

$$TF = A(S)^{-n} \exp\left(\frac{E_a}{kT}\right) = A(\Delta P)^{-\lambda} \exp\left(\frac{E}{kT}\right) \quad (2)$$

where  $A$  is constant,  $k$  is Boltzman's constant,  $E$  is the activation energy,  $T$  is the absolute temperature,  $n$  is the quotient and  $\lambda$  is cumulative damage exponent in Palmgren-Miner's rule.

So the acceleration factor (AF) can be derived as:

$$AF = \left[ \frac{S_1}{S_0} \right]^n \left[ \frac{E}{k} \left( \frac{1}{T_0} - \frac{1}{T_1} \right) \right] = \left[ \frac{\Delta P_1}{\Delta P_0} \right]^\lambda \left[ \frac{E}{k} \left( \frac{1}{T_0} - \frac{1}{T_1} \right) \right] \quad (3)$$

where  $S_1$  (or  $P_1$ ) is mechanical stress (or pressure difference) under accelerated stress conditions, and  $S_0$  (or  $P_0$ ) is mechanical stress (or pressure difference) under normal stress conditions.

### C. BX life and sample size

Traditionally, the characteristic life is defined as [3]:

$$\eta^\beta = \frac{\sum t_i^\beta}{r} \cong \frac{n \cdot h^\beta}{r} \quad (4)$$

where  $\beta$  is the shape parameter in a Weibull distribution.

As product (or part) reliability improves, failure of the part becomes less frequent in laboratory tests. It becomes more difficult to evaluate the characteristic life in (4). We can give practical definition of characteristic life as:

$$\eta^\beta \cong \frac{n \cdot h^\beta}{r+1} \quad (5)$$

If a random variable  $T$  is represented to the lifetime of product, the Weibull Cumulative Distribution Function (CDF)

of T, denoted F(t), may be defined as all individuals having an  $T \leq t$ , divided by the total number of individuals. This function also gives the probability P of randomly choosing an individual having a value of T equal to or less than t, and thus we have

$$P(T \leq t) = F(t). \quad (6)$$

If product follows Weibull distribution, the accumulated failure rate, F(t), is expressed as:

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^\beta} \quad (7)$$

When  $t=L_{BX}$  in (7), relationship between BX Life ( $L_{BX}$ ) and Characteristic Life  $\eta$  can be defined as:

$$L_{BX}^\beta \cong x \cdot \eta^\beta \quad (8)$$

where  $x = 0.01F(t)$

If (5) is inserted into (6), BX Life can be redefined as:

$$L_{BX}^\beta \cong x \cdot \eta^\beta \cong x \cdot \frac{n \cdot h^\beta}{r+1} \geq L_{BX}^{*\beta} \quad (9)$$

The simplified sample size equation can be found from (9)

$$n \geq (r+1) \cdot \frac{1}{x} \cdot \left( \frac{L}{h} \right)^\beta \quad (10)$$

If the acceleration factors in (3) are added into the planned testing time h, (10) becomes:

$$n \geq (r+1) \cdot \frac{1}{x} \cdot \left( \frac{L}{AF \cdot h_a} \right)^\beta \quad (11)$$

To respond to customer claims, a new lifetime for the compressor was set to B1 life 10 years.

### III. Laboratory experiments

For a reciprocating compressor in a domestic refrigerator, the typical working conditions were for a customer range from 0 to 43°C with a relative humidity ranging from 0% to 95%. Design conditions for transportation or operation assumed the compressor was subjected to 0.2 to 0.24g of acceleration.

As the compressor operates, the suction reed valve will open and close to allow refrigerant to flow into the compressor. A reciprocating compressor is expected to cycle on and off 22 per day. A worse case was also simulated with 98 on and off cycles per day. Under the worst case conditions, the compressor operation for 10 years may experience as many as 357,700 usage cycles.

From the test data of the worst case, pressure was 1.27 MPa and the compressor dome temperature was 90°C. For

accelerated life testing, the acceleration factor (AF) for pressure was 2.94 MPa and the compressor dome temperature was 120°C. With accumulative damage exponent,  $\lambda$ , of 2, total AF calculated from (3) was 20.9 (Table I).

TABLE I. COMPRESSOR ALT CONDITIONS

System conditions		Worst Case	ALT	AF
Pressure (MPa)	High-side	1.27	2.94	5.33 (1)
	Low-side	0.0	0.0	
	$\Delta P$	1.27	2.94	
Temperature (°C)	Dome	90	120	3.92 (2)
	Total AF (=(1) × (2))			

The test cycles of ALT calculated from (11) were 38,300 cycles for 20 sample units if the shape parameter  $\beta$  was supposed to be 2.0. This parametric ALT was designed to ensure a lifetime target – B1 life 10 years – with about a 60% level of confidence that it would fail less than once during 38,300 cycles. We also applied the duty cycles of pressure difference suction pressure,  $P_{suc}$ , and discharge pressure,  $P_{dis}$ .

To evaluate the design of compressor, a simplified vapor compression refrigeration cycle was fabricated. It consisted of an evaporator, compressor, condenser, and capillary tube. A fan and two 60-W lamps maintained the temperature within the insulated (fiberglass) box. A thermal switch attached on the compressor top controlled a 51 m<sup>3</sup>/h axial fan. The test conditions and test limits were set up on the control board. As the test began, the high-side and low-side pressures could be observed on the pressure gauge or display monitor (Fig. 4).

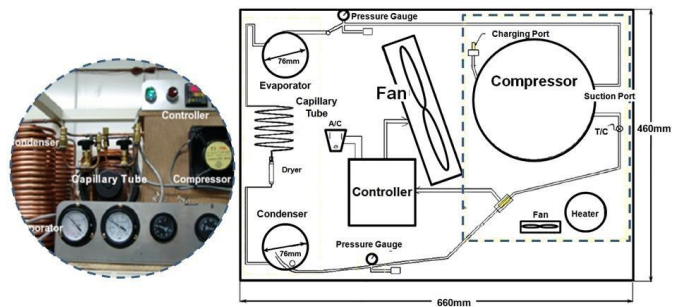


Figure 4 Equipment for the accelerated life tests.

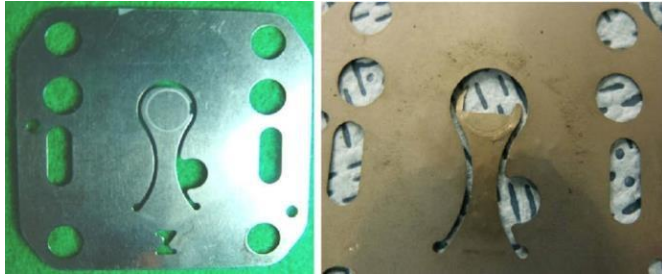
### IV. Results and discussion

#### A. Validity of parametric ALT

One sample in the first ALT ( $n = 20$ ) failed in 8,687 cycles. The confirmed value, based on the marketplace data, was 1.9. The shapes and locations of the failure in samples from the first ALT and the marketplace were similar (Fig. 5). The fracture of the suction reed valve came from design faults:

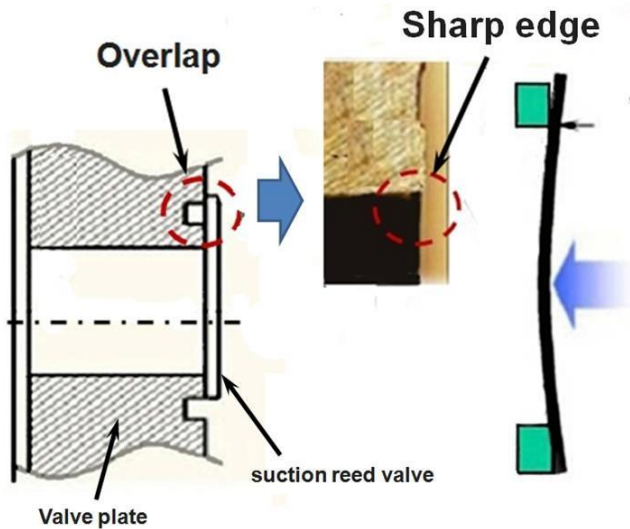


(1) had an overlap with the valve plate, (2) had a sharp edge on the valve plate, and (3) used a weak material (Fig. 6).



(a) Failed products in field (b) Crack after first ALT

Figure 5 Failed suction reed valve products from the field and after first ALT.



(a) Overlapped suction reed valve (b) Valve plate with sharp edge

Figure 6 Structure of failing suction reed valve and valve plate.

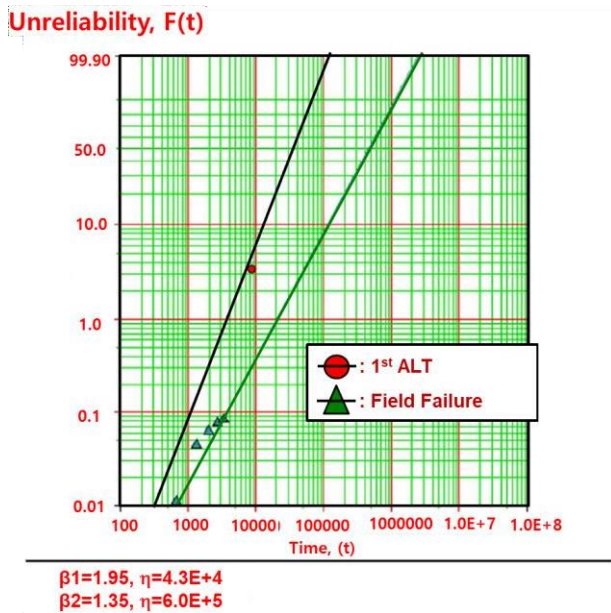


Figure 7 Field data and results of ALT on Weibull chart.

As the suction reed valve repeatedly impacted the valve plate, it fractured. The dominant failure mode of the compressor was locking due to the cracking and fracturing of the suction reed valve. We knew that the ALT methodology was valid for reproducing the failure found in the field. First, the shape of the fractured suction reed valves from the field and those in first ALT were similar. And we also knew that the ALT results and market failure data showed to have a same pattern on a Weibull plot (Fig. 7).

## B. Parametric ALTs with corrective action plans

Refrigerators returned from the field had a primary failure mode with no cooling because the reciprocating compressor did not operate. Field data indicated that the damaged products may have had a design flaw. Due to this design faults, the repetitive pressure loads could create undue stresses on the suction reed valve, causing it to fracture. To reproduce the failure mode of the compressor, parametric ALTs were carried out. Based on the first ALT and field data, we knew that the AF and  $\beta$  values were 20.9 and 1.9 (Fig. 7). For given test samples, the test cycles were calculated in Equation (11) if product lifetime was targeted to have B1 life 10 years.

In the first ALT, a compressor locked at 8,687 cycles. Disassembly of the problematic compressors from the field and the first ALT showed that the suction reed valves fractured in some regions where they overlapped with the valve plate (See Fig.5). The failed shape of the first ALT was very similar to the ones from the field. The test results confirmed that the compressor was not well designed to open and shut the suction reed valve.

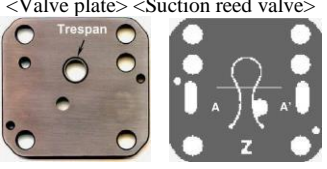

The root causes of the fractured suction reed valve came from the following improper designs: (1) an overlap with the valve plate (Fig. 6(a)); (2) a sharp edge on the valve plate (Fig. 6(b)); and (3) weak material (0.178t) used in the design of suction reed valve. These design flaws could cause the compressor to lock up suddenly when subjected to repetitive pressure loads.

To prevent the fracture of the suction reed valve from the repetitive pressure stresses over the product's lifetime, the valve plate was redesigned as follows: (1) Trespan size, C1 from 0.73 mm to 1.25 mm; (2) Adding ball peening and brush process, C2; (3) Thickness of the suction reed valve, C3 from 0.178 t to 0.203 t (4) Extending tumbling process, C4.

For the second ALT, three samples locked near 17,000 cycles. The root causes of the failed compressor were as follows: (1) the wear of the crank shaft and (2) the interference between crank shaft and thrust washer. The design improvement was given to the heat treatment on the crank shaft, C5.

In the third ALT, there were no design problems of the compressor until the test was carried out to 29,000 cycles. We therefore concluded that the modifications to the design found

TABLE II. Results of the ALTs

Parametric ALT	1 <sup>st</sup> ALT	2 <sup>nd</sup> ALT	3 <sup>rd</sup> ALT
	Initial Design	Second Design	Final Design
In 29,000 mission cycles, there is no problem in compressor	8,687 cycles: 1/20 locking	17,000 Cycles: 3/30 locking	29,000 cycles: 60/60 OK 39,000 cycles: 60/60 OK
Photo			-
Action plans	C1: Trepan size: 0.73 mm→1.25 mm C2: Adding ball peening and brush process C3: SANDVIK 20C: 0.178t→0.203t C4: Extending tumbling: 4 h→14 h	C5: FCD500 + No Heat Treatment → FCD500 + Heat Treatment on the crank shaft	-

from the first ALT were effective. Table II summarizes the parametric ALT results. With the modified design parameters, the final compressor system samples were guaranteed to achieve their lifetime target of B1 life 10 years.

## v. Conclusions

To improve the lifetime of the newly designed compressor in a refrigerator, we developed the following reliability methodology: (1) set the overall parametric ALT plan based on the product BX lifetime, (2) conduct the parametric ALT with corrective action plans until the mission cycle was obtained from the product BX lifetime, and (3) determine if the final product design satisfies the mission cycles. As a test case, we studied the reliability design of a domestic compressor returned from the field.

In the field and the first ALT, the suction reed valves in the compressor were fracturing because of the following design flaws: (1) an overlap with the valve plate; (2) a sharp edge on the valve plate; and (3) inadequate thickness of the suction reed valve (SANDVIK20 C0.178t). As corrective actions, the trepan on the valve plate was increased from 0.73mm to 1.25mm and a ball peening process was added to eliminate its sharp edge.

For the second ALT, three samples locked near 17,000 cycles because of (1) the wear of the crank shaft and (2) the interference between crank shaft and thrust washer. As action plans, we gave the heat treatment on the crank shaft.

As a result, there were no problems during the third ALT. The compressors were guaranteed to achieve the lifetime target of B1 life 10 years. By inspecting returned products from the field and carrying out parametric ALT with action plans, the developed reliability methodology proves to be effective in improving design faults of compressor system and ensuring the reliability criteria of the final design were satisfied.

This new reliability methodology might be applicable to mechanical systems such as automobiles, airplane, refrigerators, construction equipment, washing machines, and vacuum cleaners. To use this new reliability methodology, engineers should understand why products fail. That is, if there are design faults in product that is subjected to repetitive loads, the product will collapse during its lifetime. Engineers also need to know the load characteristics of a product so that the parametric ALT can be conducted until the required number of mission cycles under accelerated loading conditions. Finally, engineers can use parametric ALT to identify and correct design problems of a mechanical system.

## References

- [1] I.C. Magaziner and M. Patinkin, March–April 1989, Cold Competition: GE Wages the Refrigerator War, Harvard Business Review, vol.89(2), pp.114–124.
- [2] Woo, S., Pecht, M., O’Neal, D., 2020, Reliability design and case study of the domestic compressor subjected to repetitive internal stresses, Reliability Engineering & System Safety, 193, 106604.
- [3] Lee, S.Y., 2003, Reliability Engineering, p.73, Seoul: Hyung Seol.

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Woo has a BS and MS in Mechanical Engineering, and he has obtained PhD in Mechanical Engineering from Texas A&M. He major in energy system such as HVAC and its heat transfer, optimal design and control of refrigerator, reliability design of thermal components, and failure Analysis of thermal components in marketplace using the Non-destructive such as SEM & XRAY. In 1992.03–1997 he worked in Agency for Defense Development, Chinhae, South Korea, where he has researcher in charge of Development of Naval weapon System. Now he is working as a Senior Reliability Engineer in Side-by-Side Refrigerator Division, Digital Appliance, SAMSUNG Electronics, and focus on enhancing the life of refrigerator as using the accelerating life testing. He also has experience about Side-by-Side Refrigerator Design for Best Buy, Lowe’s, Cabinet-depth Refrigerator Design for General Electrics.