Current State of Durability Assessment for Four Consumer Product Groups

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Abstract

Four consumer product groups (Vacuum cleaners, washing machines, mobile phones and television sets) have been analysed in regard to the current state of durability assessment. The dominant failures have been determined and compared to the current test programs. Gaps in current tests as well as requirements for tests to close these gaps have been identified.

1 Introduction

Postponing obsolescence for end-user products is a task that involves different aspects. The EU project PROMPT is dedicated towards developing a test program, enabling consumer organizations and public authorities. This paper focuses on one aspect of the project, which is the measurement and assessment of durability measures with respect to product reliability and lifetime. This is a challenge because lifetime and durability measurements can be costly and time consuming. In order to specify the specific needs and gaps in the given context, four product groups have been systematically analysed. On the one hand, washing machines and vacuum cleaners represent white goods. On the other hand, smartphones and televisions represent consumer IT-products.

In a first step, the analysis is based on different input data sources. On the one hand, data from consumer reports with respect to product failures have been analysed, on the other hand, data has been gathered from expert interviews within the PROMPT consortium. From this data dominant "failure modes" are identified and the top 3 are chosen for further investigation. In the next step current existing test programs have been analysed with respect to their relevance to the given "failure modes". Gaps in testing are identified as well as areas where tests can be improved with the goal of developing new tests for better reliability assessment for consumer organizations and public authorities.

2 Dominant Failures in the product groups

To identify relevant gaps in current testing approaches the dominant failures in each product group (vacuum cleaners, washing machines, mobile phones, television sets) have to be determined. Based on various resources as well as customer surveys within the PROMPT project, the most relevant failures have been identified [1], [2], [3], [4], [5], [6]. Most of the available data is in agreement with the findings in the PROMPT project. The most notable difference is that batteries are the most critical part of cordless vacuum cleaners. This will have to be accounted for with the increasing number of cordless vacuum cleaners in the market. Table 1 shows the most relevant failed parts that are investigated. It should be noted that data aggregated in the project for mobile phones and television sets also show a large impact of software in regards to obsolescence. Software is not part of the investigation.

Vacuum cleaners	Washing machines	Mobile phones	Television sets
Battery	Electronics	Battery	Screen
Motor	Shock absorbers/ bearing	Screen	Power Supply
Cable and return mechanism	Motor	Connector	Connectors
		Speaker	

Table 1: Most relevant parts in the product groups

3 Breakdown of failure causes

To determine if there are gaps in the current testing programs, it is necessary to understand what can cause these parts to fail in more detail. Each of the identified parts can fail due to one or more failure mechanisms. These failure mechanisms are activated by various loads. It is important to know what causes these failures to determine if the current test can excite theses mechanisms to test the products. While scientific literature

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on failure modes and mechanisms of domestic appliances is scarce, guides and manuals by repair initiatives offer some insight into possible failure causes and derivable mechanisms.

3.1 Vacuum cleaners

Concerning battery-powered vacuum cleaners, the battery appears to be a major failure cause. In case of lithium-ion batteries, failures of the battery can be expected to be caused by common failure mechanisms for these batteries, i. e. cell-ageing and subsequent loss of capacity and increase of internal impedance [7].

For mains-powered vacuum cleaners, the motor and the cable are major failure causes. Failure of the motor can be caused by overheating, possibly due to clogging or by water damage due to wet filters or bags. Universal AC/DC motors which use carbon brushes may fail due to various problems associated with the brushes, e. g. wear-out of the brushes or connection problems. As vacuum cleaners are subjected to dust or dirt, accumulated debris on the brushes can cause a loss of contact between brush and commutator. Problems with carbon brushes may cause intermittent or permanent motor failure or sparking [8]. Also, coil insulation may degrade over time due to temperature and humidity causing electrical shorts.

As vacuum cleaners employ switching devices like TRIACs for motor power control, motor failures can actually be failures of the motor control. The TRIACs inside a vacuum cleaner are particularly vulnerable to operating conditions that occur when the nozzle or tube is blocked as this causes increased motor current and cuts off airflow required for cooling of the electronics. This, in turn, leads to greatly increased thermal impedance of the heatsink and high junction temperatures of the TRIACs and subsequently decreased lifetime of the TRIACs [9].

Deterioration of the cable can be accelerated by poor design of the housing, as sharp edges, or too much bending of the cable during use. Other causes include insufficient robustness of (cable, spring and break) for repeated use. Failure of the cable, return mechanism or the return brake can be further accelerated by misuse such as bending of the cable.

3.2 Mobile phones

The most reported failed hardware parts for mobile phones are the battery and screen followed by the connector and speakers. The last two having a much smaller impact in most surveys. As mentioned in the vacuum cleaners section, failure of lithium-ion batteries occurs primarily via loss of capacity and increase of internal impedance over lifetime due to cell ageing. Cell ageing and subsequent loss of capacitance may be accelerated by various factors such as state of charge/depth of discharge, the quality of the charger and battery management system and extreme ambient temperatures [3]. Besides the loss of capacitance, ageing of the battery can also lead to swelling, especially if overcharging or high ambient temperatures occur. Swelling of the battery can lead to deformation or damaging of the mobile phone or damaging of battery pack enclosures [7].

Most common failure causes for the screen are scratches and cracks or splinters which are overwhelmingly induced by drops of the phone from the hand or back pocket. In most cases, this leads to broken glass without further damage to the screen [10]. Thermal cycling can also lead to failures in packaging technologies and interconnects which can cause screen scrambling or intermittent failures of the screen [11]. The used OLEDs or LEDs can age leading to less brightness or loss of contrast. Typical ageing-related degradation mechanisms for OLEDs or LEDs used in screens are mostly driven by elevated temperatures. OLED screens are also susceptible to screen burn-in, caused by the display of static images or screen elements for long periods. To mitigate the risk of burn-in and to increase lifetime, modern screen technologies implement software-controlled methods, e.g. by local dimming or shifting the position of always-on display elements like clocks.

Apart from the major failures as shown in Table 1, the connector and speaker are less often a concern. For both parts the failure causes are mechanical loads due to drops and repeated use as well as water damage or particle intake if protective mechanisms are insufficient. Current water protection mechanisms can degrade during use and thus increases the susceptibility of the phone to water damage over time. Ingress of water can also damage other electronic components due to electrochemical migration, corrosion or conductive anodic filaments [12].

3.3 Washing machines

Defective shock absorbers are caused by too high loads, imbalanced loads or low-quality materials. Defective bearings are commonly caused by wear and tear of the bearing and accelerated by undersized bearings or poor quality materials, e. g. plastic housing.

In June 2013, a web survey was conducted by *RREUSE* (Reuse and Recycling Social Enterprises in the European Union) among members working in the field of reuse and repair to gather information about failure causes and mechanisms, repairability and product design of washing machines. Respondents pointed out several possible causes for washing machine failures. Examples are shock absorbers and bearings not designed for spinning speeds of current washing machines, leading to accelerated degradation. Often, rubber seals degrade, possibly blocking pumps or causing water or dirt ingress into bearings. Degradation of pressure switch membranes can lead to failure of the switches, causing the washing machine to take in too much water [13].

As washing machine electronics are normally subjected to moisture as well as heat, failure mechanisms for electronics can be both heat- and moisture-induced. Mechanisms induced by moisture can be expected to be similar to those of mobile phone electronics, discussed in section **Fehler! Verweisquelle konnte nicht gefunden werden.**. The formation of CAF in washing machine electronics can be expected to be less likely since washing machine PCBs and components are generally less miniaturized than mobile phone electronics. Heat-induced failure mechanisms are discussed in section 3.4 as these are the main failure causes for television sets.

Failures of washing machine power supply units (PSUs) caused by failure of non-isolated DC/DC-converters within the PSU are frequently reported [15]. As this usually leads to subsequent failure of the external input resistor, a likely failure mechanism is dielectric breakdown of the gate oxide caused by voltage peaks or gradual degradation. Failures of the PSU due to degradation of electrolytic capacitors are also possible and are discussed in section 3.4.

3.4 Television sets

Failures or defects of the screen may occur in the form of dead pixels, screen burn-in, controller defects, failures of LED backlight units (BLUs) or mechanical defects. Dead pixels are caused by malfunction of transistors in the screen which result from manufacturing defects and may be present on new devices or develop over time. Screen burn-in concerns mainly OLED displays and is discussed in section 3.2 of mobile phones.

Possible failure mechanisms of LED BLUs can be divided into failures of the LED strips and failures of the driver boards. Failure of LED strips can be caused by thermal cycling or exposure to moisture leading to interface delamination, solder fatigue or chemical degradation of the lens. Failure of driver boards can be caused by degradation of the components, e. g. MOSFET degradation due to hot carrier injection and charge trapping. In addition, failure of the driver boards can be caused by PCB assembly degradation through various failure mechanisms, e. g. solder fatigue caused by thermal cycling and the coefficient of thermal expansion (CTE) mismatch. Failure of the LED backlight can result in intermittent or persistent failure of the screen or reduction of luminous flux [16].

Failure of the PSU can be caused both by failure of the PCB assembly and degradation of electrolytic capacitors as the PSU contains most of the televisions electrolytic capacitors. Failures of assembled PCBs due to thermally induced stresses are common and well researched. Thermally induced stresses can be caused by temperature cycling or constant high temperature, both can be expected in televisions. Thermal cycling causes mechanical stresses due to repeated expansion and contraction of the assembly and CTE mismatch of the materials involved, resulting in strain and eventual fatigue of solder joints [17]. The CTE mismatch between the circuit board substrate and copper interconnections can also lead to ruptures in traces or plated through holes due to thermal cycling, resulting in open circuits or intermittent failures [18].

Ageing of electrolytic capacitors occurs via several degradation mechanisms mainly driven by heat or the electrical stress of the capacitor during use due to low voltage safety margins [19]. Therefore, mounting of electrolytic capacitors near heat-emitting components can considerably accelerate degradation [14]. However, depending on the functionality of the circuit, it may be necessary to place capacitors close to heat-emitting components as longer traces can act as both parasitic inductances and antennas and can therefore impair the function of the circuit or cause problems with electromagnetic compatibility (EMC), especially if high currents or switching frequencies are involved [5].

The operating temperature of components is also dependent on the available installation space within the appliance which is limited in compact devices like televisions. This can impede circulation and heat dissipation within the device and thereby cause increased temperatures, even more so as circulation can further decrease over lifetime, e. g. through dust deposits blocking air vents. In contrast to computers, television sets usually do not use fans for active cooling [5].

Failure of external connectors accessible by the user, e. g. HDMI, can be caused by mechanical overload or fatigue, possibly due to misuse. As internal connectors are inaccessible by the user, failures are likely the result of failure mechanisms associated with thermal stress, e. g. through thermal cycling leading to surface corrosion and fretting corrosion [20].

4 Current test program and gap analysis

4.1 Vacuum Cleaners

Test procedures for vacuum cleaners are harmonized in the EU directive 666/2013 and standards EN 60312-1 and EN 60335-2-2 among others. In 2016, a study on durability tests was prepared for the European Commission in which the suitability of existing test procedures was reviewed [1].

4.1.1 Battery

For batteries in vacuum cleaners no standardized test is yet available. In a “Review study on Vacuum cleaners” for the European commission [21] a recommendation was made to require a charge cycle lifetime of 600 cycles with a remaining capacity of 70% based on EN 61960:2011. Consumer organizations are implementing such a durability test for batteries, which discharges and charges the battery in a defined manner. These durability tests require the whole system for the test. This has the definite advantage of being a test relatively close to the real application (e. g. including battery management systems) as well as combining the battery test with the motor test but have the disadvantage of requiring relatively long test times.

The currently used system tests are a viable way for testing but have disadvantages in regard to duration. Currently, the battery is completely charged and discharged during the cyclic tests. This does not necessarily conform to the use case. Different battery capacities in combination with real use cases might lead to differing lifetimes compared to the current tests.

4.1.2 Motor

There are currently standardized tests (EN 60312-1:2017) for motor reliability of mains-powered vacuum cleaners. Battery-powered vacuum cleaners are not scope of these motor tests. Mains-powered vacuum cleaners are tested via cyclic operation under normal environmental conditions. For battery-powered vacuum cleaners, consumer organizations adopted a similar approach. The battery-powered vacuum cleaners are subjected to cyclic combined motor/battery reliability tests. Damages occurring during testing are assessed and photographed. Motor durability tests are currently performed with half-full dust bags/receptacles according to EU directive 666/2013. However there is an ongoing discussion about test conditions concerning the filling degree of bags/receptacles, corresponding test durations and the implications on motor durability for different types of motors [1], [21].

As discussions in the past have shown, the motor reliability depends on the system, therefore possible test approaches are limited. The current test approach to use the system as a test vehicle seems the most feasible and changes will require a detailed analysis to test various technologies equally.

4.1.3 Cable and return mechanism

To determine the durability of the return mechanism, cyclic tests are performed by consumer organisations with the number of cycles exceeding the number required during the estimated product lifetime [22]. Damages occurring during testing are assessed. Currently, the tests are based on EN 60335-1 for the return mechanisms with a defined number of use cycles. Failure of the cable itself makes up a small fraction of these failures. These are most likely failures due to misuse of the customer, e. g. sharp folding or squeezing of the cable between or around doors. Cables are standardized in DIN EN 61242 and a minimum requirement for robustness is given.

Generally, the failures for cable and return mechanism are covered by current tests, but discussions about finetuning of the test procedure, e. g. angle of pull and release, might return more realistic test results.

4.2 Mobile Phones

For mobile phones, it can be noted that a significant number of reported issues are software-related. The focus will be on hardware-related reliability issues as long term software reliability is difficult to test and might require other solutions like regulations for minimal support period.

4.2.1 Battery

For batteries, there are no specific durability tests implemented. Most commonly, battery functionality is tested in the initial state, i. e. usage time (capacity) and charge time. The applied drop tests can be counted as testing the mechanical robustness, though the applicable real-world scenarios are limited. Drops of the phone constitute an overstress for the battery. In case of failure, this means breaking of the battery housing and allowing humidity to interact with the lithium or short-circuiting the battery, possibly setting the device on fire. Drops are one possible kind of overstress while other possible scenarios include bending of the phone due to various circumstances. With regard to the battery, such mechanical overstress tests permit conclusions about safety rather than lifetime.

Durability tests for batteries have to determine ageing, i. e. the change of capacity due to temperature and number of charge cycles. Similar to battery tests of other products, the battery management system has to be considered. Parameters like charge rate and maximum and minimum stored energy as defined by the battery management system are influencing the lifetime.

4.2.2 Screen

The standard test procedures for mobile phones already include tests for the most typical causes of screen failures. These tests are:

- tumble tests for shock resistance (based on EN 60068–2–31) which typically lead to cracks or dead screens
- scratch resistance tests (based on ISO 1518) which test the resistance of the screen against scratches with a hardness test pencil under five different loads and
- water resistance tests (based on EN 60529) which could lead to diverse failures, including various problems with the screen

All current tests cover faults associated with robustness against overstresses which are also some of the most common failure causes for screens of mobile phones. Failures due to degradation of the screen over lifetime are not covered. As lifetime degradation of the screen is less common, it has to be evaluated if the effort for such tests is in proportion to possible issues. When designing a test covering screen burn-in, the mitigation technologies described in section 3.2 have to be taken into account.

The functional relevant screen components offer very little robustness in regards to humidity, therefore protective measures are implemented. This usually starts on the level of the singular LED/OLED and extends to the housing of the screen and phone itself. These protective measures can degrade over the lifetime of the phone. Current tests are not able to evaluate the long-term degradation of these protective measures. Since a mobile phone has various possible entry points (frame, speakers, connectors and camera) for water, different measures are taken for protection against water [23]. This results in water resistance being very system dependent which has to be accounted for when developing tests for water resistance over lifetime. Tests need to either be done on system level or a very complex evaluation of multiple individual parts is required. Also, it should be kept in mind that manufacturers do not claim their phones are to be used in water or high humidity environments and declare such uses as misuse.

4.2.3 Connector

Current testing programs include the connector when testing for water resistance and mechanical drops. In both cases the system-wide robustness is tested. In real life condition connectors are exposed to repeated mechanical loads by plugging in and unplugging.

While customer organizations are not specifically testing the connectors for cyclic reliability, there is already an industrial certification program available (USB Implementers' Forum (USB-IF) Integrators List (IL)). Such a certificate requires a durability test based on EIA-364 for electrical connectors. In this test program, for USB micro family connectors, 10.000 cycles of insertion and extraction are required.

4.2.4 Speaker

Durability related failure causes for speakers are mechanical loads and ingress of humidity, water and particles. The standard test procedures related to these issues are:

- tumble tests for shock resistance (based on EN 60068–2–31) which can damage the speaker but also the water protection mechanism
- water resistance tests (based on EN 60529) which can damage the speaker when bypassing the protective mechanism

The current water resistance test does not assess the durability of the protective mechanism. Mechanical shock and other environmental loads can degrade these protective mechanisms, causing failure later on in product life. As explained in [23], protective methods differ between smartphones and use various materials. These will degrade under different conditions and require various specific tests (e. g. humidity, temperature, UV light and various chemical tests).

4.3 Washing Machines

Washing machines are commonly subjected to endurance tests by consumer organisations. These tests consist of a number of various washing cycles approximately corresponding to the number performed during the expected lifetime of the machine. There are no reliability tests for specific failure causes or components.

4.3.1 Electronics

The currently employed endurance tests also stress the electronics in the washing machine, but since washing cycles are repeated in close succession the tests will naturally not perfectly replicate real conditions. For electronics, this can result in smaller thermal cycles if the system cannot cool down fast enough. Active power loss can also reduce or slow down humidity ingress into the electronics. This can result in the test being less harsh on the electronics than the real life use condition.

Currently there are no specific tests for electronics employed. Alternatively to a test of the complete washing machine, the electronics can be exposed to tests (e.g. based on IEC 60068 test procedures) individually or even broken down further into it sub-components, e. g. capacitors. In such cases, suitable test conditions and requirements have to be defined. Developing such tests will be challenging, even more so as the tests need to be accelerated and suitable for various types of washing machines.

4.3.2 Shock absorbers/bearings

Currently, there are no specific tests for bearings or shock absorbers employed. The current endurance tests stress the bearings and absorbers as they are used in the application. Individual testing may be feasible and test results may allow to determine the robustness in a relative measure but extrapolating test results to product lifetimes will be difficult. For a lifetime estimation, an ageing model is needed which connects the test results to lifetime results. There is a standardized approach to calculate lifetime of bearings (ISO 281), but this model does not account for all reliability influencing factors. Also, washing machines may include sensors to handle imbalances which may change lifetime results during real life application.

4.3.3 Motor

The current test program covers the reliability of the motor. , Sufficiently long cool-down phases are necessary to avoid deviation of test results from real life application due to the quick succession of cycles. To implement an individual test of the motor, ageing models are required which can differ between washing machines and motors. Therefore designing such tests can be challenging. Investigating if an individual test or quality check for the carbon brushes can deliver more easily information about the durability might be worthwhile as the brushes are one of the more critical components of the motor.

4.4 Television Sets

Current tests of consumer organisations are only conducted with new devices and include inspections of image and audio quality, usability and environmental characteristics. The tests neither involve disassembly and inspection of internal parts nor reliability tests of the television set or sub-assemblies [24].

The typical use profile for television sets involves mainly thermally induced stresses and long periods of use. Therefore, possible reliability tests need to induce accelerated ageing, possibly by means of constant high temperature or temperature cycling.

4.4.1 Screen

Tests by consumer organisations include visual inspection of the screen to check for manufacturing defects. Reliability tests of the screen are not currently conducted by consumer organisations. Mechanical damage of the screen can likely be attributed to misuse. As most failure mechanisms of the screen are activated by thermally induced stress, feasible tests may include thermal cycling, constant high temperatures or a combination to cause accelerated ageing. Tests can also include active use to induce power loss, which will cause increased temperatures more similar to the application.

4.4.2 Power Supply

Current tests concerning the PSU only include measurements of power consumption in various modes of operation and do not test the reliability of the power supply. Failures of the PSU are likely caused by either thermomechanical degradation of the PCB assembly or degradation of electrolytic capacitors accelerated by high temperatures. Therefore, suitable tests also involve thermal cycling, constant high temperatures or active power cycling.

4.4.3 Connectors

Currently, consumer organisations perform visual inspections to evaluate the usability of external connectors. There are currently no tests for connector reliability. As internal connectors are vulnerable to thermally induced stress, reliability tests can be conducted along with those for PCBs. Reliability tests for external connectors require either repeated bending or plugging and unplugging of connectors. Typically external connectors plugged and unplugged only a few times over the product life, so the time for such test can be reasonably short.

5 Conclusion

The current durability testing programs have to balance the challenge of being feasible, treating every device of a category equally and delivering results that are understandable and comparable. This leads to different categories of tests.

System tests: the product is repeatedly used as is to replicate its lifetime in an accelerated manner

Partial system tests: a specific function or component of the product is tested as part of the complete system (e.g. motor tests for vacuum cleaners)

Robustness tests: loads that can be considered overstress but may happen a few times during normal use over the lifetime are applied to the product

These tests have the advantage that they can be applied to any product of its category since the product is not manipulated or altered and used as intended by the manufacturer. This is especially true for robustness and system tests. Partial system tests for vacuum cleaners have already shown in the discussion about the filling level of the dust bags/receptacles how equitable testing of dissimilar products belonging to the same category can become a challenge in the development of more specific tests. Nevertheless, system tests are not a panacea as they are usually of long duration and can only be applied to products with relatively few cyclic uses during their lifetime. Television sets are a good example with a system test taking years to complete.

For cases such as televisions, accelerated tests have to be developed which may also only test specific subcomponents. Such tests still have to ensure equitable testing for all products which will be challenging. Typically, accelerated tests focus on specific failure mechanisms and as shown failure mechanisms are manifold, especially in complex electronic systems. Specific tests will have to accommodate for product-specific design choices to enable fair and comparable testing.

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