Springer

KSME

Journal of Mechanical Science and Technology 29 (6) (2015) 2341~2348
www.springerlink.com/content/1738-494x(Print)/1976-3824(Online)
DOI 10.1007/s12206-015-0526-y

Life prediction of brazed plate heat exchanger based on several accelerated life test data †

Mu-Seong Chang, Tae-Kook Park, Baek-Ju Sung and Byung-Oh Choi*

Reliability Assessment Center, Korea Institute of Machinery & Materials, Daejeon, 305-343, Korea

(Manuscript Received October 20, 2014; Revised January 19, 2015; Accepted February 4, 2015)

Abstract

This paper presents a life prediction method based on several accelerated life test data for brazed plate heat exchanger. For this purpose, accelerated life tests were performed with pressure cycle and fluid temperature as accelerating stresses. Statistical analyses of the two test data sets and their combination were conducted. As a result, the shape parameter of Weibull distribution, the accelerating index of pressure cycle, the activation energy, and the life cycles under normal use conditions for the brazed plate heat exchanger were obtained.

Keywords: Brazed plate heat exchanger; Accelerated life test; Temperature-nonthermal model; Inverse power law model; Life prediction; Statistical analysis

1. Introduction

In today's competitive marketplace, product designers are under pressure to reduce product lead times. For example, the product lead times in the automobile industry, which often exceeded 48 months 10 years ago, are now less than 24 months [1]. Accelerated life tests are becoming popular in today's industry because of the need to obtain life test data quickly.

The three widely used types of acceleration methods are the following: (1) overstressing, (2) increasing usage rates, and (3) tightening the failure threshold [2]. Among these methods, the most common acceleration method is overstressing. This method is performed by applying stress levels that exceed the level a product will encounter under normal use conditions. Then, the lifetime under normal use conditions is predicted using accelerated life test data and accelerated life models.

Nelson [3] provided a comprehensive review of background materials, practical methodologies, basic theories, and examples of the accelerated life tests. Chapter 7 of Yang [2], Chapter 6 of Elsayed [4], and Chapters 18–20 of Meeker and Escobar [5] also discussed additional information on these topics. Nelson [6] also provided an extensive list of references on accelerated life test plans. Escobar and Meeker [7] outlined some of the basic ideas behind accelerated life tests and describe the most commonly used accelerated life models. Park et al. [8] explored three types (Overstressing, increasing usage rates, and tightening the failure threshold) of acceleration methods in the life tests of secondary rechargeable batteries to reduce test period. The practical applications of the accelerated life tests include cylinders of a pneumatic system [9], pump motor assembly [10], and blower motor of an automobile [11].

A brazed plate heat exchanger (BPHE) was developed from the conventional plate heat exchanger (PHE) out of the need for a compact PHE under high pressure and temperature [12]. BPHEs have the highest level of thermal efficiency and durability in a compact size. Similar to gasket PHE, BPHE is composed of a series of corrugated metal plates but without the gaskets, tightening bolts, frame, or carrying and guide bars [12]. The corrugated plate design has extremely high heat transfer coefficients, enabling a more compact design. The unit's stainless steel plates are vacuum brazed together to make a produce a piece that can withstand high pressure and temperature. BPHEs offer a number of advantages: a sealed and gasket-free construction, compactness, high temperature and pressure capability, and high thermal efficiency. These advantages make BPHEs ideal for industrial oil cooling; refrigerant evaporators and condensers; and residential and light commercial heating, ventilation, and air conditioning (HVAC) systems [12].

Bogaert and Boles [13] investigated BPHEs, defining the thermal and hydrodynamic performances of BPHEs and comparing them in terms of the hydraulic diameter parameter. Stasiek et al. [14] provided typical experimental results of the heat transfer and pressure drop of BPHEs for various geometries and Reynolds numbers and compared these results with

*Corresponding author. Tel.: +82 42 868 7170, Fax.: +82 42 868 7082
E-mail address: bochoi@kimm.re.kr
† Recommended by Associate Editor Seong Beom Lee

Table 1. Specifications of a test sample.

Number of heat plates	10 ea.
Heat transfer area	0.275 m^2
Rated pressure	4.5 MPa
Internal volume	0.24/0.3 L
Rated temperature	130°C
Material	Stainless steel

literature data. Ayub [15] presented a literature survey on gasket PHEs and new correlations between evaporative heat transfer coefficient and friction factor. Mencke et al. [16] presented an overview of BPHEs and their applications and compared the performance of BPHEs with those of shell-and-tube and coaxial heat exchangers. Han et al. [17] provided experiment results of evaporative heat transfer and pressure drop in BPHEs with different refrigerants and chevron angles. Longo [18] presented the experimental heat transfer coefficients and pressure drops measured during different vaporizations inside BPHEs.

The main purpose of this paper is to predict the life cycles of BPHEs under normal use conditions based on several accelerated life test data. For this purpose, accelerated life tests were performed twice. Accelerating stress in the first accelerated life test is the pressure cycle. In the second test, pressure cycle and fluid temperature are the accelerating stresses. Sec. 2 introduces the structure of the BPHE used in this study, its failure modes and mechanisms, and its test equipment. Sec. 3 presents the accelerated life test plans for BPHEs. Sec. 4 presents basic theory of Weibull distribution and accelerated life models as well as statistical results of the analysis of several accelerated life test data. The representative parameters of the lifetime distribution and the accelerated life model for BPHEs are estimated from combined accelerated life test data. The characteristic life and B_{10} life cycles under normal use conditions are also predicted using the representative parameters. Sec. 5 states some concluding remarks.

2. Failure analysis of brazed plate heat exchanger

A BPHE consists of a series of thin corrugated metal plates that are brazed together to improve heat transfer efficiency. It consists of stainless steel plates and two reinforced plates. The plates are brazed together in a vacuum furnace to form a completely pressure-resistant unit. The two fluids flow in separate channels. One fluid flows in the odd-numbered channels, whereas the other flows in the even-numbered channels. Only one fluid temperature is considered in the life test. The structure and specifications of the BPHE used in this paper are shown in Fig. 1 and Table 1. The material of the BPHE is stainless steel, which possesses advantages in terms of anticorrosion property, strength, and manufacturability.

The typical failure mode of a BPHE is fluid leakage. The leakage is generally induced by deformation, crack, breakage

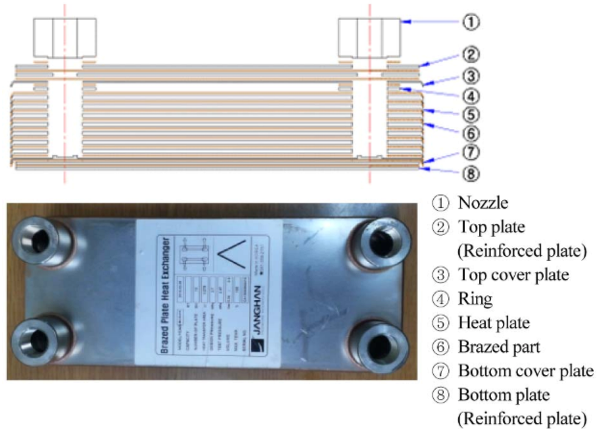

Fig. 1. Structure of a BPHE.

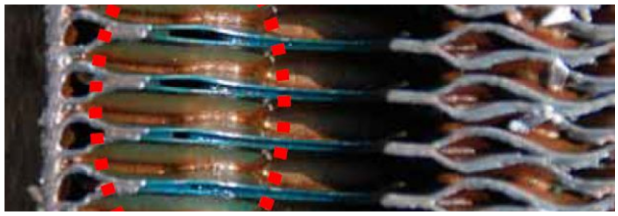

Fig. 2. Breakage of the brazed part obtained from accelerated life test.

of the brazed part and deformation, and breakage of the heat plate. Fig. 2 shows breakage of the brazed part after accelerated life test was finished. Reinforced plate and nozzle are structurally strong and robust to the pressure and temperature. However, the heat plate, which is made of thin materials with chevron pattern to improve heat transfer efficiency, can be easily deformed by stress factors. The bonding strength of the brazed part decreases at high fluid temperature. The loads applied on the heat plate and brazed part are high under high pressure. Thus, lifetime of BPHEs decrease at high fluid temperature and under high pressure.

Table 2 summarizes the failure modes and mechanisms of BPHEs. The equipment for the BPHE life test consists of a typical hydraulic power unit, with pilot solenoid valve, relief solenoid valve, and solenoid valve for removing residual pressure to apply pressure cyclically. It also includes oil heater and extra air-cooled oil cooler to maintain a constant oil temperature. Fig. 3 shows the equipment for the BPHE life test.

3. Accelerated life test plans

The results of Sec. 2 shows that the main failure mode of BPHEs is the leakage by structural breakage. The typical accelerating stresses on the life of an industrial heat exchanger are pressure cycle and fluid temperature [19, 20]. Between the two accelerating stresses, the pressure cycle is the most significant stress contributing to the main failure mode of BPHEs. Pressure cycle test is conducted according to SAE J1597 [19]. Pressure is initially increased from zero to the test pressure

Table 2. Failure modes and mechanisms for BPHEs.

Component	Function	Failure mode	Failure mechanism
Heat plate	Heat exchanger, flow path, pressure retaining	Deformation	Heat/fatigue
		Breakage	Shock/fatigue/freeze
Brazed part	Brazing, flow path, pressure retaining	Deformation	Shock/fatigue
		Crack	Heat/fatigue
		Breakage	Shock/freeze
Reinforced plate	Pressure retaining	Deformation	Heat/shock/fatigue
Nozzle	Inlet, outlet	Crack	Fatigue

Fig. 3. Equipment for the BPHE life test.

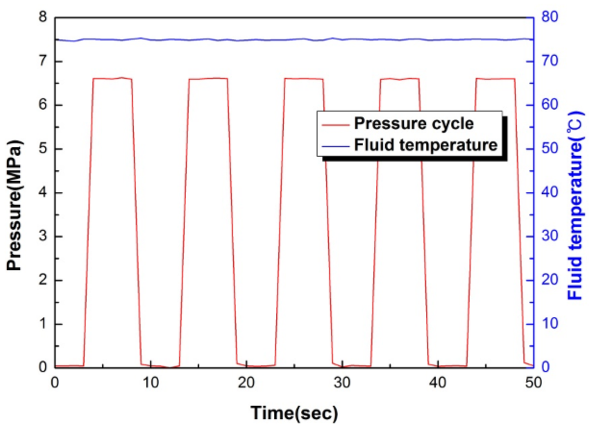

Fig. 4. Stress loading method for pressure cycle and fluid temperature.

and then maintained for five seconds at such level before dropping it to zero where it is maintained for another five seconds at zero. The next accelerating stress is fluid temperature. Fig. 4 shows accelerating stress loading method for pressure cycle and fluid temperature.

Random BPHE samples have been tested under several different stress levels. The level of applied stresses should not be high enough to induce different failure modes (or failure mechanisms) that might occur under normal use conditions [4, 21]. The stress levels of pressure cycle are 4.5, 5.5, and 6.5 MPa. Design pressure of BPHEs considered in this paper is 4.1 MPa, and pressurized test is generally performed at 110% (about 4.5 MPa) of the design pressure. This pressure is used in the closest stress level to the normal use conditions. The higher stress levels are determined in 1 MPa increments. Moreover, a failure mode of the sample obtained from the pretest at 6.5 MPa is verified to be the same as the one under normal use conditions. In the case of fluid temperature, 60, 75, and 90°C are selected as stress levels considering normal use conditions and test equipment situations.

Sample size is an important factor that affects test cost, capacity of test equipment, test time, and accuracy of estimates [2]. The sample size for each stress level is set to five in this paper for practical reasons. The lifetime of BPHEs is usually given in the number of cycles, and one cycle in this paper is equal to 10 seconds. Periodic monitoring is performed to check for failure. A life cycle of a BPHE sample can be defined as the amount of time until leakage. The lifetime data of a BPHE are called interval-censored data, which, however, reflect an uncertainty as to the exact times the products failed within an interval [21]. In this paper, life cycles are used instead of interval-censored data for convenience.

4. Statistical analysis of several accelerated life test data

4.1 Lifetime distribution and accelerated life models

The two-parameter Weibull distribution is by far the most widely used distribution for lifetime data analysis [22] and is the most common distribution in mechanical engineering fields [23]. Thus, it is assumed that the life cycles of BPHEs follow Weibull distribution. The cumulative distribution function of Weibull distribution is written as Eq. (1):

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\eta} \right)^{\beta} \right], \qquad t > 0 \tag{1}$$

where $\beta > 0$ is the shape parameter, and $\eta > 0$ is the scale parameter as well as the characteristic life. When $\beta > 1$, the failure rate increases with time; for $0 < \beta < 1$, the failure rate decreases with time. The value β determines the shape of the distribution as described by the physics of failure, and the value η is a measure of durability that can vary depending on the material [22].

The inverse power law (IPL) model (or relationship) is commonly used for nonthermal accelerated stresses, such as pressure, voltage, electrical current, humidity, pressure cycle, thermal cycle, vibration, load, and so on. The equation of the IPL model [24] can be expressed as follows:

$$L(V) = \frac{1}{A \cdot V^n}, \qquad A > 0 \tag{2}$$

where L represents a quantifiable life measure (The characteristic life of Weibull distribution), V is the nonthermal stress level, and A and n are model parameters to be determined. The parameter n is a measure of the effect of the nonthermal stress on the lifetime and is the accelerating index of nonthermal stress. A large value of n indicates a high degree of nonthermal stress dependence.

If the temperature and the nonthermal stress (Pressure cycle in this paper) are applied simultaneously in a test, the temperature–nonthermal model is used. This model is given by [24]

$$L(V,T) = \frac{C}{V^n \cdot \exp\left(-\frac{E_a}{k \cdot T}\right)}, \qquad C > 0 \tag{3}$$

where T is the absolute temperature in Kelvin (K), E_a and C are the model parameters to be determined. The k is a Boltzman's constant ($k = 8.6171 \times 10^{-5}$ eV/°C) and E_a is the activation energy in electron volt (eV) [2]. The higher the activation energy is, the longer the lifetime is.

One of the important concepts of accelerated life test is acceleration factor (AF), defined as the ratio of a lifetime under normal use condition to that at test stress level. The AF of Weibull distribution can be expressed as $AF = L_{use}/L_{test} = \eta_{use}/\eta_{test}$, where η_{use} and η_{test} are the scale parameters of Weibull distribution under normal use condition and at test stress level, respectively.

4.2 Case 1: Pressure cycle stress

The first accelerated life test is performed only with the pressure cycle stress. Accelerated life model is considered for this case is the IPL model. The life cycles obtained from the three stress levels are listed in Table 3. Fluid temperature of case 1 is set to 50°C. Start and end cycles in Table 3 denote cycles at the start and end of the interval when the failure occurred.

In accelerated life tests, the failure mode of BPHEs is assumed to remain unchanged while stress increases from normal use conditions to the highest stress level. As the failure mode of BPHEs is reflected by the shape parameter β of Weibull distribution, the shape parameter at each stress level should be the same, which means $\beta_1 = \beta_2 = \beta_3$. Equality test of shape parameters is conducted to confirm the consumption.

Table 3. Life cycles for case 1 test.

Sample No.	4.5 MPa		5.5 MPa		6.5 MPa	
	Start cycle	End cycle	Start cycle	End cycle	Start cycle	End cycle
1	84620	90180	41490	42531	10134	11224
2	90180	90565	44170	45009	12990	13334
3	100139	108131	45009	46161	20538	20953
4	108131	114819	52630	54948	28652	28923
5	136343	140502	58547	59751	30950	31408

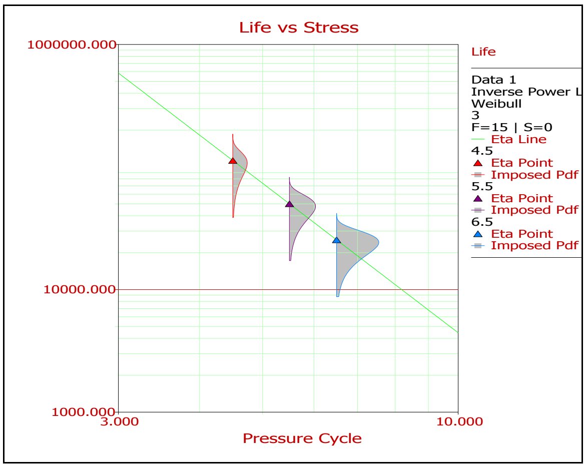

Fig. 5. Life-pressure cycle relationship plot for case 1 (from ALTA 7).

In this paper, likelihood ratio test is used to compare the shape parameters of three different stress levels. The value of the likelihood ratio test statistic T is equal to 4.4548 for case 1 and is less than or equal to the chi-square (4.6052). Thus, the shape parameter estimates do not differ statistically at 10% significance level.

From the statistical analysis of the life cycles for case 1, maximum likelihood estimates of β, A, and n are 4.775, 1.9929×10^{-8}, and 4.0529, respectively. Statistical analysis and graphical presentation of life cycles are done in ALTA and MINITAB software. Fig. 5 shows the life–stress (Pressure cycle) relationship plot of the life cycles obtained from case 1. The scale parameter of BPHEs under normal use conditions is obtained as η_{use} = 584507 life cycles by substituting V = 3.0 MPa into Eq. (2).

4.3 Case 2: Fluid temperature and pressure cycle stresses

The second accelerated life test is performed with two stresses, namely, fluid temperature and pressure cycle. The accelerated life model considered for case 2 is the temperature–nonthermal model. The life cycles obtained from the five stress levels are listed in Table 4.

The value of the likelihood ratio test statistic T is equal to 4.8261 for case 2 and is less than or equal to the chi-square

Table 4. Life cycles for case 2 test.

Sample No.	Fluid temperature (°C)	Pressure cycle (MPa)	Start cycle	End cycle
1	90	4.5	29,897	30,226
2	90	4.5	27,256	27,941
3	90	4.5	35,177	38,219
4	90	4.5	33,508	34,733
5	90	4.5	30,376	30,873
6	90	5.5	31,413	31,912
7	90	5.5	28,585	28,999
8	90	5.5	32,602	33,560
9	90	5.5	30,637	31,413
10	90	5.5	20,904	21,957
11	90	6.5	8,074	8,521
12	90	6.5	10,414	11,090
13	90	6.5	15,641	16,016
14	90	6.5	13,701	14,361
15	90	6.5	10,030	10,414
16	75	6.5	12,478	12,992
17	75	6.5	17,768	18,741
18	75	6.5	12,478	12,992
19	75	6.5	18,437	19,452
20	75	6.5	9,298	10,030
21	60	6.5	15,641	16,016
22	60	6.5	13,974	14,557
23	60	6.5	10,655	11,580
24	60	6.5	18,506	19,127
25	60	6.5	19,648	21,305

(7.7794). Thus, the shape parameter estimates do not differ statistically at 10% significance level. From the statistical analysis of life cycles for case 2, maximum likelihood estimates of β, C, E_a, and n are 4.2511, 1.1887×10^6, 0.0106, and 2.4734, respectively. Figs. 6 and 7 show life–stress (Fluid temperature, pressure cycle) relationship plots of life cycles obtained from case 2. Based on the E_a value of 0.0106 and Fig. 6, fluid temperature stress does not largely affect the life cycles of BPHEs.

The scale parameter of BPHEs under normal use conditions is obtained as η_{use} = 114,684 life cycles by substituting T = 323.15 K (50°C + 273.15) and V = 3.0 MPa into Eq. (3).

4.4 Case 3: Combination of cases 1 and 2

The results of cases 1 and 2 show that pressure cycle is more important than fluid temperature. The predicted scale parameters of the two cases are significantly different from each other. The life cycles of cases 1 and 2 are combined for a more accurate analysis. Table 5 shows the test conditions in case 3, and the groups in Table 5 are based on each test condition. Weibull probability plots of all groups are shown in Fig. 8, and the slope of group 3, shape parameter β, differs greatly from those of other groups. Thus, life cycles of group 3 are excluded from the subsequent analysis.

Accelerated life model considered for case 3 is the temperature–nonthermal model as well. The value of the likelihood ratio test statistic T is equal to 5.3154 for case 3 and is less than or equal to the chi-square (10.6446). Thus, the shape parameter estimates do not differ statistically at 10% significance level. From the statistical analysis of the life cycles for case 3, maximum likelihood estimates of β, C, E_a, and n are 4.216, 96281, 0.1667, and 3.9173, respectively. Figs. 9 and 10 show the life–stress relationship plots of the combined life cycles for cases 1 and 2. Based on the results, both fluid temperature and pressure cycle stresses affect the life cycles of BPHEs.

Table 5. Test conditions considered in case 3.

Case	Group	Fluid temperature (°C)	Pressure cycle (MPa)	Sample size
1	1	50	4.5	5
1	2	50	5.5	5
1	3	50	6.5	5
2	4	90	4.5	5
2	5	90	5.5	5
2	6	90	6.5	5
2	7	75	6.5	5
2	8	60	6.5	5

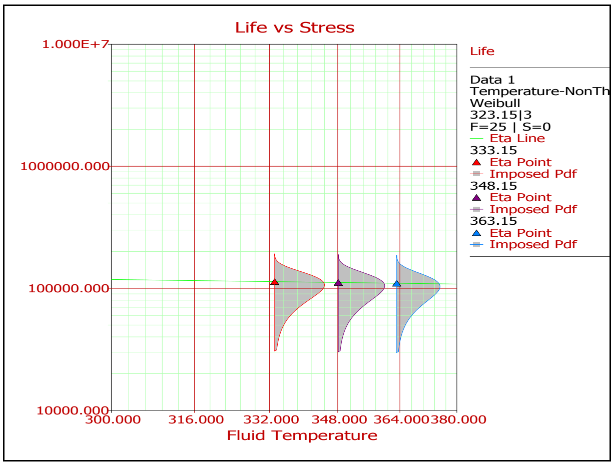

Fig. 6. Life–fluid temperature relationship plot for Case 2 test (from ALTA 7).

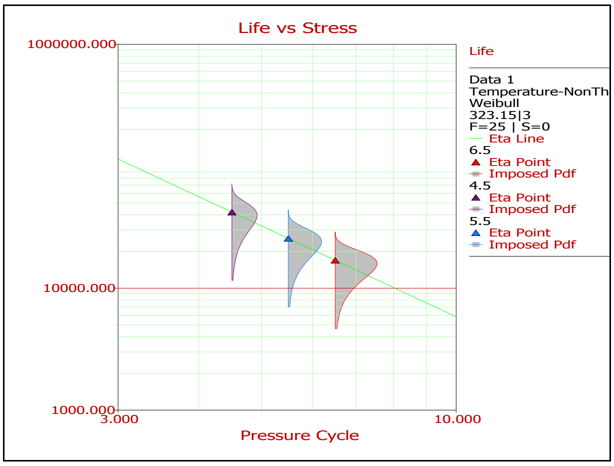

Fig. 7. Life–pressure cycle relationship plot for Case 2 test (from ALTA 7).

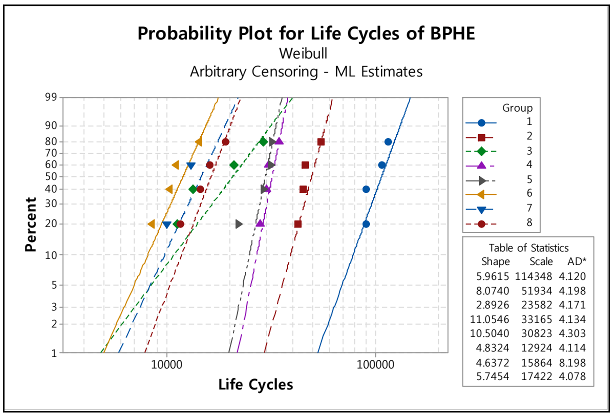

Fig. 8. Weibull probability plot of life cycles obtained from cases 1 and 2 (from MINITAB 17).

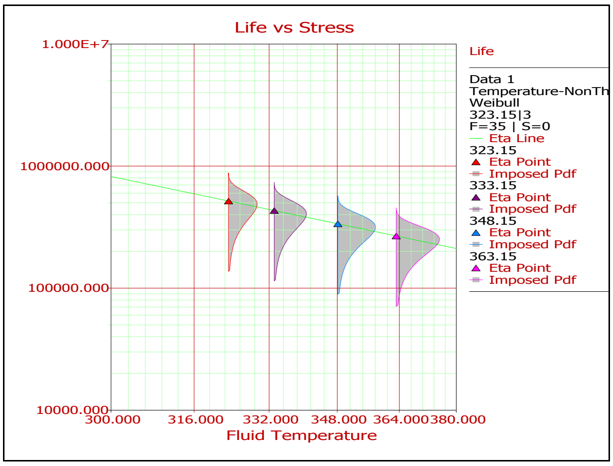

Fig. 9. Life–fluid temperature relationship plot for case 3 (from ALTA 7).

Table 6. Summary of test results based on the three cases.

Parameter	Case 1	Case 2	Case 3
A	1.9929×10^{-8}	-	-
C	-	1.1887×10^{6}	96,281
n	4.0529	2.4734	3.9173
E_a	-	0.0106	0.1667
β	4.7750	4.2511	4.2160
η_{use}	584507	114684	517374

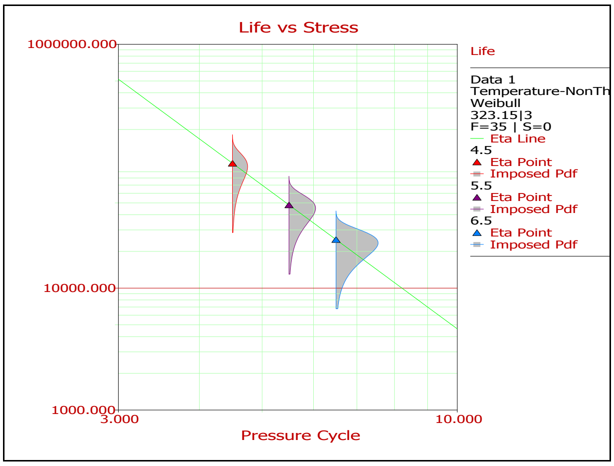

Fig. 10. Life–pressure cycle relationship plot for case 3 (from ALTA 7).

The scale parameter of BPHEs under normal use conditions is obtained as η_{use} = 517374 life cycles by substituting T = 323.15 K and V = 3.0 MPa into Eq. (3).

Based on the three cases, Table 6 presents the estimated parameters of Weibull distribution and accelerated life models for BPHEs. Table 6 also provides the predicted scale parameters (Life cycles) under normal use conditions. According to the estimated results of n, E_a, β, and η_{use}, case 3 can be considered the most meaningful case.

Consequently, both fluid temperature and pressure cycle stresses affect the life cycles of BPHEs. The accelerating index of pressure cycle n and the activation energy E_a in the temperature–nonthermal model are estimated as 3.9173 and 0.1667, respectively.

For most failure mechanisms in electronic components, the activation energy is in the range of 0.3 eV to 1.5 eV [3]. Thus, the activation energy of the BPHEs is relatively low, but varies according to failure mechanisms and product types. Fluid temperature is identified as a relatively insignificant stress on the BPHEs.

The AF between the scale parameters under normal use conditions (50°C and 3.0 MPa) and at 90°C and 6.5 MPa is

$$
\begin{aligned}
AF &= \frac{L_{use}}{L_{test}} = \frac{\eta_{use}}{\eta_{test}} \\
&= \left(\frac{6.5}{3.0}\right)^{3.9173} \cdot \exp\left(-\frac{0.1667}{8.6171\cdot10^{-5}}\left(\frac{1}{323.15}-\frac{1}{363.15}\right)\right). \\
&= 20.6728\times1.9337 = 39.975.
\end{aligned}
$$

Such AF value implies that testing a BPHE at 90°C and 6.5 MPa for one hour is equivalent to testing the BPHE at 50°C and 3.0 MPa for about 40 hours.

The shape parameter described by the failure mode of BPHEs is 4.216, and the scale parameter under normal use conditions of 50°C and 3.0 MPa is predicted to be 517374 life cycles. Using the estimates of the shape and scale parameters, B_{10} life cycles of BPHEs can be estimated as follows:

$$B_{10} = \eta \cdot \{-\ln(1-0.1)\}^{1/\beta} = 303{,}383 \text{ life cycles.}$$

5. Conclusions

This paper presented a life prediction method based on two accelerated life test data for BPHEs. The conclusions of this study are as follows:

- The leakage by structural breakage is identified as the main failure mode of BPHEs.
- The accelerating stresses affecting the life cycles of BPHEs are fluid temperature and pressure cycle. According to the analysis results, pressure cycle is a more sig-

nificant accelerating stress.
- Combining two different sets of accelerated life test data provides a more accurate analysis.
- The representative parameters of the final selected temperature–nonthermal model are as follows:
  • Accelerating index of pressure cycle (n): 3.9173.
  • Activation energy (E_a): 0.1667.
- The shape parameter of Weibull distribution for BPHEs is 4.216.
- The characteristic life and the B_{10} life under normal use conditions of 50°C and 3.0 MPa are predicted to be 517374 and 303383 life cycles, respectively.
- Above all, the valuable data on the BPHEs, namely, β, n, E_a, and life cycles (Characteristic life and B_{10} life) under normal use conditions based on the test results were obtained. These data are especially useful for reliability qualification tests.

Accelerated life tests are generally performed under controlled conditions in a laboratory. Thus, field data on BPHEs are necessary to verify the validity of the accelerated life test results.

Acknowledgment

This paper was supported by the Korea Institute for Advancement of Technology (Project no.: N0000998).

References

[1] G. S. Wasserman, *Reliability verification, testing and analysis in engineering design*, Marcel Dekker, Inc., New York (2003).
[2] G. B. Yang, *Life cycle reliability engineering*, John Wiley & Sons, Inc., New Jersey (2007).
[3] W. Nelson, *Accelerated testing: statistical models, test plans, and data analysis*, John Wiley & Sons, New Jersey (1990).
[4] E. A. Elsayed, *Reliability engineering*, Wiley, New Jersey (2012).
[5] W. Q. Meeker and L. A. Escobar, *Statistical methods for reliability data*, Wiley (1998).
[6] W. Nelson, A bibliography of accelerated test plans part II–references, *IEEE T. Reliab.*, 54 (3) (2005) 370-373.
[7] L. A. Escobar and W. Q. Meeker, A review of accelerated test models, *Stat. Sci.*, 21 (4) (2006) 552-577.
[8] J. I. Park, J. W. Park, M. Jung, Y. H. Huh and S. J. Bae, Cycle-life test time reduction in secondary rechargeable batteries by combining different types of acceleration, *Journal of the Society of Korean Industrial and Systems Engineering*, 31 (4) (2008) 153-161.
[9] G. Han and Y. Fu, Tri-stress accelerated life test for cylinders, *Procedia Eng.*, 16 (2011) 554-563.
[10] S. J. Park, S. D. Park, K. S. Kim and J. H. Cho, Reliability evaluation for the pump assembly using an accelerated test, *Int. J. Pres. Ves. Pip.*, 83 (4) (2006) 283-286.
[11] W. G. Shin and S. H. Lee, A development of accelerated life test method for blower motor for automobile using inverse power law model, *Int. J. Mod. Phys. B*, 22 (9-11) (2008) 1074-1080.
[12] K. Thulukkanam, *Heat exchanger design handbook*, CRC Press (2013).
[13] R. Bogaert and A. Bolcs, Global performance of a prototype brazed plate heat exchanger in a large Reynolds number range, *Exp. Heat Transfer*, 8 (4) (1995) 293-311.
[14] J. Stasiek, M. W. Collins, M. Ciofalo and P. E. Chew, Investigation of flow and heat transfer in corrugated passages - I. experimental results, *Int. J. Heat Mass Tran.*, 39 (1) (1996) 149-164.
[15] Z. H. Ayub, Plate heat exchanger literature survey and new heat transfer and pressure drop correlations for refrigerant evaporators, *Heat Transfer Eng.*, 24 (5) (2003) 3-16.
[16] E. Mencke, J. Larsson, Y. Persson, A. Olsson, A. Dahlquist and P. Eriksson, Brazed plate heat exchangers and their applications, *ASHRAE Trans.*, 111 (2005) 813-821.
[17] D. H. Han, K. J. Lee and Y. H. Kim, Experiments on the characteristics of evaporation of R410A in brazed plate heat exchangers with different geometric configurations, *Appl. Therm. Eng.*, 23 (10) (2003) 1209-1225.
[18] G. A. Longo, Hydrocarbon refrigerant vaporization inside a brazed plate heat exchanger, *J. Heat Transf.*, 134 (10) (2012) 101801-1-10.
[19] *SAE J1597*, Laboratory testing of vehicle and industrial heat exchangers for pressure-cycle durability (2008).
[20] *SAE J1542*, Laboratory testing of vehicle and industrial heat exchangers for thermal cycle durability (2008).
[21] M. S. Chang, J. H. Shin, Y. I. Kwon, B. O. Choi, S. C. Lee and B. S. Kang, Reliability estimation of pneumatic cylinders using performance degradation data, *Int. J. Precis. Eng. Man.*, 14 (12) (2013) 2081-2086.
[22] R. B. Abernethy, *The new Weibull handbook*, Abernethy, R. B. (2004).
[23] B. Bertsche, *Reliability in automotive and mechanical engineering: determination of component and system reliability,* Springer (2008).
[24] *Accelerated life testing reference*, Reliasoft publishing (2007).

Mu-Seong Chang received his Ph.D. degree in industrial and systems engineering from Changwon National University in 2007. He is a senior researcher at the Reliability Assessment Center of the Korea Institute of Machinery & Materials, Korea. His research interests include reliability engineering, accelerated life testing methodology, and applied statistics.

Tae-Kook Park received his M.S. degree in mechanical engineering from Korea Maritime University in 1999. He is a senior researcher at the Reliability Assessment Center of the Korea Institute of Machinery & Materials, Korea. His research interests are heat exchanger and reliability research about machinery components.

Baek-Ju Sung received his Ph.D. degree in electrical engineering from Chungnam National University in 2006. He received his M.S. and B.S. degrees in electrical engineering for Busan National University in 1992 and 1990, respectively. His research interests are electrical actuator and reliability research about machinery components.

Byung-Oh Choi received his B.S. degree in mechanical engineering from Hanyang University, Korea, in 1978 and his M.S. degree from South Dakota State University in 1985. He received his Ph.D. degree from the University of Missouri-Rolla, USA, in 1991. He is currently the director of the Reliability Assessment Center at the Korea Institute of Machinery and Materials, where he is a distinguished research fellow.