공학석사학위논문

# 휴대용 전자기기의 품질보증 남용방지용 장치에 대한 성능 저하 모델 개발

# A Performance Degradation Model for Warranty Abuse Detection in Portable Electronics

2013 년 8 월

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지도교수 윤 병 동

이 논문을 공학석사 학위논문으로 제출함

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기계항공공학부

최 승 혁

최승혁의 공학석사 학위논문을 인준함

2013 년 6 월

위 원 장 김 윤 영 (인)

부위원장 윤 병 동 (인)

위 원 김 도 년 (인)

# Abstract

## A Performance Degradation Model for Warranty Abuse Detection in Portable Electronics

Seunghyuk Choi
School of Mechanical and Aerospace Engineering
The Graduate School
Seoul National University

The market for portable electronics (i.e. smartphones, tablet PCs, laptops) has been expanding gradually and customers' expectations for high reliability cause various controversial issues. Industry use of a liquid damage indicator (LDI) as a method for warranty abuse is one of the problems receiving customers' attention. As the price for electronic devices has increased, customers have become more concerned about warranty policies of electronic device manufacturers. Some customers have even abused the warranty service and made unfair profit. As a result, electronic device manufacturers have decided not to provide warranty service for damage resulting from the fault of customers, especially as it relates to liquid-damaged products. Electronic device manufacturers have increasingly employed LDIs in products to detect if a device has been damaged by liquid. An LDI is a sticker which consists of multiple layers. The LDI changes in color from white to red when it comes in contact with liquids. When a customer takes his/her device to a service center, the staff will first check the LDIs' color in the device and will refuse to provide warranty service for any device with red LDIs.

However, existing LDIs exhibit inconsistencies in characteristics which can lead to improper warranty denials. Many websites and a few broadcast media sources have presented examples of LDI's showing a faulty alarm based on environmental conditions. At least one major electronics manufacturer, Apple Inc., has been sued over the LDIs' poor performance and therefore a possibly unreasonable warranty policy. However, no quantified engineering data existed for objective evaluation of the LDIs' performance. Therefore, for the benefit of the public and the protection of electronics manufacturers', a need arose to develop a method that quantifies LDI performance.

In this study, a performance degradation model for an LDI has been developed and validated. The model was developed with following three steps; 1) accelerated life testing of LDIs on two substrates, 2) performance degradation model development based on the test results, and 3) model validation with environmental cyclic test of LDIs attached in iPhone 3 handsets.

**Keywords:** Warranty Abuse Detection
Liquid Damage Indicator
Accelerated Life Testing
Image Processing
Performance Degradation Model
Validation Test

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# Nomenclatures

| | |
|---|---|
| $R_i$ | red values in i$^{th}$ pixel |
| $G_i$ | green values in i$^{th}$ pixel |
| $B_i$ | blue values in i$^{th}$ pixel |
| $P(x)$ | probability of $x$ |
| $T$ | temperature |
| $R(T)$ | reaction rate at temperature $T$ |
| $A$ | scaling factor of the Arrhenius model |
| $E_a$ | activation energy of the Arrhenius model |
| $k$ | Boltzmann's constant |
| $AF(T)$ | acceleration factor at temperature $T$ |
| $n$ | cycle number of accelerated life test |
| $D(n;T)$ | performance degradation |
| $t$ | test time |
| $S(t)$ | survival rate at time $t$ |
| $m(t)$ | number of survived test samples by the time t |
| $d_i$ | number of failed (or censored) test samples at the i$^{th}$ time interval |
| $\tau$ | number of survived test samples at the time interval |
| $\lambda$ | expected number or failures per a unit $\tau$ |

|  |  |
|---|---|
| $CF(\tau)$ | cumulative failure curve of the test samples |
| $j$ | number of piece on estimated hazard rate curve |
| $F_j$ | number of failures in piece $j$ |
| $E(x)$ | mean value of $x$ |
| $Var(x)$ | variance estimates of $x$ |

# Chapter 1. Introduction

Portable electronics (e.g., smartphones, tablet PCs, laptops) make our lives better by providing useful applications. The market for these products is expanding continuously. As electronics have become more expensive and more widely used, customers have become more sensitive to warranty services when defects are found in their devices. According to a study from SquareTrade, Inc., 31% of iPhone 3G models failed in the first 22 months. Two-thirds of those failures were considered to be caused by user abuse or accidental damage; 25% of the failures were due to water damage [1, 2].

As electronic devices have become more expensive, some people have abused warranty policies and electronics manufacturers have paid too much to settle warranty claims. Therefore, some portable electronic device manufacturers have introduced liquid damage indicators (LDIs) into their products to control costs. These indicators allow companies to refuse to provide warranty or replacement service when the indicator suggests that the damage is due to user abuse.

An LDI is a thin adhesive tape that consists of several layers. When liquid contacts an LDI’s edge, it absorbs water and turns red. When a customer visits a service center with his/her faulty device, an employee checks the color of LDIs in it and warranty service may be denied if the LDIs are red.

However, this policy of refusing customers’ claims based on LDI color, rather than examining the actual root cause of failure, is based on faulty logic. Many websites and a few broadcast media sources have presented cases of LDIs changing color due to small amounts of sweat, drops of rain, or a humid atmosphere. In fact, in April 2010, one major electronics company was sued for denying warranty service to customers based on inaccurate LDIs. Also, in 2011, the company agreed to make a payment to a customer in a lawsuit filed for the breakdown of her device supposedly caused by water damage. The customer insisted that she had never let her device contact water, but the LDIs in her device were red [3]. Moreover, in May 2013, the electronics company agreed to pay $53 million to settle a class-action suit which was filed in 2010 [4].

However, most electronic manufacturers are still employing LDIs in their products. Without quantified information about reliability of LDI performance, the same problem will likely continue. Therefore, there is a need to develop a method that quantifies LDI performance

We executed accelerated life tests with LDIs and developed a performance degradation model that predicts LDI characteristics under various conditions. These results will quantify LDI performance to the benefit of both portable electronic device manufacturers and consumers. This thesis is organized as follows: Chapter 2 overviews LDI-related warranty policies that detect customers’ warranty abuse and introduces controversial issues. Chapter 3 reviews the basic ideas and theories of accelerated life testing (ALT). Chapter 4 presents the pre-tests and condition settings for ALT with LDIs. Chapter 5 describes ALT procedures, test results, and data processing. Chapter 6 explains development of the performance degradation model. Chapter 7 attempts to validate the performance degradation model with cyclic environmental tests under use conditions of two smartphone sets. Finally, Chapter 8 summarizes the content of the research works and discusses the results.

# Chapter 2. Review of Warranty Abuse Detection Methods in Electronic Devices

As shown in Figure 1, an LDI consists of a transparent polyethylene terephthalate (PET) top film, an indicator layer, and an adhesive layer. The indicator layer is made of a porous paper (for quick liquid absorption) and a red ink dye. LDI thickness is approximately 0.3 mm [5]. Upon water contact at the tape edge, the porous paper quickly absorbs the water, and red ink from the dye diffuses into the paper layer. The paper layer remains red after the LDI dries out. The PET top film prevents the color from changing due to water contact from the top. Therefore, the LDI works as a water contact sensor by revealing whether or not the portable electronics may have experienced direct water contact with submersion.

According to technical data from an LDI manufacturer, the best performance is obtained when the LDI is used within 18 months from the date of manufacture. The technical data shows that the LDI can perform properly under conditions of -40℃ to 65℃ and is resistant to highly humid conditions (95% relative humidity at 55℃). According to the technical data, the LDI does not turn red from exposure to condensing steam at room temperature [6-8].

The LDI attached to electronic devices are located in various positions (e.g., headphone jack, dock-connector housing, under batteries, on main-boards). While these areas can get wet by submersion in water they can also be affected by small amounts of sweat or a drop of rainfall. Many devices include more than one LDI in different positions. An example of the locations of LDIs in an electronic device is shown in Figure 2.

According to the current warranty policies of Apple Inc., when a customer visits a service center with his/her malfunctioning device, an employee first checks the color of the LDIs. Warranty service is refused if any LDI's color is red. Upon the customer's further insistence, a secondary check is executed to investigate the corrosion state of electronic parts in the device. This secondary check leads to a final decision whether or not the warranty service will be provided. This is a time-consuming process that inconveniences customers. In many cases, the customers decide to pay the repair cost or purchase a new device.

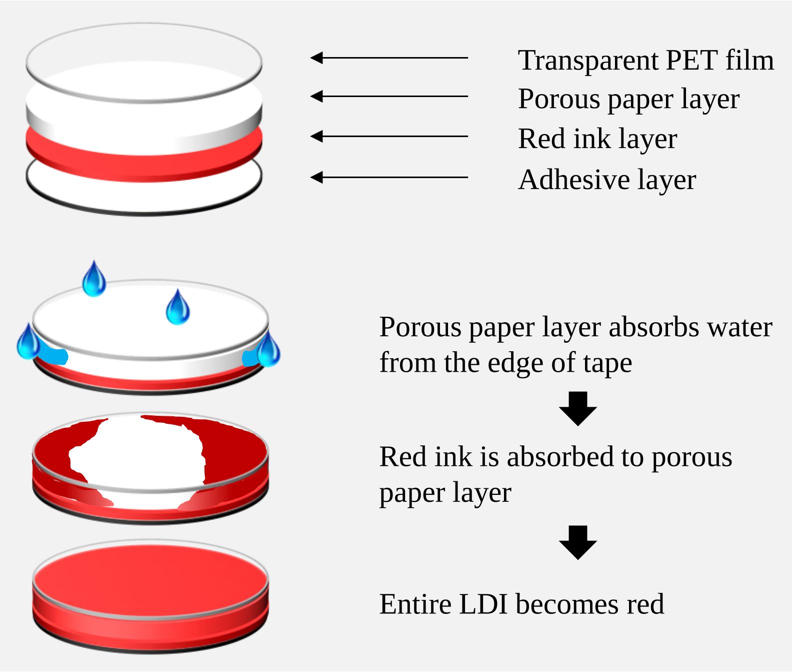


**Figure 1 Schematic diagram of warranty abuse detection.**

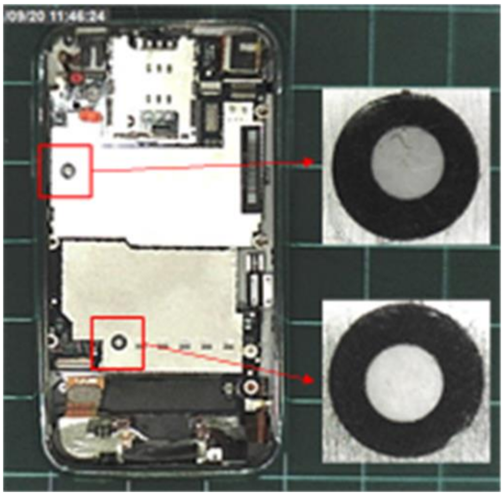


**Figure 2 Locations of LDIs in a sample smarphone set.**

# Chapter 3. Overview of Accelerated Life Tests

Due to rapidly changing technologies and customers' requirements for higher reliability and wider use conditions, today's manufacturers need a large amount of information about their product in a very short time. In addition, modern products are commonly designed to operate several years or even decades without failure. In some cases, it is impractical to conduct a test under normal use conditions to get information related to the life of products, such as failure time distribution.

Therefore, the accelerated life test is often used by manufacturers to acquire life and reliability information of products and detect their failure mechanisms and modes so that they can be corrected in the design process [9]. A stress condition must be imposed to significantly reduce the duration of the test without shifting a failure mechanism. Stress conditions have to be suitably designed to ensure success of the accelerated life test. Stress factors can be any physical variables (i.e., temperature, humidity, cycling rate) that affect performance degradation and life of the products [10-12]. Then, the life information at the accelerated stress levels is used to predict the life at the normal stress level. Statistical models with reasonable model assumptions should be employed to build a relationship between life models under use and stress conditions [13].

This chapter presents the state-of-the-art knowledge for the accelerated life test. Section 3.1 describes the stress acceleration method for accelerated life tests. Section 3.2 explains the various types of stress factors and related stress-life models for each stress factor. Section 3.3 reviews general procedures for accelerated life tests and analysis of test data.

## 3.1 Stress Acceleration

### 3.1.1 Acceleration method

Stress can be accelerated by increasing the use rate for products which are typically used intermittently (e.g. microwave ovens, laundry machines, printers, or copiers, etc.). Fatigue testing by increasing the cycling rate or frequency is a good example for this. On the other hand, for products which are used continuously throughout the day (e.g. sensors, lights, server computers, displays), increasing the use rate is unpractical for stress acceleration. In this case, a level of stress such as temperature, humidity, or voltage can be increased for accelerated life tests. The stress level should be accelerated appropriately for test time reduction and maintaining the major failure mechanism. Otherwise, the information from the accelerated life test data can’t be used to extrapolate life information under normal use conditions.

### 3.1.2 Stress applying method

The most common stress applying method for accelerated life tests is constant-stress acceleration. For the constant-stress accelerated test, the stress applied to a test sample is constant through the entire test duration as shown in Figure 3. It is easy to apply constant stress to a test sample and analyze test data. Many researches and test data have been reported employing constant-stress accelerated tests [9].

Step-stress accelerated tests and progressive-stress accelerated tests are executed to consider the cumulative effect of stress, as shown in Figure 4 and Figure 5. These methods enable remarkable test time reduction. However, it is difficult to develop a physical model that explains the effect of stress rise to the failure of a test sample [16, 19].

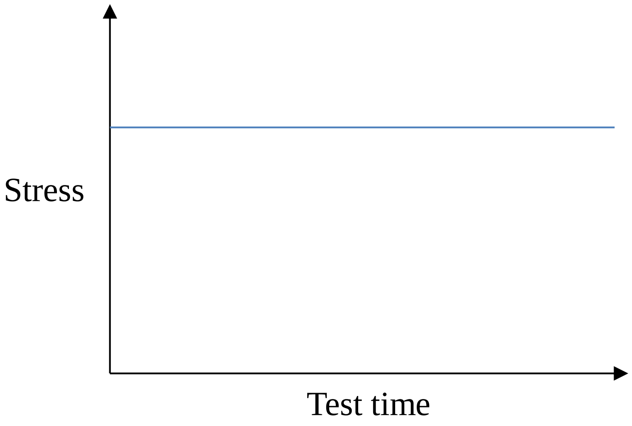


**Figure 3 Constant-stress accelerated test.**

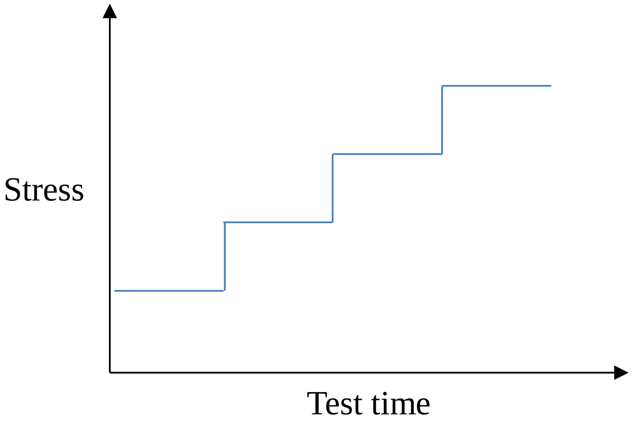


**Figure 4 Step-stress accelerated test.**

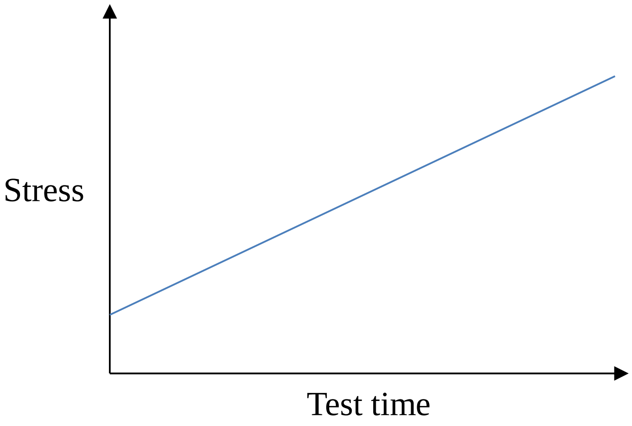


**Figure 5 Progressive-stress accelerated test.**

## 3.2 Types of Stress and Related Stress-Life Models

Appropriate stress-life relationship is important for extrapolation of accelerated life test results to life information under normal use conditions. In this section, various types of stress factors and related stress-life models for each stress factor are reviewed.

### 3.2.1 Temperature for stress acceleration

In general, temperature is related to a chemical reaction rate and thus affects the degree of degradation and reliability of a product. Increasing temperature is a commonly employed method for accelerated life tests for many products such as LEDs, relays, batteries, etc. [10]. When temperature is the only stress factor for the accelerated life test, the Arrhenius model is often used to extrapolate test data to life distribution at different conditions [10]. The Arrhenius model describes the effect of temperature on the chemical reaction rate and can be expressed as:

$$R(T) = A \cdot \exp\left(\frac{-E_a}{k \cdot T}\right) \tag{1}$$

where $R(T)$ denotes a reaction rate with the temperature $T$ [K]. $A$ is a scaling factor that drops out when calculating acceleration factors, $E_a$ [eV] denotes the activation energy that is the critical parameter in the model, and $k$ [eV/K] is the Boltzmann's constant. The value of $E_a$ depends on the failure mechanism and the material involved. In a specific case, $k$ can be replaced with the universal gas constant [10]. An acceleration factor, the ratio of reaction rate at a temperature $T_1$ to the one at $T_2$, is computed as:

$$AF(T_1) = \frac{R(T_1)}{R(T_2)} = \exp\left[\frac{-E_a}{k} \cdot \left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] \tag{2}$$

### 3.2.2 Humidity for stress acceleration

Humidity is also a critical physical parameter in the failure mechanisms of many engineering systems or devices. The failure mechanism related to corrosion is strongly affected by humidity. Performance degradation of plastic packaged electronic devices, printed circuit boards, and the paint and coating used for various materials are typical examples related to relative humidity as a main stress factor [10]. When relative humidity is a concerning stress factor for an accelerated life test, the Eyring-Arrhenius model is often used for extrapolation of test results. This model is expressed as:

$$R(T,RH) = A_1 \cdot T^m \cdot \exp\left(\frac{-E_a}{k \cdot T}\right) \cdot \exp\left(A_2 \cdot RH + \frac{A_3 \cdot RH}{k \cdot T}\right) \tag{3}$$

where $R(T,RH)$ denotes a reaction rate with the temperature $T$ [K] and the relative humidity $RH$ [%]. $E_a$ [eV] denotes the activation energy and $A_1$, $A_2$, $A_3$, $m$ are model parameters related to the particular physical/chemical process. $k$ [eV/K] is the Boltzmann's constant [10].

### 3.2.3 Non-thermal parameters for stress acceleration

For the stress factor of a non-thermal parameter such as voltage or fatigue, the inverse power model is commonly used. This model can be employed for data analysis of an accelerated life test with electric insulators, dielectric materials, bearings, filaments, etc [9]. The inverse power model can be expressed as:

$$R(V) = \frac{1}{A \cdot V^B} \tag{4}$$

where $R(V)$ denotes a reaction rate with the non-thermal stress $V$ and $A$, $B$ are model parameters calculated from test data [10].

## 3.3 Procedures for Accelerated Life Tests

This section describes general procedures for accelerated life tests, including major failure mechanism selection, condition settings, and data analysis.

### 3.3.1 Major failure mechanism

Multiple mechanisms may exist for failure of a product. However, it is impractical and financially infeasible to find all the failure mechanisms and execute accelerated life tests for each. Therefore, engineers should select the major failure mechanism (i.e., the one with most frequent occurrence and most critical to the failure of a product) before executing the accelerated life test for it [17]. If there is no information about the major failure mechanism, engineers can employ failure analysis such as FTA or FMEA [17, 18]. An example of FMEA is presented in Table 1.

**Table 1 An example of FMEA for a pneumatic cylinder.**

| **Primary components** | **function** | **Failure mode** | **Failure mechanism** | **Failure effect** | **Evaluation for Failure criticality** | | |
|---|---|---|---|---|---|---|---|
| | | | | | **frequency** | **severity** | **criticality** |
| **Piston seal** | Internal leakage prevention | Leakage | Wear | Minimum working pressure degradation | Medium | High | 7 |
| | | Friction | Lubrication failure | Efficiency degradation | High | High | 9 |
| | | Pressure down | Fatigue | Pressure resistance degradation | Low | Medium | 3 |
| **Rod seal** | External leakage prevention | Leakage | Wear | Minimum working pressure degradation | Medium | High | 7 |
| | | Friction | Lubrication failure | Efficiency degradation | High | High | 9 |
| | | Pressure down | Fatigue | External leak | Medium | High | 7 |
| **Cylinder tube** | Preservation of cylinder structure and stiffness | Damage | Fatigue | Pressure resistance loss,<br>Leak | Low | Medium | 3 |
| | | Trans-formation | Shifting load | Efficiency degradation | Low | Low | 1 |
| **Head and rod cover** | Prevention of internal tube tightness | Joint breakage | Over pressure | External leak | low | Low | 1 |

### 3.3.2 Condition settings

After selecting the major failure mechanism, the level of the main stress factor should be defined for the accelerated life test. The selected failure mechanism should be accelerated with a greater level of the main stress factor for test time reduction. However, too much stress acceleration from the main stress factor may change the major failure mechanism between accelerated condition and normal condition. For example, if the major failure mechanism of a product is defined as a specific chemical reaction, it can be accelerated with higher temperature related to activation energy. However, acceleration of temperature to a level that is too high can cause another type of chemical reaction or physical damage by thermal expansion. In cases like this, data from the accelerated life test can't be used as life information of the product because the major failure mechanism shifted [9].

Therefore, appropriate condition setting is the most important factor for an accelerated life test. Range of stress should be defined by pre-tests or investigation of physics of failure for a target product. Generally, two or three stress levels are selected for an accelerated life test to consider test time reduction while maintaining the major failure mechanism [9].

### 3.3.3 Data analysis

Data analysis for an accelerated life test includes life distribution selection, validity check for accelerated life test data, stress-life model selection, parameter calculation and life prediction of a target product under normal conditions. Commonly used life distribution includes normal distribution, lognormal distribution, exponential distribution or Weibull distribution. Validity of acquired accelerated life test data is checked by comparison of life distribution for each test condition. Then, an appropriate stress-life model is selected considering the major failure mechanism and model parameters are calculated from accelerated life test results [10-12].

# Chapter 4. Pre-tests for Accelerated Life Tests of Liquid Damage Indicators

Definition of test conditions is the most important part for accelerated life tests. As portable electronics are globally used, their use conditions vary widely from extremely hot to cold and dry to humid. This study employed an iPhone 3 from Apple Inc. Apple determined a use temperature range for iPhone as -20 to 45℃, and relative humidity as 5 to 95%. To confirm the main stress factor for LDI's color change without direct water contact, we executed pre-tests. From the perspective of warranty abuse detection, two pre-tests (a high humidity test and a temperature cycle test) were performed with the aim to observe the performance of the LDI on different substrates and to decide the main stress factor for the accelerated life tests. Four different substrates commonly used in smartphones were considered: glass, aluminum, flexible printed circuit board (FPCB), and flame retardant composition 4 (FR-4). In this chapter, the procedures for pre-tests and condition settings for accelerated life tests are described.

## 4.1 Main Stress Factor

### 4.1.1 High humidity resistive test

Many websites and a few broadcast media outlets have pointed out false alarms of LDIs under highly humid conditions. We conducted high humidity resistive tests of LDIs attached on the four different substrates. We attached LDIs on the substrates and took the test samples in an environmental chamber which was set to 55℃ and 95% R.H. We observed the color of the LDIs for 7 days, but they remained unchanged, as shown in Figure 6.

**Figure 6 High humidity resistive test.**

### 4.1.2 Temperature cyclic test

As the LDIs attached on different substrates showed great resistiveness against highly humid conditions, we changed the stress condition to consider cycling. We attached LDIs on the four substrates and applied a temperature cycle between -35℃ and 55℃. After a few cycles, the LDIs attached on glass, aluminum, and FR-4 showed color change. On the other hand, the LDI attached on FPCB did not trigger, as shown in Figure 7. Therefore, we decided the main stress factor for the accelerated life test of LDI should be temperature cycle. We considered resistiveness against temperature cycling for LDIs attached on glass and FPCB substrates during the accelerated life test.

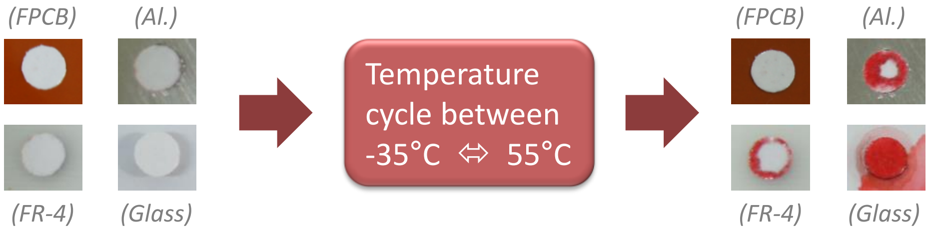


**Figure 7 Temperature cyclic test.**

## 4.2 Condition Setting

The definition of the stress level for the accelerated life test is an important part of the test, as mentioned in section 3.3. Thus, in the accelerated life test of the LDI, the temperature difference should be defined appropriately for test time reduction and to maintain the major failure mechanism. Therefore, we performed two more pre-tests: 1) temperature cyclic tests under conditions of both high and low temperature ranges, and 2) temperature stabilization tests.

### 4.2.1 Temperature cyclic test under high and low temperature ranges

As mentioned earlier, portable electronics are globally used and their use conditions vary widely from extremely hot to cold. To check the false alarm rate under both hot and cold conditions, we performed temperature cyclic tests both under high and low temperature ranges to consider the widely varying use conditions observed in actual product use. As shown in Figure 8, LDIs showed better performance under high temperature range than was observed under low temperature range.

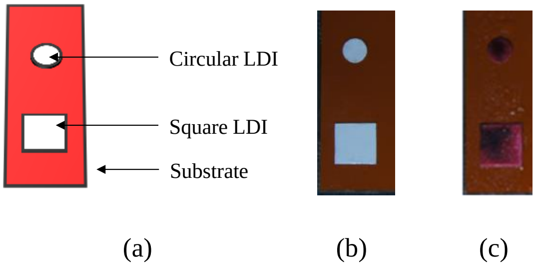
**Figure 8 LDI's performance under high and low temperature ranges**

Therefore, the accelerated life tests for LDIs were conducted under low temperature ranges and test conditions are presented in Table 2. Test conditions were designed to consider the environmental requirements of iPhones specified by the manufacturer, Apple Inc. Tests 1 and 2 are accelerated conditions whereas tests 3 and 4 are within the use conditions specified by Apple Inc. for the iPhone series. These tests require two environmental chambers to simulate the stress conditions.

**Table 2 Conditions for the accelerated life tests**

| Test No | Conditions in Chamber 1 | Conditions in Chamber 2 |
|---|---|---|
| 1 | -30℃ | 25℃, 95% R.H. |
| 2 | -25℃ | 25℃, 95% R.H. |
| 3 | -20℃ | 25℃, 95% R.H. |
| 4 | -15℃ | 25℃, 95% R.H. |

As shown in Figure 9, the test samples examined two different shapes of LDI on the FPCB or glass: 10mm × 10mm square and 6mm-diameter circular shape. The ALTs were conducted ten times for each test condition on FPCB and glass substrates, respectively. The LDIs used in the tests were 3M water contact indicator tape 5557 [6-8].



(a) (b) (c)

**Figure 9 Schematic diagram of a test sample (a), pictures before the test (b), and after the test (c).**

### 4.2.2 Temperature stabilization test

Definition of duration for each temperature cycle was a critical parameter for test time reduction and appropriate main stress acceleration. Therefore, we conducted a temperature stabilization test to observe the temperature changing aspect on the surface of test samples and define duration for temperature cycle.

We attached thermocouples on the surface of a test sample and measured the temperature while the test sample was put into an environmental chamber which was set to lower than 0℃. Temperature stabilization tests were performed under two conditions, considering the accelerated life test condition. As shown in Figure 10 and Figure 11, the test samples’ surface temperature dropped and stabilized in about 10 minutes when put into an environmental chamber which was set to -10℃. Stabilization of temperature took about 30 minutes when the chamber was set to -35℃. We referred to these results when deciding the duration of each temperature cycle for the accelerated life tests.

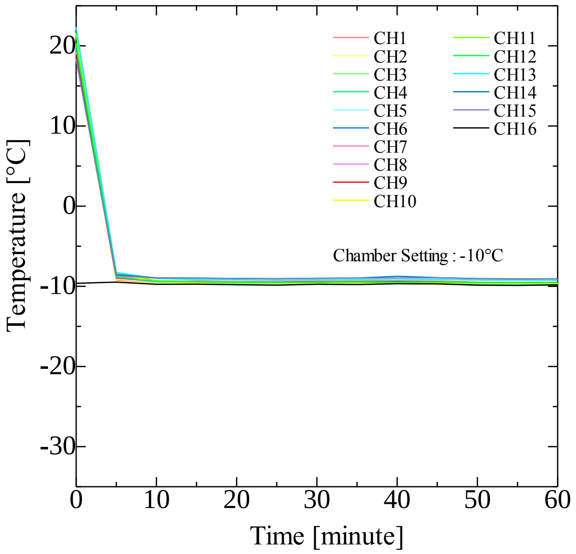


**Figure 10 Temperature stabilization test (20°C to -10°C).**

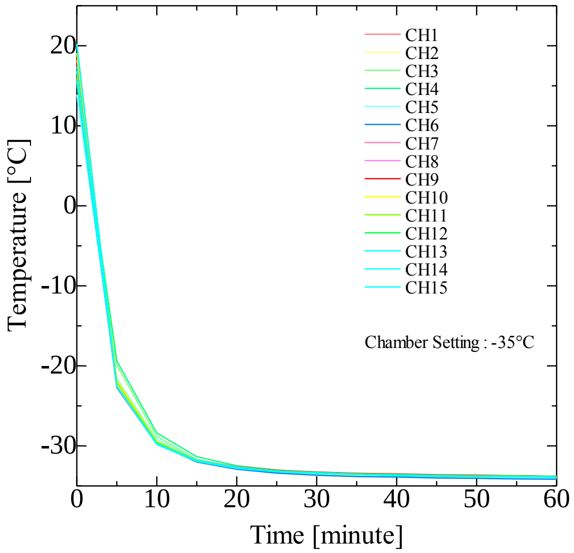


**Figure 11 Temperature stabilization test (20°C to -35°C).**

# Chapter 5. Accelerated Life Tests of Liquid Damage Indicators

Accelerated life tests (ALTs) provide information about the lifetime distribution of a product in a short time by applying a high stress level to the product. For development of a performance degradation model, this section presents the ALT procedures and results for ALT of LDIs that are used as warranty abuse detectors in electronics. Section 5.1 depicts the overall procedure of the ALTs. Section 5.2 provides the test results.

## 5.1 Procedure of the Accelerated Life Tests

### 5.1.1 Steps for the accelerated life tests

The ALTs were executed in the following steps.

Step 1 – Execute a 30-min. test for a sample in Chamber 1.

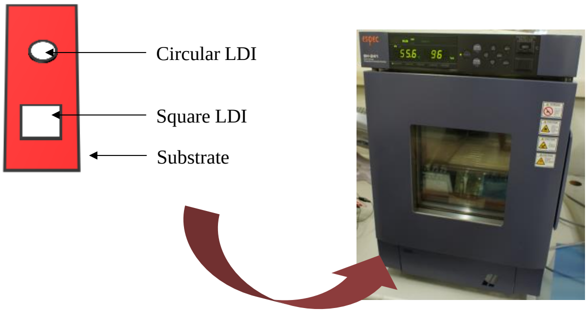
Step 2 – Execute a 5-min. test in Chamber 2 as soon as the sample is taken out from Chamber 1.

Step 3 – Take a picture of the sample after Step 2 under predefined light and angle conditions.

Step 4 – Repeat Steps 1 to 3 until the sample experiences 50 cycles or the LDIs turn red entirely.

Figure 12 presents procedures of the accelerated life tests for LDIs.

*Step 1) 30 minutes in Chamber 1*



*Step 2) 5 minutes in Chamber 2*

*Step 3) Picture Taking at a Fixed Angle*

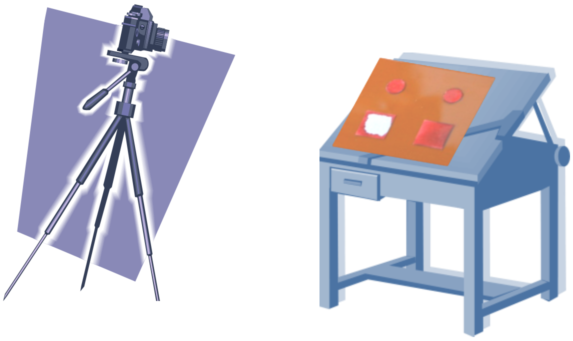


**Figure 12 Procedures of the accelerated life test.**

### 5.1.2 Quantification of performance degradation

As the LDI contacts liquid or water its color changes from white to red. This study quantified the color change by observing the RGB composition of pixels in the pictures (from Step 3). As shown in Figure 13, all pictures are composed with arrays of pixels and they have quantitative values for each of the three additive primary colors, red, green, and blue. Therefore, the pictures can be quantified using those RGB values. Since white and red pixels are of great interest, they were chosen for the quantification. To understand the RGB composition of the white and red pixels, we randomly picked ten white and red pixels, respectively, from ten test samples for each test condition and calculated their mean RGB values, as shown in Table 3. The white and red pixels show far more differences in G and B values than R. That is because, a white pixel has high R, G and B values while a red pixel only has high R values but low G and B values.

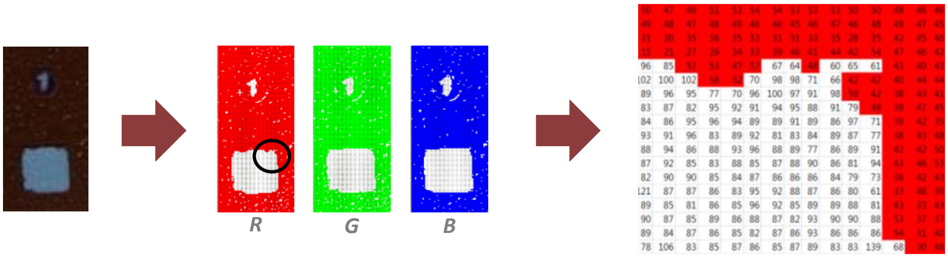


**Figure 13 Image processing (RGB color model)**

**Table 3 RGB values for white and red pixels of LDI**

| **Test No.** | **White pixel** | | | **Red pixel** | | |
|---|---|---|---|---|---|---|
| | ***R value*** | ***G value*** | ***B value*** | ***R value*** | ***G value*** | ***B value*** |
| 1 | 127 | 135 | 119 | 55 | 15 | 17 |
| 2 | 117 | 125 | 109 | 74 | 25 | 23 |
| 3 | 112 | 121 | 109 | 82 | 42 | 40 |
| 4 | 127 | 137 | 126 | 97 | 71 | 61 |

When an LDI is triggered, the color of it gradually changed to red from the outside. As shown in Figure 13, red regions are always in the middle of the test sample whether the LDIs are triggered or not. We measured G and B values of the pixels in these red regions, and calculated the mean and standard deviation of them to quantification of color. Then, a pixel in the pictures was counted as a white if Eq. (5) was satisfied: where the addition of $G_i$ and $B_i$ denote G and B values of *i*th pixel, respectively. $G_{i,red}$ and $B_{i,red}$ represent the G and B values of *i*th pixel in the red regions. We multiplied 5 to standard deviations of $G_{i,red}$ and $B_{i,red}$ to reduce data fluctuation by noise. Then the white area metric, which implies the degree of performance degradation on an LDI, is then defined as:

$$\begin{aligned}&\text{White pixel [\%]} = \\ &P[G_i + B_i > Mean\left(G_{i,red}\right) + Mean\left(B_{i,red}\right) + 5\left\{std\left(G_{i,red}\right) + std\left(B_{i,red}\right)\right\}]\end{aligned} \tag{5}$$

## 5.2 Results

Initially, the color classification rule confirmed the 100% white area in the LDIs on test samples. As the tests progressed, the LDI gradually turned red; therefore, the percentage of white area decreased. Tests were ended when the cycle number reached 50 or the entire LDI turned red. The results of LDI color change under four ALT conditions on the FPCB substrate and the glass substrate are shown in Figure 14 to Figure 21. As the range of temperature change $\Delta T$ increased, the white area decreased more rapidly. In addition, LDIs on a glass substrate show greater decreasing rate of the white area compared to the LDIs on the FPCB.

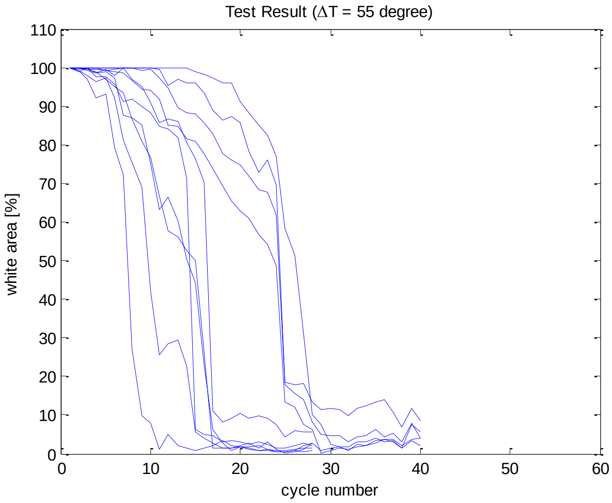


**Figure 14 Results of the ALT on FPCB substrate.**

**(Δ*T* = 55°C between -30°C and 25°C)**

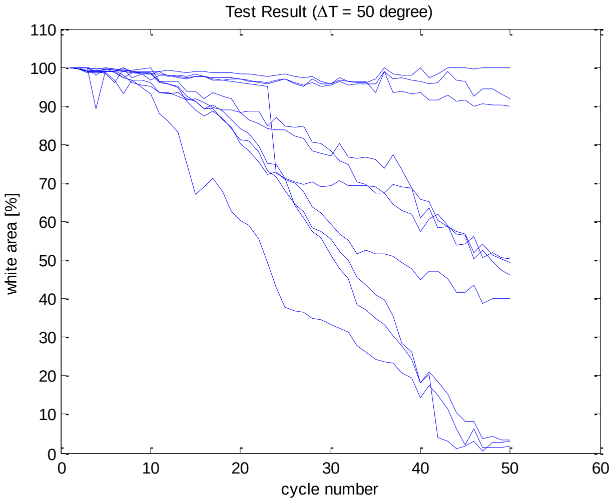


**Figure 15 Results of the ALT on FPCB substrate.**

**(Δ*T* = 50°C between -25°C and 25°C)**

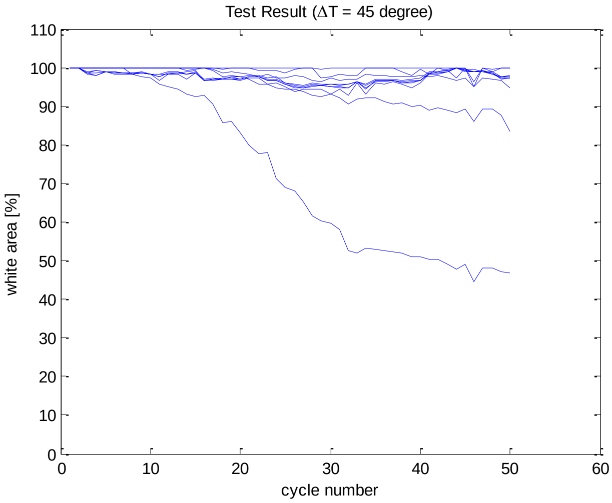


**Figure 16 Results of the ALT on FPCB substrate.**

**(Δ*T* = 45°C between -20°C and 25°C)**

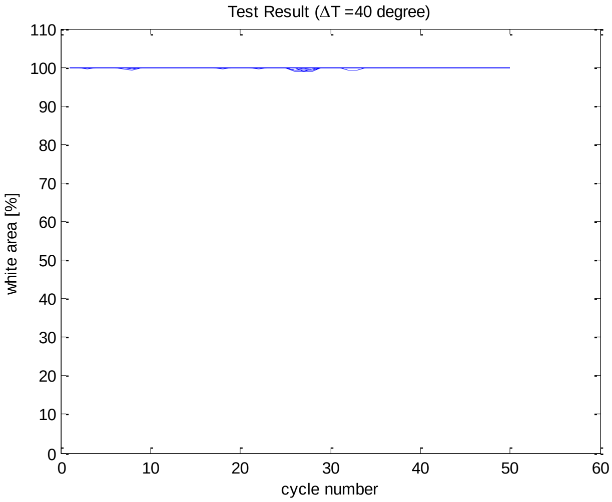


**Figure 17 Results of the ALT on FPCB substrate.**

**(Δ*T* = 40°C between -15°C and 25°C)**

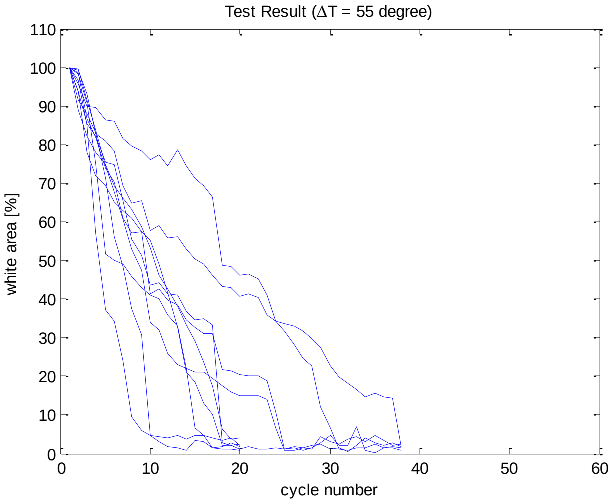


**Figure 18 Results of the ALT on glass substrate.**

**(Δ*T* = 55°C between -30°C and 25°C)**

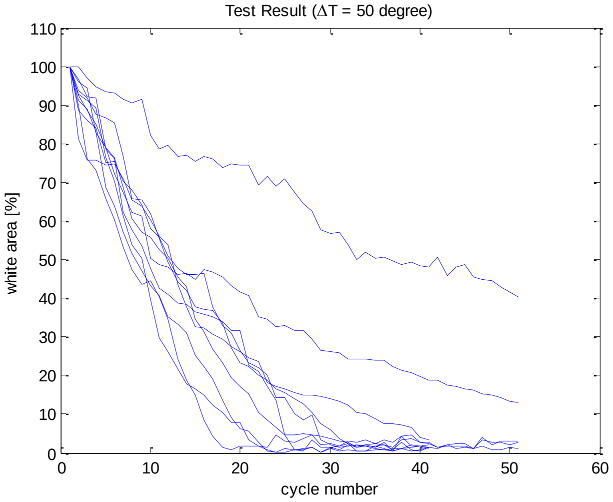


**Figure 19 Results of the ALT on glass substrate.**

**(Δ*T* = 50°C between -25°C and 25°C)**

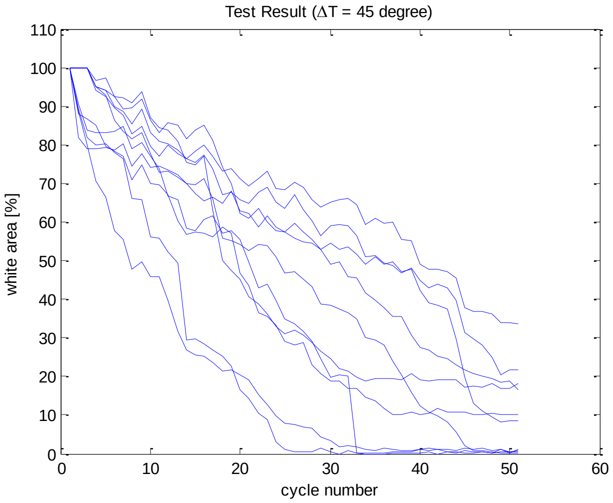


**Figure 20 Results of the ALT on glass substrate.**

**(Δ*T* = 45°C between -20°C and 25°C)**

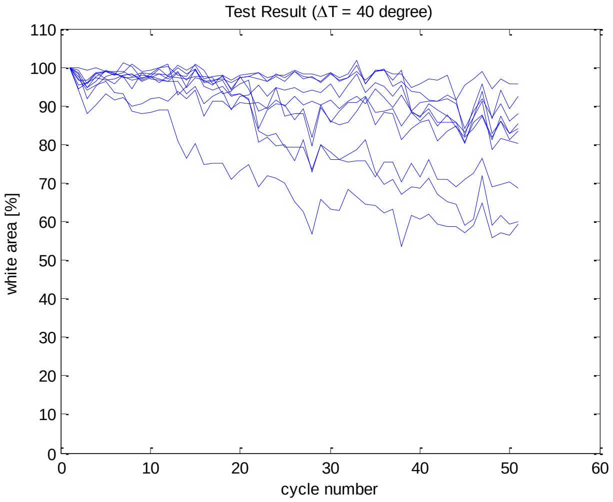


**Figure 21 Results of the ALT on glass substrate.**

**(Δ*T* = 40°C between -15°C and 25°C)**

# Chapter 6. Development of a Performance Degradation Model

This section describes the development of a performance degradation model using the ALT results obtained in Section 5. This performance degradation model can provide life information of the LDIs used in smartphones under various use conditions.

## 6.1 Arrhenius Relationship

Since temperature turned out to be the main stress factor in this study, the Arrhenius model seems to be suitable to analyze the life test data [9]. The Arrhenius model is often used to predict failure acceleration due to temperature change, expressed as:

$$R(T) = A \cdot \exp\left(\frac{-E_a}{k \cdot T}\right) \tag{6}$$

where $R(T)$ denotes a reaction rate with the temperature $T$ [K]. $A$ is a scaling factor that drops out when calculating acceleration factors, $E_a$ [eV] denotes the activation energy that is the critical parameter in the model, and $k$ [eV/K] is the Boltzmann's constant. The value of $E_a$ depends on the failure mechanism and the material involved. In specific cases, $k$ can be replaced with the universal gas constant. An acceleration factor, the ratio of reaction rate at a temperature $T_1$ to the one at $T_2$, is computed as:

$$AF\left(T_1\right)=\frac{R\left(T_1\right)}{R\left(T_2\right)}=\exp\left[\frac{-E_a}{k}\cdot\left(\frac{1}{T_1}-\frac{1}{T_2}\right)\right] \tag{7}$$

## 6.2 Performance Degradation Model for LDI

As the white area values in Figures 4 and 5 imply the degree of performance degradation of an LDI, this study employs the values in Eq. (6) for developing the performance degradation model. A degradation-path model is often used for modeling performance degradation [10, 11], and can be expressed as:

$$D\left(n;\ T\right)=D_\infty\times\left[1-\exp\left\{-R\left(T_{use}\right)\times AF\left(T\right)\times n\right\}\right] \tag{8}$$

where $D(n; T)$ is the performance degradation for a device such as an LDI at time $n$ [cycle] and temperature $T$ [K], $D_\infty$ is an asymptote of the model, $R(T_{use})$ is the reaction rate at the use temperature $T_{use}$ [K], and $n$ is the number of cycles.

For applications, such as LDI, where the effect of $D_\infty$ is negligible, $D(n; T)$ can be simplified as a linear function of $n$ [10, 11], computed as:

$$\begin{aligned}D\left(n;\ T\right)&=D_\infty\times\left[1-\exp\left\{-R\left(T_{use}\right)\times AF\left(T\right)\times n\right\}\right]\\&\approx D_\infty\times R\left(T_{use}\right)\times AF\left(T\right)\times n\\&=D_\infty\times R\left(T\right)\times n\end{aligned} \tag{9}$$

As shown in Figure 14 to Figure 21, the performance degradation model should be 100 at the initial state. Therefore, using the life test results and Eq. (9) the performance degradation model was developed as:

$$
\begin{aligned}
D_{LDI}\left(n;\ \Delta T\right) &= 100 + D_{\infty} \times R\left(T\right) \times n \\
&= 100 - A_0 \cdot \exp\left(\frac{-E_0}{k \cdot \Delta T}\right) \times n
\end{aligned}
\tag{10}
$$

where $D_{LDI}(n;\ \Delta T)$ denotes the degradation-path which is the white area of the LDI; $A_0$ and $E_0$ are model parameters that are concerned with material characteristics and the activation energy which are computed as 9,541 and 3,610 [J/mol] for LDIs on the FPCB substrate and 798.4 and 2,235 [J/mol] for LDIs on the glass substrate, respectively; $k$ is replaced with the universal gas constant which is 8.314 [(J/K•mol]]; $\Delta T$ is the temperature difference between Chambers 1 and 2; $n$ is the number of cycles; $D(0;\ \Delta T)$ is 100 at the initial state (when $n = 0$). Figure 22 and Figure 23 present the developed performance degradation model under the four test conditions for each substrate. Through these results, it is concluded that the LDI can be triggered under normal use conditions, even if the device does not come into direct water contact (see $\Delta T$=45°C and $\Delta$T=40°C).

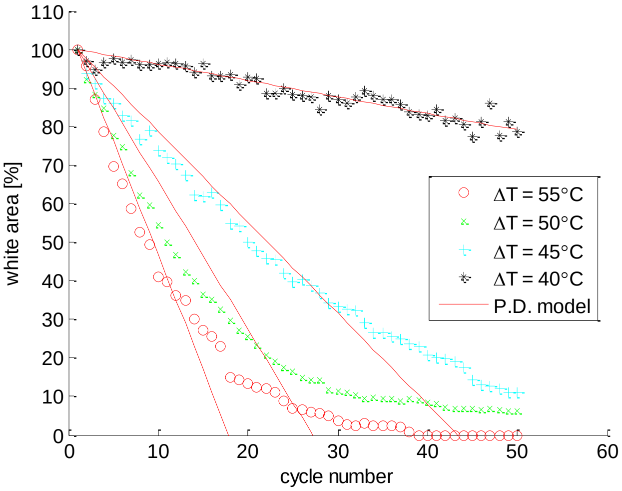


**Figure 22 Results of ALT and the performance degradation model for LDI on the glass substrate.**

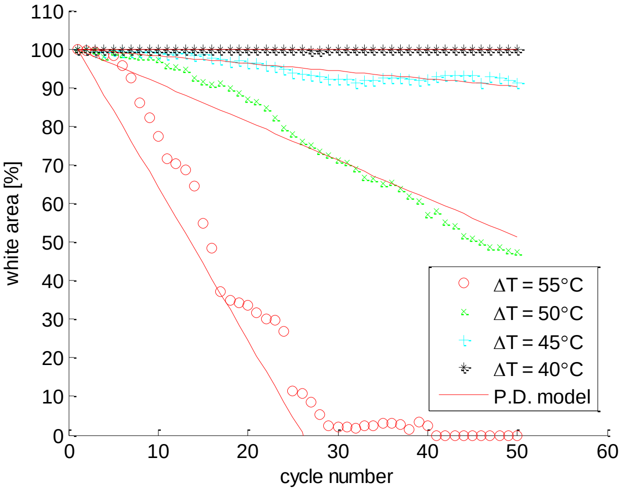


**Figure 23 Results of ALT and the performance degradation model for LDI on the FPCB substrate.**

# Chapter 7. Validation Tests for the Performance Degradation Model

Prior to validation tests, it is important to define a failure margin, $D_f$, in terms of the white area metric. Warranty service claims typically indicate that a device with even partial color change of the LDI has been damaged by water. Because of this, this study sets $D_f$ to 85% white area. Generally, the liquid contact occurs along the LDI's edge. This implies that a smaller LDI size tends to result in a greater white area metric value because of a higher ratio of the edge to the area. It is believed that the failure margin (85%) is related to a lower percentage (or greater color change) in the case of smartphones because the LDI size in smartphones is normally smaller than the size used in the test.

This validation study used cyclic environment tests with two iPhone 3 sets. The LDIs were attached inside the smartphones on the headphone jack and on the mainboard, in locations similar to the original locations of the LDIs in the iPhone 3. The smartphones underwent cyclic environmental tests to validate the performance degradation model. The test condition for validation was between -15 to 25℃ and 95% R.H.; both within the manufacturer specified user condition ranges of the smartphone.

By substituting the temperature difference $\Delta T$ = 40 into the performance degradation model in Eq. (10), it is confirmed that the LDIs under the specified condition start to respond after about 16 (on the glass substrate) to 81 (on the FPCB substrate) temperature cycles.

The color of the LDI on the mainboard did not change until the iPhones experienced 50 temperature cycles. However the LDIs inside the headphone jack turned fully red after an average of 10 cycles. Some reasons can explain the result. First, the LDIs on the headphone jack were exposed to the atmosphere directly and therefore could be triggered more easily by a naturally condensed droplet on the surface of the iPhone. Second, the LDIs on the headphone jack are located near a glass substrate which is much more likely to draw moisture from the air than the FPCB substrate. Therefore, the LDIs on the headphone jack would be triggered earlier than the performance degradation model which was developed based on LDIs attached to an FPCB substrate.

On the other hand, the LDIs attached on the mainboard are in contact with only a subtle amount of air inside of electronic devices, which in turn contains only a small amount of moisture. Likewise, naturally condensed droplets on the surface of the iPhones could not directly reach the LDIs attached on the mainboard. Therefore, LDIs attached on the mainboard were not triggered by small amounts of naturally condensed droplets and temperature cyclic conditions. As a result of these tests, it is strongly recommended that manufacturers attach LDIs to inner parts of electronic devices (e.g., on the mainboard or under the batteries) to appropriately detect water damaged devices while limiting possible false water damage reports from poorly placed LDIs.

# Chapter 8. Conclusion and Discussion

To detect customer warranty abuse from water damage of electronic devices, manufacturers use LDIs in their products. However, this warranty abuse detection system for identifying water damage has led to numerous customer complaints and lawsuits because of the doubtful performance of LDIs. We executed accelerated life tests to confirm the performance of the water damage indicators. Results indicate that an LDI can be triggered by climate changes without direct liquid contact or submersion. An empirical performance degradation model was developed to predict the life performances of LDIs in smartphones under various use conditions. Finally, the validation study was performed using two smartphone sets.

The results showed that the LDIs in an electronic device can turn red without submersion but through temperature cyclic conditions within the specified use stress level. Results showed that LDIs directly exposed to the atmosphere can be triggered by a small amount of naturally condensed droplets on the surface of devices. LDIs not exposed to the atmosphere were significantly more resistant to these factors. In addition, results showed that substrates such as glass, when used in an actual smartphone set, draw moisture more easily than FPCB.

Therefore, to minimize false reporting of water damage, LDIs should be attached to inner parts of devices and should not be directly exposed to the atmosphere. The mathematical model developed for this work can be treated as a quantified performance degradation model for LDIs attached in any portable electronics. Electronic device manufacturers should be aware of the potential for false alarms from LDIs due to condition changes. Manufacturers should take the performance degradation model into account when they designate their smartphone use conditions or when making a decision on warranty service against perceived water damage.

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# 국문 초록

최근 스마트폰이나 태블릿 PC와 같은 휴대용 전자기기가 보편화 되면서 그에 대한 시장규모가 꾸준히 성장하고 있다. 이에 따라 전자제품의 품질보증 서비스에 대한 관심이 높아지고 있는데, 이와 관련하여 품질보증 남용을 위해 설치된 침수라벨의 성능에 대한 논란이 확대되고 있다. 침수라벨은 전자제품 출시 전 기기 내부에 부착되며 물이나 액체에 닿으면 변색되는 기능을 가지고 있으며, 소비자가 제품 사용 중에 기기를 물에 빠뜨렸는지 판단할 수 있는 기준이 되고 있다. 변색된 침수라벨을 가지고 있는 제품은 소비자의 과실로 인한 파손 가능성이 크다고 판단되어 추후 품질보증 서비스의 제공이 되지 않는다.

하지만 최근까지 품질보증 서비스를 받지 못한 다수의 소비자에게서 침수라벨의 오작동에 대한 주장이 끊임없이 제시되면서 이에 대한 집단 소송으로 문제가 확산되고 있다. 이러한 문제의 해결을 위해서는 다양한 환경에서 침수라벨의 성능을 보이는 정량적인 기준과 올바른 침수라벨의 설치 방법에 대한 공학적 근거가 필요하다.

이에 본 논문에서는 침수라벨의 가속수명시험을 통해 성능저하 모델을 제안하여 다양한 환경 내 침수라벨의 성능을 정량화하였다. 가속수명시험의 결과 분석에는 RGB 색상 모델을 이용한 이미지 프로세싱 기법을 도입하였다. 다양한 환경에서 수행된 가속수명시험의 결과로부터 침수라벨의 성능을 예측하는 모델 구축에는 Arrhenius Relationship을 도입하여 실제 제품 이용 환경에서의 침수라벨의 성능을 예측하였다. 또한 실제 스마트폰을 이용하여 모델 검증 시험을

수행함으로써 제안된 성능저하 모델의 유효성을 밝혔으며, 침수라벨의 올바른 설치 기준에 대한 공학적 의견을 도출하였다.

**주요어:** 품질보증 남용방지
침수라벨
가속수명시험
이미지 프로세싱
성능저하 모델
모델 검증 시험

**학 번:** 2011-23344