



PROMPT

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1 Summary on Test Results and Specification for Batteries and Electronics

In this deliverable the main focus is to document the analysis done so far and to derive recommendations for a test plan for batteries and electronics that will be the base for work package 6.

Key Findings for Tests of Battery Cells (Chapter 2.1):

State of the art on lithium-ion battery ageing and modelling was analysed. Two sets of experiments for evaluation of ageing and extraction of model parameters has been executed (small batteries and mobile phone batteries):

- Same ageing behaviour of small and large batteries but significant differences in ageing parameters
- Fast charging leads definitively to higher cycle degradation but high temperature and voltage are also crucial. Small variation of charging current can have crucial effect of cycle number
- Increase of internal resistance results accordingly
- Long term measurements are required for each new type of battery. Short time testing is sufficient to exclude insufficient products and guaranty minimum quality criteria.
- The battery degradation depends to a high degree and very sensitively on temperature, cell voltage and charging current. Those parameters are not only dependent on the use case but also on the battery management of the device and the applied charging procedure. Thus, the same battery cell will perform differently in different products. Therefore the longevity of the battery can't be evaluated outside the electronic product.
- Minimum quality criteria have been defined

Key Findings for Tests of Battery Cells (Chapter 2.1):

In order to perform battery testing in a real use environment including the battery management (charging, use of product) a test program was conducted for lithium-ion battery systems. The program was exemplified for cordless tools of 18V class on 8 multi-functional battery platforms for cordless tools from different manufacturers.

- An application oriented test principle has been demonstrated, that considers battery lifetime within the battery management of the tested products. It can be transferred to other product groups.

Key Findings for Tests of Electronics (Chapter 3):

In a theoretical analysis a test approach has been proposed and derived, which is based on mission profiles and accelerated tests. The methodology is applicable to different product groups and involves the separate accelerated loading of electronic modules.

- Concrete test conditions have been derived for electronics in washing machines and televisions.
- Main environmental conditions are covered: Temperature, Humidity, Temperature Cycling
- A sequential load has been proposed to cover different environmental loads with a minimum number of samples. So the methodology is applicable to organisations with limited access to samples (consumer organisations, market surveillance, ...)

2 Test Development for Rechargeable Batteries and Management

2.1 Secondary battery assessment and ageing model

2.1.1 Test method

Rationale, background and state of the art of lithium-ion battery ageing and test procedures was described in the deliverable report D3.2. Two types of batteries were examined. The first one is a 3 Ah commercial mobile phone battery. The cathode active material is NMC and the anode consists of graphite. The second battery is a 0.17 Ah small pouch cell with LiCoO₂ as the cathode active material and graphite anode active material. Further battery specifications are listed in Table 1. While the mobile phone battery represents advanced high voltage technology and very high energy density, the small 0.17 Ah battery represents conventional state of the art lithium-ion technology.

Table 1: Battery Specifications

3Ah cell		0.17 Ah cell	
	Specification		Specification
cathode active material	NMC	cathode active material	LiCoO ₂
anode active material	Graphite	anode active material	Graphite
nominal capacity	3 Ah	nominal capacity	0.17 Ah
max. charging current	1 C	max. charging current	1 C
max charging voltage	4.4 V	max charging voltage	4.2 V
weight	53 g	weight	3.5 g
volume	18.5 cm ³	volume	2.22 cm ³
energy density	222 Wh/kg / 636 Wh/l	energy density	179 Wh/kg / 282 Wh/l

To investigate the ageing mechanisms several cycle tests were performed under different charging conditions including varied charging current rate and depth of discharge (DoD) by using a multichannel MACCOR battery test system. In order to exclude ageing mechanisms that are not directly related to cycling, calendar ageing tests were performed as well so that their different effects can be distinguished. Reference performance tests (RPTs) were performed periodically to access the battery's basic parameters like capacity, internal resistance and voltage profile. Each RPT comprises a full discharge/charge cycle at 0.5 C current rate. Batteries were stored in environmental chambers, that maintained a constant temperature of 35 °C and 50 °C respectively.

Cycle Test

Cycle tests were performed with 18 of the 3 Ah batteries and 18 of the 0.17 Ah batteries. For this test, the batteries were charged according to a constant current – constant voltage (CC-CV) protocol with a cut-off voltage of 3 V. Various current rates were applied for charging, ranging from 0.3 C to 1.5 C as shown in Table 2. The batteries were discharged with a constant current of 0.5 C until a fixed state of charge (SoC) was reached. After a certain number of cycles (the equivalent of 200 full cycles) three consecutive RPTs were conducted to measure the battery parameters.

Table 2: Cycle test matrix (O: 0.17 Ah, X: 3 Ah cells)

Temperature	SOC	Charge rate				
		0.3 C	0.5 C	0.67 C	1 C	1.5 C
35 °C	100 % – 90 %	X	O	X	XO	O
	100 % – 50 %	X	O	X	XO	O
	100 % – 0 %	X	O	X	XO	O
50 °C	100 % – 90 %	X	O	X	XO	O
	100 % – 50 %	X	O	X	XO	O
	100 % – 0 %	X	O	X	XO	O

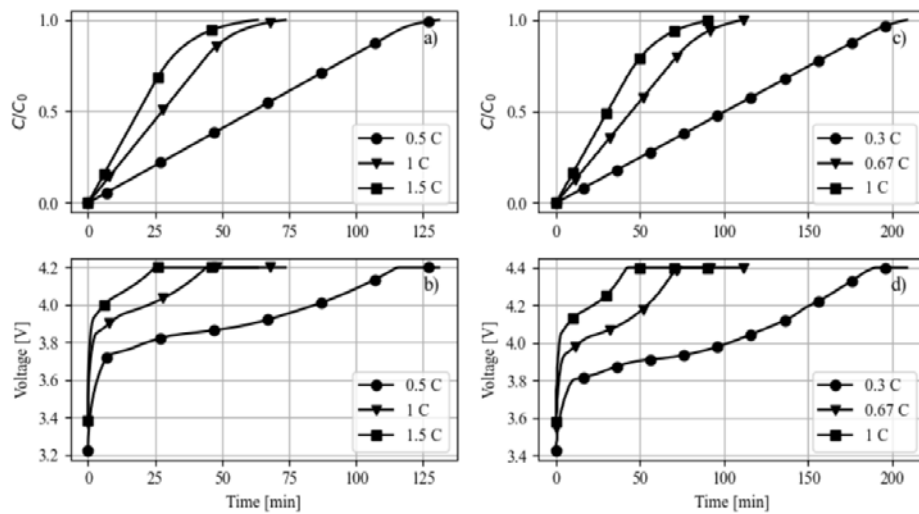


Figure 1: Charge profile of 0.17 (a, b) and 3 Ah (c, d) cells as function of charge C-Rate

The charge profile of both battery types is shown in Figure 1 highlighting two important characteristics:

- The relative time at high voltage (which accelerates calendar ageing) is higher for the larger C-rates.
- The charging time is not much reduced if the current is increased from 1C to 1.5 C (0.17 Ah battery) or from 0.67 to 1 C (3 Ah battery). The advantage of higher c-rate is, that up to ca. 70% of capacity can be reached at a shorter time during charge.

Calendar Test

Calendar tests were performed on 12 of the 3 Ah batteries and 12 of the 0.17 Ah batteries, 6 of each battery type at 35 °C and 6 at 50 °C. The batteries were charged at 0.5 C current until a defined SoC was reached. This was followed by a rest period of three weeks before the cells were fully discharged. The same RPTs as for the cycle tests were performed afterwards.

Table 3: Calendar test matrix (O: 0.17 Ah, X: 3 Ah)

Temperature	SOC		
	100 % – 90 %	100 % – 50 %	100 % – 0 %
35 °C	XO	XO	XO
50 °C	XO	XO	XO

2.1.2 Results of lithium ion battery testing

The results of calendar ageing of capacity are shown in Figure 2. The degradation at 100 % SOC is much higher compared to lower SOC. The 3 Ah cell degrades less compared to the 0.17 Ah cell, but faster after 1500 h at 50 °C and 100 % SOC.

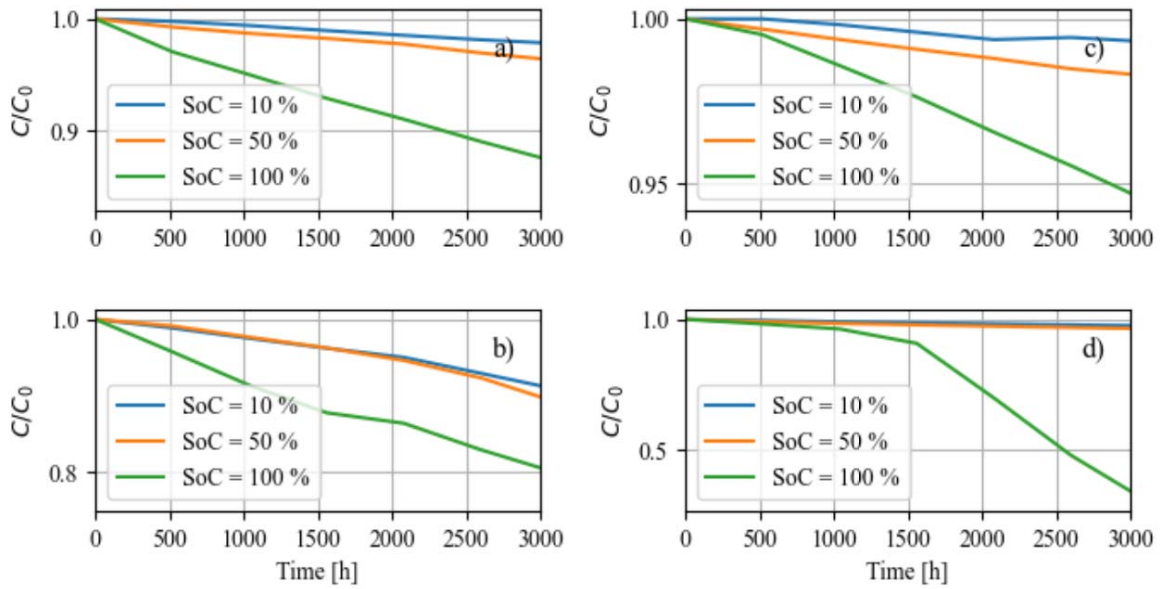


Figure 2: Calendar ageing of capacity a) 0.17 Ah, 35°C; b) 0.17 Ah, 50 °C; c) 3Ah, 35°C; d) 3Ah, 50 °C

The results of cycle ageing as function of charge current (C-rate) and depth of discharge are shown in Figure 3. During the first 400 cycles the 0.17 Ah batteries are characterized by much higher cycle degradation compared to the 3 Ah cell, but only at full cycles. The degradation at high C-rate is significantly higher compared to the ageing at lower charging current.

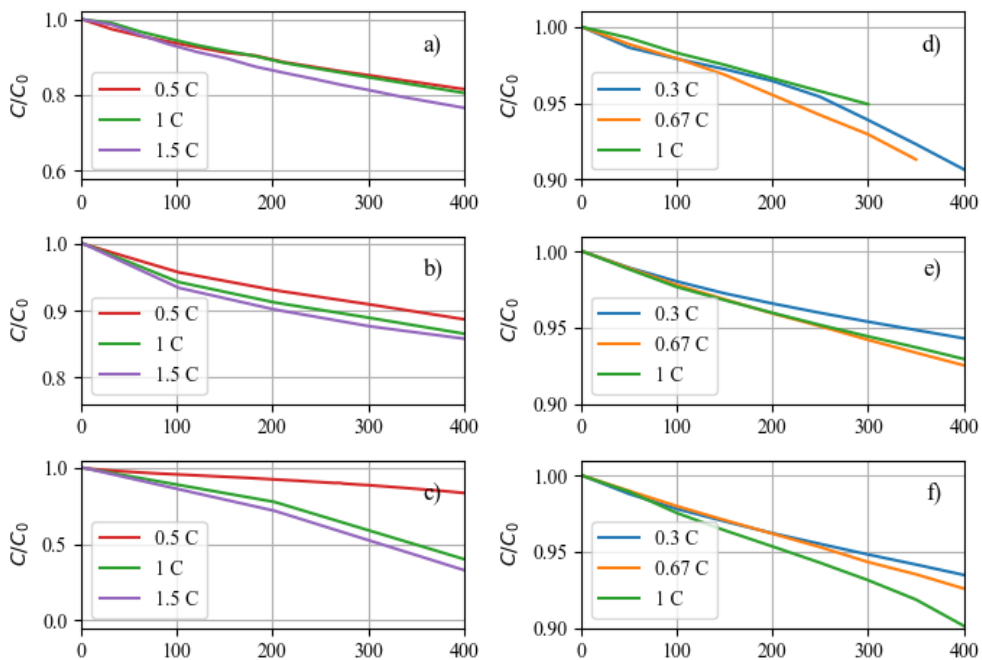


Figure 3: Capacity degradation as function equivalent cycle number and charge C-rate for the 0.17 Ah cell (a-c) and the 3 Ah cell (d-f) at increasing depth of discharge (a, d) - 10 %; b, e) - 50 %; c, f) - 100 %)

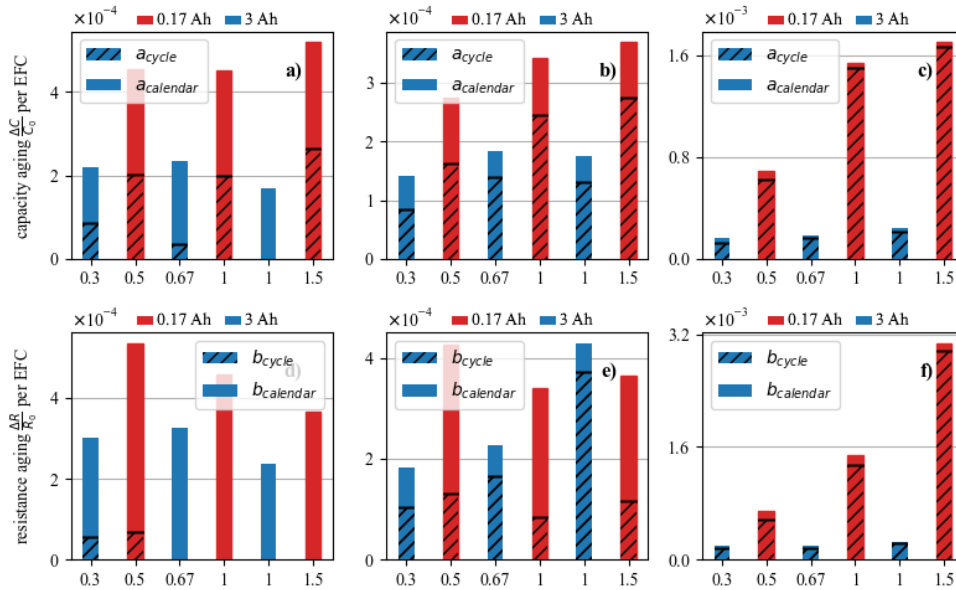


Figure 4: Degradation of capacity and cell resistance; distinction between calendar and cycle ageing at a), d) 10% DOD; b), e) 50% DOD and c), f) 100 % DOD

The influence of calendar ageing during cycling is highlighted in Figure 4. At a low depth of discharge the ageing is clearly dominated by the calendar ageing and not by the equivalent cycles. The charge current plays a minor role; for the 3Ah cell the ageing is even lower at the highest charging current. At 50% depth of discharge the cycle degradation is higher than the calendar ageing but the calendar ageing is still significant, in particular for the 0.17 Ah cell and for the resistance increase. Here, ageing increases with charge current. At full cycles the degradation is dominated by the cycling and not the storage time. The 0.17 Ah cell degrades much faster than the 3Ah cell. The results of 100% cycle depth for the complete testing time are shown in fig.5. A significant difference in long term cycling behavior between the 0.17 Ah and the 3 Ah is visible. While the 0.17 Ah cell is characterized by higher capacity loss from the beginning, the 3 Ah cell starts with lower cycle degradation until a certain transition point is reached where the capacity degrades fast. This tipping point significantly depends on charging current. The 3 Ah cell achieves the typical criterion of lower than 20 % degradation at 500 full cycles for all charging currents, but with lower charging current (0.3-0.67 C) more than 1000 cycles can be achieved.

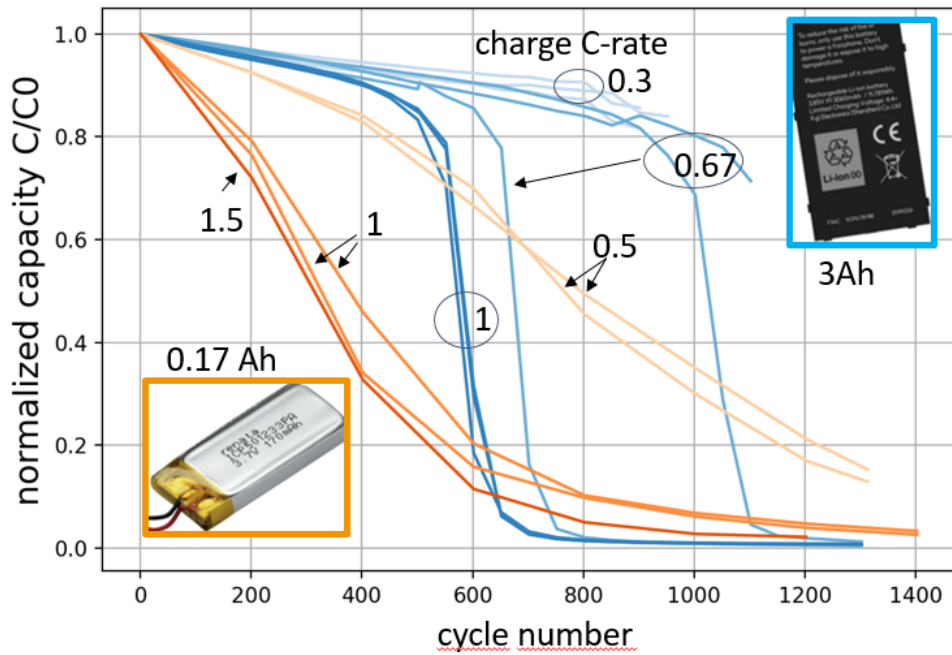


Figure 5: Capacity degradation during long time cycling as function of charge current, 35 °C, 100 % DOD (the numbers in the diagram indicate the C-rate)

Based on the results shown in Figures 1-5 we fitted the parameters for the used ageing model of capacity and internal resistance that incorporates temperature, depth of discharge, cycle number and charging current.

The resistance and capacity degradation during cycling was modelled as function of cumulated charged capacity Q according to equation 1 and 2 based on a holistic ageing model that is generally accepted for lithium-ion batteries¹:

$$R/R_0 = 1 + \beta_{res} \cdot Q \quad (1)$$

$$C/C_0 = 1 - \beta_{cap} \cdot \sqrt{Q} \quad (2)$$

Similarly, the calendar ageing factors were calculated according to equation 3 and 4

$$C/C_0 = 1 - a_{cap} \cdot t^{0.75} \quad (3)$$

$$R/R_0 = 1 + a_{res} \cdot t^{0.75} \quad (4)$$

The voltage dependency of calendar ageing is fitted according to equation 5 and 6:

$$a_{Vres} = a_{1Vres} \cdot V + a_{2Vres} \quad (5)$$

$$a_{Vcap} = a_{1Vcap} \cdot V + a_{2Vcap} \quad (6)$$

¹ J. Schmalstieg, S. Käbitz, M. Ecker, and D. U. Sauer, "A holistic ageing model for Li(NiMnCo)O₂ based 18650 lithium-ion batteries," *J. Power Sources*, vol. 257, pp. 325–334, 2014, doi: 10.1016/j.jpowsour.2014.02.012

DOD	Depth of discharge or charge
C Rate	The Rate of battery change and discharge
R_0	Initial resistance
C_0	Initial capacitance
R	Actual resistance
C	Actual capacitance
$a_{Vcap}, a1_{Vcap}, a2_{Vcap}$	voltage dependence of capacity calendar ageing and its fitting parameters
$a_{Vres}, a1_{Vres}, a2_{Vres}$	voltage dependence of resistance calendar ageing and its fitting parameters
β_{-}	Cycle ageing factor for resistance
β_{+}	Cycle ageing factor for capacitance
Q	total charged battery capacitance

As an example, the ageing factors for the 0.17 Ah battery are shown in Table 4. The cycle ageing factors of capacitance and resistance as function of total charged capacity and state of charge are shown in Figure 6.

Table 4: Obtained ageing factors for 0.17 Ah cell

Mean SOC	Temperature [°C]	acap * 1000	ares * 1000
10%SOC	50	0.175	0.517
10%SOC	40	0.058	0.212
10%SOC	35	0.045	0.181
50%SOC	50	0.205	0.589
50%SOC	40	0.093	0.532
50%SOC	35	0.058	0.43
100%SOC	50	0.466	1.100
100%SOC	40	0.343	0.994
100%SOC	35	0.295	0.729

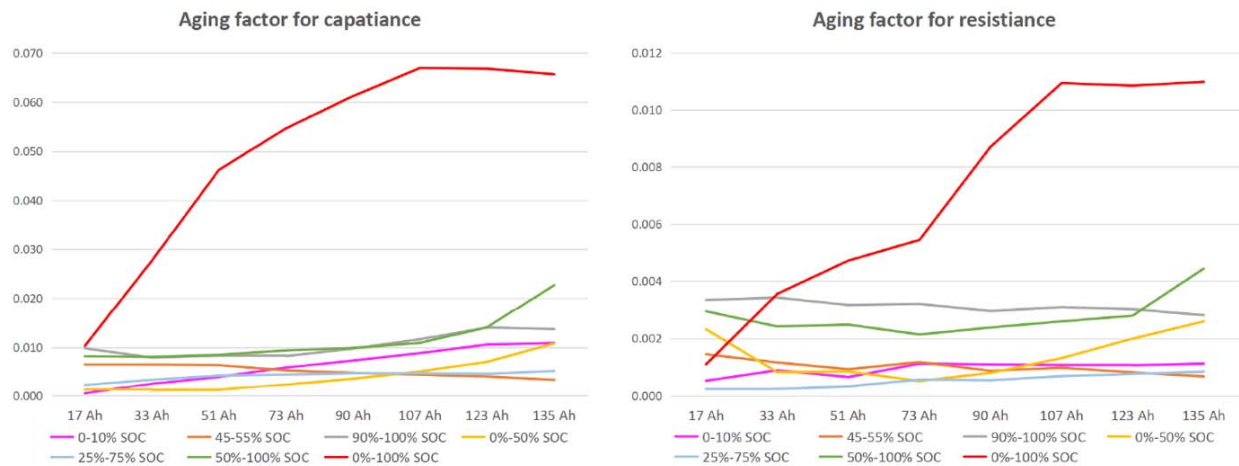


Figure 6: Cycle ageing factors of the 0.17Ah cell as function of charged capacity and state of charge

For the 0.17 Ah cell, the calendar ageing showed a time dependency between linear and square root function. The cycle ageing shows a linear ageing dependency as function of total throughput charge Q for the resistance and a square root ageing for the capacity for all experiments except full cycling as can be seen in Figure 6.

2.1.3 Conclusions

The ageing and degradation behavior of lithium-ion batteries can be fitted with easy to use ageing factors and allows a valid prediction of capacity and resistive changes during use in a certain range of cycles and use conditions. On the other hand, the ageing parameters differ significantly for each battery type and results from one type of battery cell can't be used for a different cell. Hence long term measurements are required for each new battery type. On the other hand, short time testing is sufficient to exclude insufficient products and ensure minimum quality criteria. As can be seen in Figure 5, only a small number of approx. 10 cycles is sufficient to conclude that the 0.17 Ah battery shows much less performance than the 3 Ah battery and that only the 3 Ah battery will achieve the 500 cycles 80 % criterion.

As shown in this study, the battery degradation depends to a high degree and very sensitively on temperature, cell voltage and charging current. Those parameters are not only dependent on the use case but also to a great extent on the battery management of the device and the applied charging procedure. Thus, the same battery cell will perform differently in different products. Therefore the longevity of the battery can't be evaluated outside the electronic product.

Suggestion of minimum quality criteria

Of the battery cell:

- Capacity reduction after 25 cycles, 0.5 C, 35 °C < 1 %
- Increase of internal resistance 25 cycles, 0.5 C, 35 °C < 1 %
- Degrease of capacity after 20 days at 50 °C fully charged < 2 %
- Increase of internal resistance after 20 days at 50 °C fully charged < 2 %

For battery management evaluation (if such data available):

1. Charging

- Prevention of charge at temperature below 0°C
- Limiting of maximum current
- Reduction of charge current at temperature below 10°C and above 35 °C
- Adaptive charge current during fast charge
- Adaptive end of charge voltage during ageing
- Single cell control in battery packs
- Use of standardized battery management system
- User interface to optimize parameters for longer battery life time (trade-off to usable capacity)

2. Discharge (= control during device operation and storage)

- Limiting of discharge current
- Monitoring battery temperature
- Provisions for avoidance of deep discharge (during storage etc.)
- Battery operation data logging for end of life decisions
- Lowering application power when battery is aged
- Single cell control and cell balancing in battery packs
- Use of standardized battery management system

2.2 Battery test program for application of different loading conditions

Within Working Package 3 of the PROMPT-Project Stiftung Warentest invented a test program focused only on rechargeable batteries with respect to the consumer perspective. The test program was presented in deliverable report 3.1. The test program was conducted at lithium-ion battery systems for cordless tools of 18V class. 8 multi-functional battery platforms for cordless tools from different manufacturers were selected (see Table 5). All batteries have a nominal voltage of 18-20 V and a nominal capacity of 2.0-2.5 Ah.

Table 5: Test specimen

Manufacturer	Battery
Black&Decker	BL2018ST
Bosch Professional	GBA 18V 2.0Ah M-B
Bosch	PBA 18V 2,5Ah W-B
Einhell	18V 2,0 Ah Power X-Change
Parkside	PAP 20 A1
Makita	BL1820B
Metabo	18 V, 2,0 Ah 625596000
Worx	WA3551.1

The results of the test were published online at Stiftung Warentests website test.de (<https://www.test.de/Werkzeugakkus-im-Test-Diese-System-Akkus-halten-besonders-lange-5665195-0/>), as well as in the journal test (test 11/2020 pages 74-78, Stiftung Warentest).

2.2.1 Durability test - Cycle stability

To assess the cycle stability of the batteries, the batteries were charged with the corresponding chargers and discharged in two different tools (cordless drill/driver and blower). The cordless drill/driver represents an oscillating high discharge while the blower represents a continuous high discharge. 400 charging and discharging cycles were conducted. A discharge cycle in the drill/driver consists of a repeated sequence of 5 screwdriving and 1 drilling operations. The load is provided by a controlled brake. The brake is controlled to recreate the typical discharge current curves for drilling and screwdriving measured in a functional test. In the blower at the highest power level in continuous operation. From cycle to cycle the two devices (cordless drill/driver, blower) are exchanged. If the battery did not fail it faced 200 cycles in a blower and 200 cycles in a cordless drill/driver. Every 50 cycles the actual capacity was measured. For each model two batteries were tested (batch 1 and batch 2). The course of the capacity is presented in Figure 7 and Figure 8. Table 6 summarized the reached cycles and the capacity decrease after 400 cycles.

During the 400 cycles of testing both Makita samples failed and could no longer be charged or discharged. All other specimen reached 400 cycles without malfunction. The loss of capacity was between 11 % and 22 % compared to the initial capacity. The comparison of the two batches depict only small differences, which indicates the reliability of the new method.

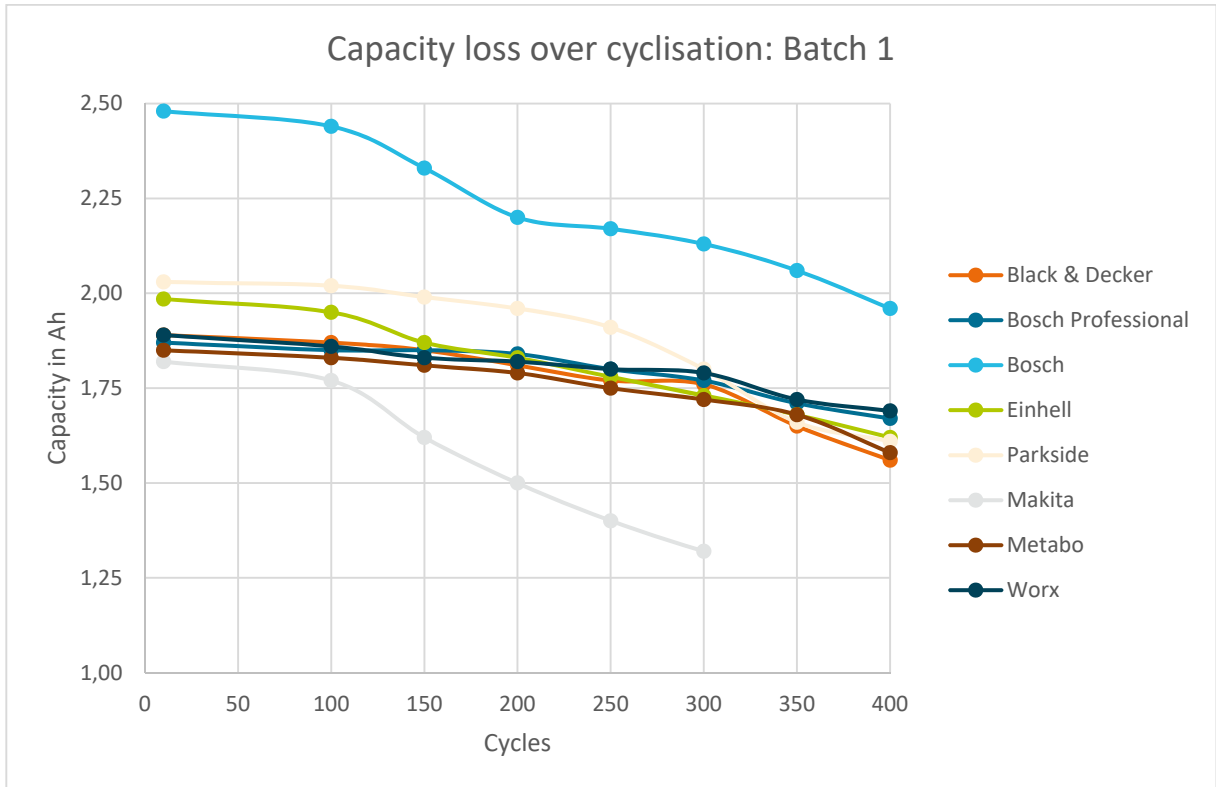


Figure 7: Capacity loss over cyclisation: Batch 1

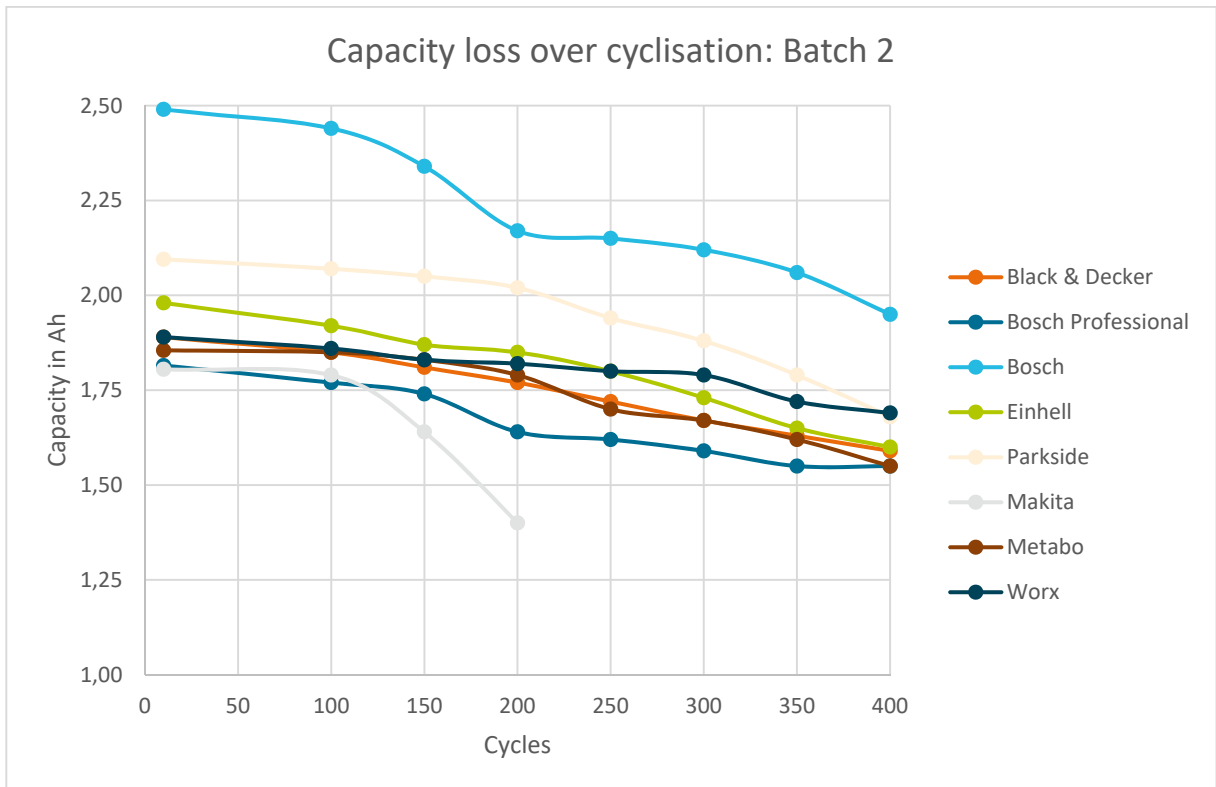


Figure 8: Capacity loss over cyclisation: Batch 2

Table 6: Capacity loss after 400 cycles

Batch	Batch 1		Batch 2	
	Reached cycles	Relative capacity loss	Reached cycles	Relative capacity loss
Black&Decker	400	17%	400	16%
Bosch Professional	400	11%	400	15%
Bosch	400	21%	400	22%
Einhell	400	18%	400	19%
Parkside	400	21%	400	20%
Makita	304	-	249	-
Metabo	400	15%	400	16%
Worx	400	11%	400	11%

The method is similar to the daily use of power tools batteries by consumers. It includes also the activity of the battery management system. This is the great benefit of the new developed method compared to automatic cyclization test facilities. The automatic cyclisation basically tests only the reliability of the battery cells. Control interactions by the battery management system during charging and discharging are not included. However, the new testing method suffers due to its big time and budget demand. Nevertheless, the method is very promising for future battery tests.

2.2.2 Durability test - Self-discharge and calendric ageing

To test the calendric ageing of the batteries, the fully charged batteries were stored at 40 °C and a relative humidity of 50 % for 120 days under constant conditions without intermediate charging. Two scenarios were investigated. In the first scenario the battery is stored solo. In a second scenario the battery is stored placed in the corresponding charger. The charger is not plugged in so charging is prevented. Both scenarios are representing daily life scenarios of power tool batteries.

The storage temperature of 40 °C leads to an accelerated ageing of the batteries according to the RGT rule (van't Hoff's rule). An increase of 10 K leads to doubled reaction speed. So, the ageing is accelerated by a factor of 4 assuming a regular storage temperature of 20 °C. 120 days at 40 °C represent approximately 480 days (15 month). Higher storage temperature is not reasonable, because the RGT rule gets more and more inaccurate and high temperatures exceeding the realistic conditions could trigger uncommon ageing mechanisms, which would not appear in daily life.

The results of the calendric ageing tests are presented in Table 7. It is important to note that the relative capacity loss was calculated based on the actual capacity and the origin capacity. A calculation based on the nominal capacity was not feasible due to very different manufacturing dates and thus different ageing prehistory. All batteries show significant loss of capacity during 120 days of storage. However, the capacity can partly be recovered by a long charging phase of 12 hours. After the capacity recovery most batteries have lost less than 10 % of their origin capacity. So, all batteries are considered as functioning. This recovery process must be taken into account for future tests. Comparing the solo and the charger storage scenarios no significant differences were found. Some batteries aged faster in the charger some during solo storage. Noteworthy, in two cases a higher capacity after storage compared to the before storage capacity was measured. This effect is most likely caused by the different and unknown storage history of the batteries. To minimize these effects a 12 hour charging phase before the ageing test should be included.

Table 7: Results of calendric ageing of batteries at 120 days at 40 °C

Specimen	120 days solo storage		120 days storage in charger	
	Relative capacity loss after storage	Relative capacity loss after storage and 12 h charging	Relative capacity loss after storage	Relative capacity loss after storage and 12 h charging
Black&Decker	16 %	1 %	18 %	-2 %
Bosch Professional	10 %	7 %	10 %	4 %
Bosch	13 %	7 %	15 %	9 %
Einhell	6 %	2 %	10 %	3 %
Parkside	15 %	10 %	5 %	-1 %
Makita	65 %	15 %	22%	11 %
Metabo	7 %	0 %	9 %	2 %
Worx	11 %	2 %	12 %	4 %

Due to the quite low decrease of capacity observed, it is assumed that 120 days at 40 °C are not enough to assess the calendric ageing of batteries over the whole battery lifetime. But it leads to differencing results representing the initial ageing behavior. An extension of the test time would be desirable. Based on a minimum battery lifetime of 6 years, the test time sums up to 1.5 years. For most applications a calendric ageing test of batteries is not feasible due to time restrictions.

2.2.3 Conclusions

Based on the experience from the battery test the following test methodology is proposed. To also include products with built in batteries, the capacity measurements were replaced by a measurement of operations with a fully charged battery (represented by operation time or steps).

Battery ageing can be divided into ageing by use – cyclic ageing and ageing by progress of time – calendric ageing. Both ageing mechanisms lead to a decreasing battery capacity and an increasing internal resistance. Depending on the usage scenario both mechanisms could be dominant. For products with 50 or more average charging cycles per year the cyclic ageing is considered as dominant. Extreme charging states (fully charged or fully discharged) also accelerate battery ageing. Testing for calendric ageing is usually not feasible in a reasonable testing time. With a given testing time of 6 months an acceleration of a factor of 12 is needed to simulate at least 6 years. The needed storage temperature to achieve this acceleration would exceed the common storage conditions by far.

The test for cyclic ageing of a battery starts with the definition of the product lifetime. Based on the lifetime and a typical usage scenario the expected number of charging and discharging cycles is calculated. If the number of cycles is too high to be tested in reasonable time, it is valid to define a minimum number of cycles (first approach: 50% of the expected cycles). Based on the typical usage scenario a test scenario is invented. To reduce the testing time the test scenario includes only intense usage phases and excludes breaks or low usage phases. For example: a typical usage scenario for a smartphone consists of calls, navigation, messageing, taking photos, video streaming, internet activities and standby. Most power consuming is the streaming via WiFi. So, the test scenario could be limited to streaming.

The testing scenario is repeated until the defined test cycles are reached. One test cycle consists of a complete discharge and a complete charge of the battery. A discharge cycle starts with a fully charged battery and ends with the automatic turning off of the device. The cyclic ageing test is conducted with the corresponding charger for charging.

Because the capacity measurement of built in batteries is complicated, the operation time (e.g. smartphone: streaming time) or completed operation steps (e.g. drilling machine: number of holes) during the test scenario

are used instead. This approach is more comprehensive and closer to the consumer experience compared to the measurement of the capacity. The current operating time/steps are recorded every 100 cycles.

After reaching the final number of discharging/charging cycles the current operating time/steps are recorded a last time. Depending on the product category and the number of cycles (minimum criterion or complete lifetime simulation) a failure limit can be defined between 60% and 80% of the original operating time or steps. If any product did not reach the final number of cycles due to any kind of breakdown, it did not pass the test either.

3 Test Development for Electronics/Electronic Control Units

In this deliverable the main focus is to derive a test plan for electronics that will be verified in work package 6. Prior deliverables have been focused on different possible test approaches and their advantages and disadvantages as well as on the failures and failure mechanisms that may happen in the electronic control units (ECUs). For this deliverable we have decided on an ECU only test approach. To derive a test suitable for covering lifetime and a broad spectrum of users' broad mission profiles are estimated. Based on these mission profiles and typical failure mechanisms for electronics a number of tests are chosen. By using ageing models the test time is determined depending on the mission profile.

The method, which is based on determination of mission profiles and deriving test parameters is focused on washing machines and televisions for this deliverable. We chose these two product groups due to their long lifetime and harsher environment (washing machines). Smartphones usually are used for a comparatively short time which makes failures of the ECU a lesser concern. Most failures are related to screen or battery. For a vacuum cleaner the ECU is comparatively simple and ECU failures are therefore also less of a concern. As mentioned before, the method used in this deliverable can also be used on both of these product groups.

3.1 Mission Profile

As reported in deliverable D3.1 and D3.3 causes for failures due to degradation of an ECU are mainly related to thermal loads (cyclic and constant) as well as humidity loads. Based on this premise the mission profiles are investigated.

3.1.1 General environmental loads

One consideration needs to cover the environment products are used in as these conditions are always present even if the product is not in use. Certain failure mechanisms, especially humidity related failure mechanisms, can be more susceptible to environmental load when the product is actually not used. This means electronics also degrade during storage or standby.

In Europe, humidity and temperature can have a broad range. For example in the Netherlands humidity can range between 75% to 90% r.H. at an average daily temperature of 3°C to 18°C, see Figure 9. In Portugal humidity can reach 75% to 80% r.H. at 10°C to 20°C, see Figure 10. This shows that humidity loads can be very high all year around. But this data does not account for specific local conditions. For example the measured temperature can be influenced by sun radiation and temperatures in small enclosed rooms like a shack may reach far higher values. Air in coastal regions can also carry water aerosols which are not included in the measured relative humidity. On a global scale climates in tropical regions can reach a nearly constant level of 85% r.H. at about 26°C for all year around.

Additionally a daily temperature swing of 10K has been assumed. This is considerably high, but the impact on lifetime and test will be very small, as seen during the calculation of the number of test cycles.

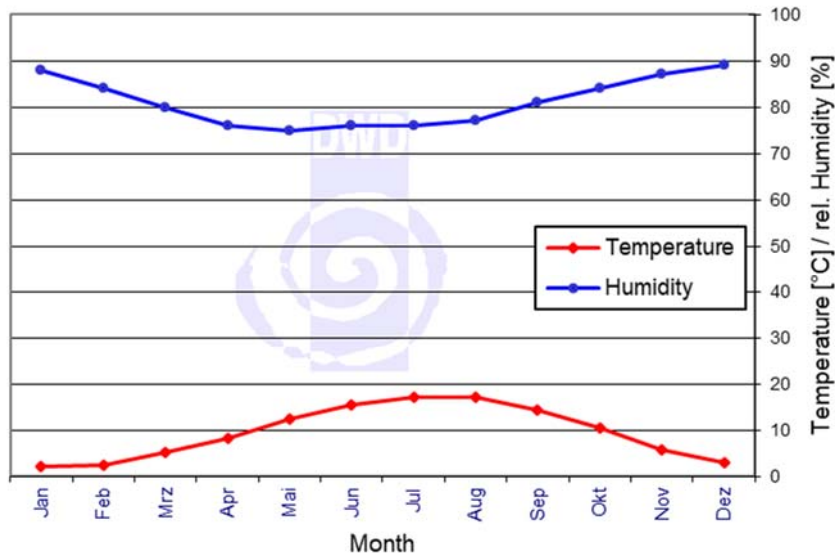


Figure 9: Netherlands, humidity, temperature; 2007 Deutscher Wetterdienst, Offenbach/ Main

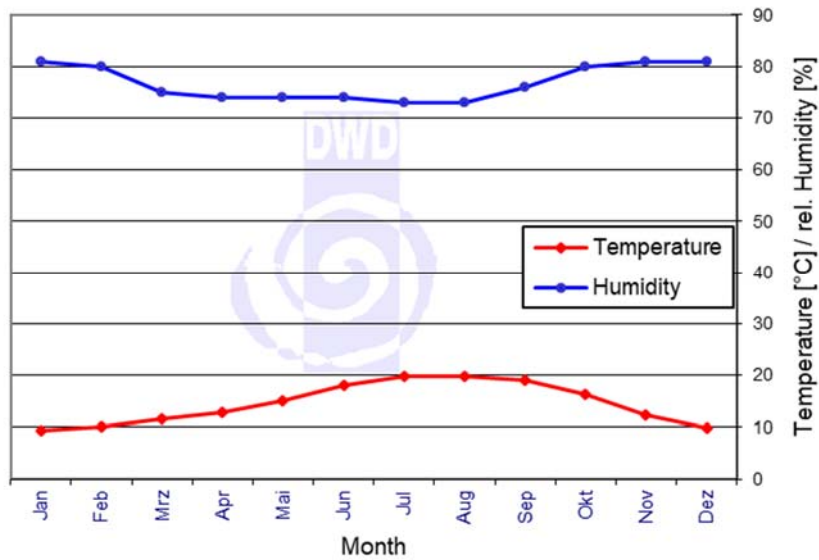


Figure 10: Portugal, humidity, temperature; 2007 Deutscher Wetterdienst, Offenbach/ Main

Since the local climate is of importance it has been decided to use a humid cellar and a hot humid shack as some base worst case environmental scenarios. In this case we assumed for the cellar a temperature of about 18°C and a relative humidity of 85% r.H. For the hot and humid shack 30°C and 80% r.H. have been assumed under the assumption of additional sun radiation and water aerosol in coastal environment.

Table 8: Worst case scenarios for use conditions in consumer goods regarding temperature and humidity

Scenario	Temperature	Humidity
Hot/humid shack	30°C	80% r.H.
Cellar	18°C	85% r.H.

3.1.2 Washing machine

Some general assumptions have been made for the use case of the washing machine and its ECU.

- 600 washing cycles (minimum), 1840 cycles (STIWA requirement)
- Cycle duration = 1,5h
- Electronics temperature 85°C (worst case: hot washing program + power loss)
- Vibration assumed irrelevant: No relevant damage to electronics (no excitation of resonant frequencies)

The temperature of the electronics is an assumed value for calculation purposes. Measurements across multiple different washing machines would have to be done to achieve a more realistic result and to see if there is a strong similarity with only small variation. Alternatively, measurements could be done for each washing machine beforehand and then the test parameters could be recalculated respectively. Similarly to temperature the humidity conditions in the local environment of the ECU during a washing cycle are unknown. In a worst case scenario, up to 100% r.H. can be assumed.

3.1.3 Television

For the television it is assumed that the ECU undergoes a temperature increase during use of up to 30K. This is a broad simplification as temperature distribution will be inhomogeneous and also strongly depends on the cooling implementation. Therefore an individual measurement for each TV is recommended.

The local relative humidity will be affected due to the temperature increase during use. As an example, in a room environment of 85% r.H. at 18°C a power loss and local temperature increase at the ECU will lead to a local relative humidity of 17% r.H. This would imply an acceleration factor of over 1000 when tested at 85% r.H. A typical rule of thumb is that an influence of humidity below 30% r.H. can be neglected. This correlates with the fact that the corrosion rate of most metals reaches possible lifetime reducing values between 40% and 60% r.H.

Furthermore, the scenarios of low amount of use (1 h/day) and high amount of use (6 h/day) have been used for further investigation as well as one to three number of use cycles per day. The number of use cycles will influence the number of temperature cycles that have to be tested.

The assumed worst-case environmental scenarios in Table 8 seem unusually harsh for an environment where a person will use a television. Therefore an average room scenario (23°C, 55% r.H.) is additionally investigated.

- Temperature increase due to power loss at ECU, $\Delta T = 30 \text{ K}$
- Investigated scenarios
 - Low amount of use: 1 h/day
 - High amount of use: 6 h/day
 - 1-3 use cycles/day
- Additional environmental scenario: average room at 23°C and 55% r.H.

3.2 Test

Test scenarios have to be derived based on the mission profiles. Ageing models are required to calculate the test time and a stress level an ECU has to be exposed to. For this purpose ageing models for typical failure mechanisms in electronic equipment have been used with parameters that are suggested in the standard JEDEC JEP122 and which are often used in the industry when the concrete failure of an ECU is unknown. The models assume a certain stress during use and during test and calculate an acceleration factor for the test condition. Since the most relevant loads for failure in electronics are assumed to be temperature cycles, constant temperature and humidity respective models have been chosen.

3.2.1 Ageing models

For temperature loads over a period of time the Arrhenius model has been chosen, see Equation 1.

$$A = e^{\left(\frac{E_a}{k} \left(\frac{1}{T_{use}} - \frac{1}{T_{stress}} \right) \right)}$$

Equation 1: Arrhenius model for calculation of temperature dependent degradation

- E_a = activation energy depending on the failure mechanism, typical value ~0.7 eV
- k = Boltzmann constant
- A = acceleration factor between use and stress (test) environment

The activation energy in the model describes the degradation of a failure mechanism in dependence of the temperature. Suggested values for unknown failures are about 0.7 eV. The values used depend on the application field, where the model is being applied. For example, in the automotive industry the activation energy is assumed to be 0.45 eV. This is much more conservative and will increase test time and cost as well as safety margins.

For humidity loads the peck model is chosen (alternatives are Lawson or exponential models), see Equation 2.

$$A = \left(\frac{RH_{stress}}{RH_{use}} \right)^n e^{\frac{E_a}{k_B} \left(\frac{1}{T_{use}} - \frac{1}{T_{stress}} \right)}$$

Equation 2: Peck model for degradation due to humidity and temperature

- n = empiric model parameter, typical value = 2.7 (corrosion)
- E_a = activation energy, typical value = 0.7
- A = acceleration factor between use and stress (test) environment

The model expands the Arrhenius model with the aspect of humidity. Typical failure mechanisms, like corrosion or other electro-chemical mechanisms always have a temperature dependence, therefore the presence of temperature in the model is needed. The empirical parameter n for the humidity dependence will change depending on the ECU and its components. The used value of 2.7 is based on corrosion observed in typical surface mounted packages on PCBs.

For temperature cycle loads a simplified Coffin-Manson model is used, see Equation 3.

$$A = \frac{N_{use}}{N_{stress}} = \left(\frac{\Delta T_{stress}}{\Delta T_{use}} \right)^{\frac{1}{c}}$$

Equation 3: Simplified Coffin-Manson model for low cycle fatigue

- c = Coffin-Manson exponent; typical value for solder joint fatigue $c = 0.4$
- A = acceleration factor between use and stress (test) environment

The Coffin-Manson model is used to describe the degradation of an interconnect / material exposed to repeated slow mechanical stress changes. In the simplified version of the model the mechanical stress is replaced by the equivalent of a temperature cycle. In an electronic package usually a temperature change causes mechanical stress due to the difference of the thermal expansion coefficients of the materials involved. As a result of temperature changes the materials expand differently. Thus deformations and mechanical

stresses occur. The repetition of such events will cause a slow degradation of the involved materials and their interfaces.

3.2.2 Test parameters

The ageing models calculate an acceleration factor between the stress during use, as defined in the mission profile, and stress during test, which can be chosen. In theory this could allow a decrease in test time by increasing the stress during the test. Realistically this is limited by a change of failure mechanisms that occur during test, when the stress is increased. Since the behavior at high stress is usually unknown the test conditions are often limited to the maximum stress during use or as defined in the mission profile.

In this case, temperature storage, temperature cycle and humidity-temperature storage tests are chosen to represent the mission profile with the following conditions:

- Temperature storage test (TS): 85°C
 - Based on Standards:
 - IEC 60068-2-2
 - JESD22-A103 (originally component level focus)
- Temperature cycle test (TC): -20°C – 85°C
 - Based on Standards:
 - IEC 60068-2-14
 - JESD22-A104 (originally component level focus)
- Humidity-Temperature storage test (HTS): 85°C, 85% r.H.
 - Based on Standards:
 - IEC 60068-2-67
 - JESD22-A101/A102

To reduce the number of ECUs needed for testing and to allow for a better coverage of interaction for failure mechanisms a sequential test order is proposed. Of course, this has the disadvantage of an increased overall test duration. The order of the test sequence is chosen based on the possible interaction of failure mechanisms, as shown in Figure 11.

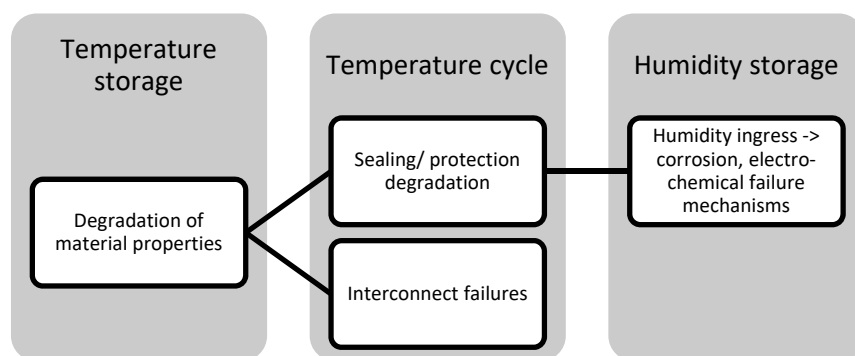


Figure 11: Test sequence and possible interaction of failure mechanisms

For example, the exposure to a temperature stress can lead to a degradation of a material, which can change its material properties. This can in consequence accelerate the degradation of sealing or protection against humidity or influence fatigue failures. A prior degradation of sealing and protections will change the failure behavior during a humidity test as the ingress of humidity to critical locations can be much faster. Such a failure chain can be actually much more realistic than a singular humidity test, as in reality the product will be exposed to all load conditions.

3.2.3 Washing machine test requirements

The required test duration/number of cycles have been calculated based on the mission profile, ageing models and test parameters.

For the humidity storage test the test duration has been calculated as shown in Figure 12 for different lifetimes. The test duration as calculated doesn't include the period of active use. As mentioned in the mission profile the use condition could be as high if not higher than the test condition and therefore no acceleration is happening during the test. The period of active use has to be either added to the calculated test duration or tested separately.

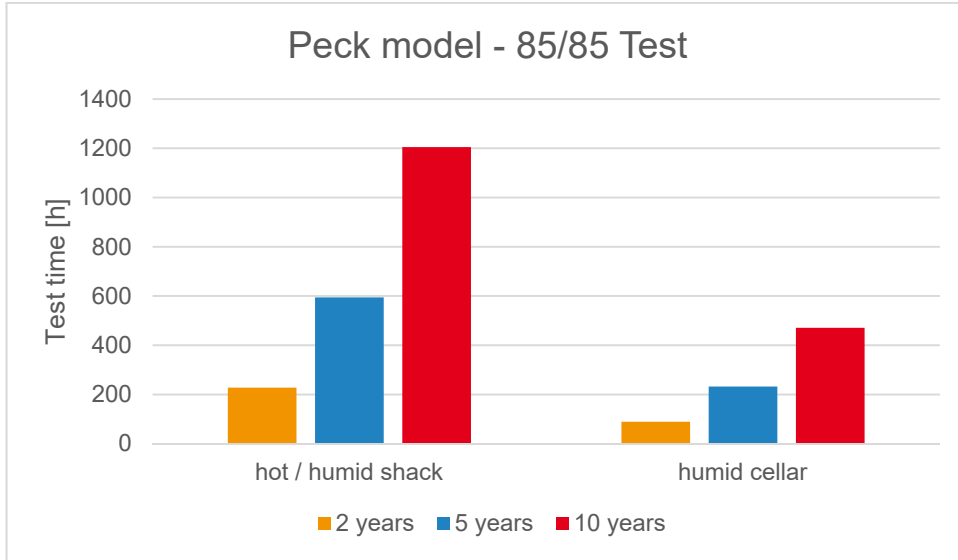


Figure 12: Washing machine - test duration humidity-temperature storage test

The result of the test duration for the temperature storage test can be seen in Figure 13.

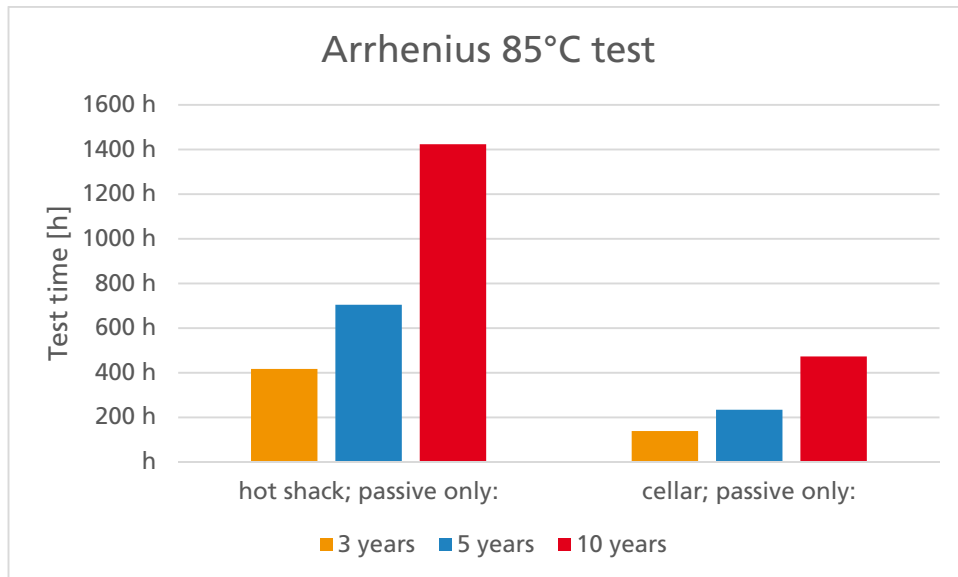


Figure 13: Washing machine - test duration temperature storage test

The results are very similar to the humidity test, because the acceleration due to humidity in the humidity test is very small compared to the influence of temperature.

The number of temperature cycles to be tested can be seen in Figure 14

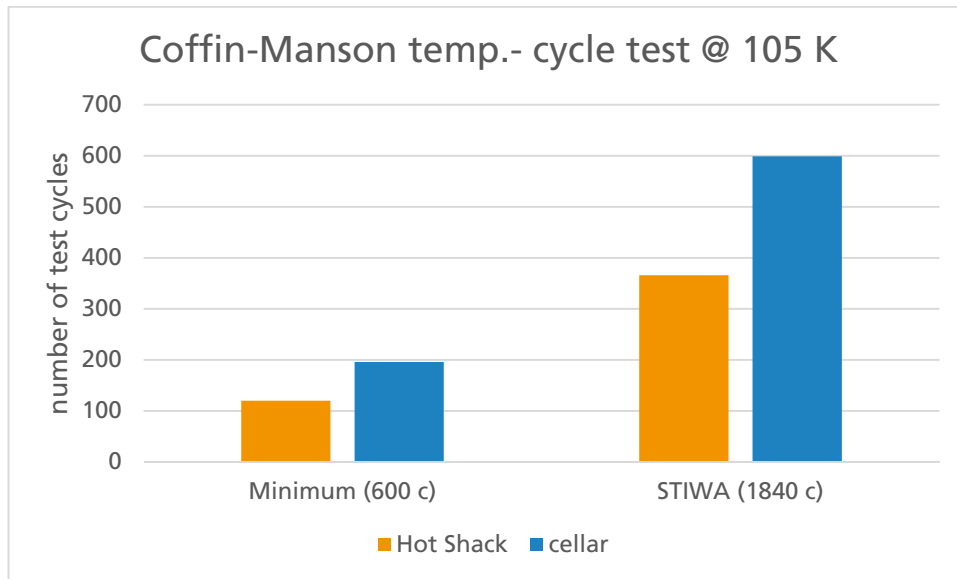


Figure 14: Washing machine – test cycles for temperature cycle test

The daily temperature changes of 10K lead to 11 cycles during test after 10 years of use.

Since all tests have temperature conditions as a component of their test there is a certain overlap which can lead to over testing. To minimize this over testing the time at extended temperatures during the humidity and temperature cycle test will be subtracted from the temperature storage test.

For the temperature cycling test a dwell time of 15 minutes per cycles is assumed to transform the number of cycles into hours at high temperature.

Due to the fact that all three tests are to be done at the same high temperature (85°C) the time at elevated temperatures can simply be subtracted from the temperature storage test without recalculation with the help of an acceleration factor.

The new test time for the temperature storage test calculates as follows:

- $TS_{test_new} = TS_{test} - HTS_{test} - TC_{time}$

For the washing machine with a lifetime of 10 years the test durations/cycles are shown in Table 9.

Table 9: Calculated test duration / number of cycles for a washing machine and 10 years of lifetime

Scenario	TS	TC (STIWA)	HTS
Cellar	-148	366	471 h
shack	128.5	599	1204 h

As can be seen the duration of the temperature storage test become very small or even negative depending on the scenario. This is caused by the low acceleration of the humidity part of the humidity-temperature storage test, which is therefore in similar length as the temperature storage test. Overall the temperature storage test can probably be neglected for the washing machine as long as a similar humidity-temperature storage test is executed.

Ideally the humidity test is executed with bias voltage applied to the ECU to more realistically reproduce the failure mechanisms, which can be difficult for an ECU-only test. Overall following test procedure is derived for the washing machine, see Figure 15.

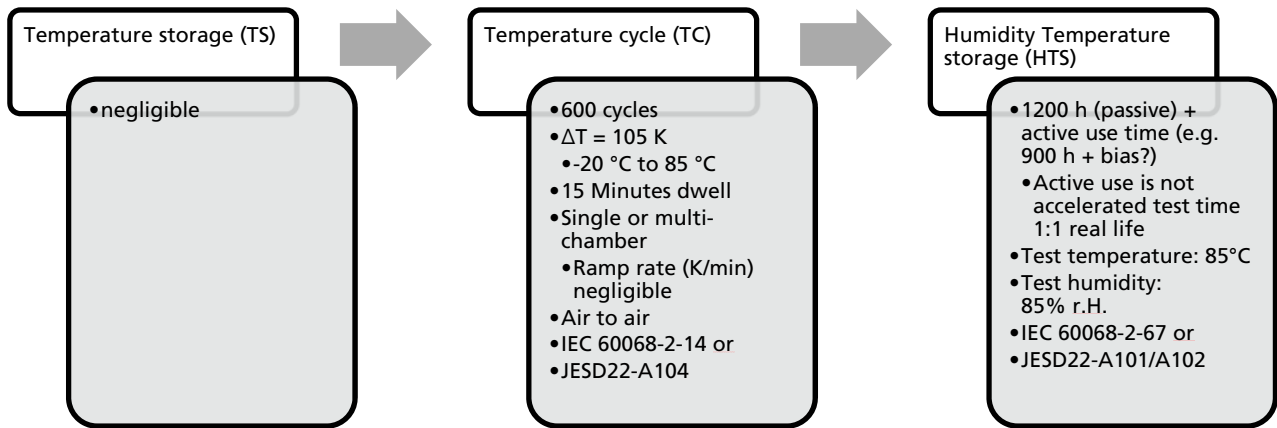


Figure 15: Suggested test procedure for the washing machines

3.2.4 Television test requirement

Based on the mission profile, ageing models and test parameters the test duration or number of cycles that have to be tested have been calculated. The scenarios investigated are named “hot”, which represents the hot shack, “cold” which represents the cellar and “room” or “RT case” which represents the average room mission profile.

The test duration has been calculated as shown in Figure 16 for the humidity storage test for a different number of years of lifetime and scenarios. As mentioned before during use the power loss leads to an increase of the local temperature and a decrease of the local humidity, therefore it was assumed that during use humidity has no impact on the ECU. This causes the scenario with a low use intensity to be more critical with regards to humidity loads compared to the scenario with a high use intensity.

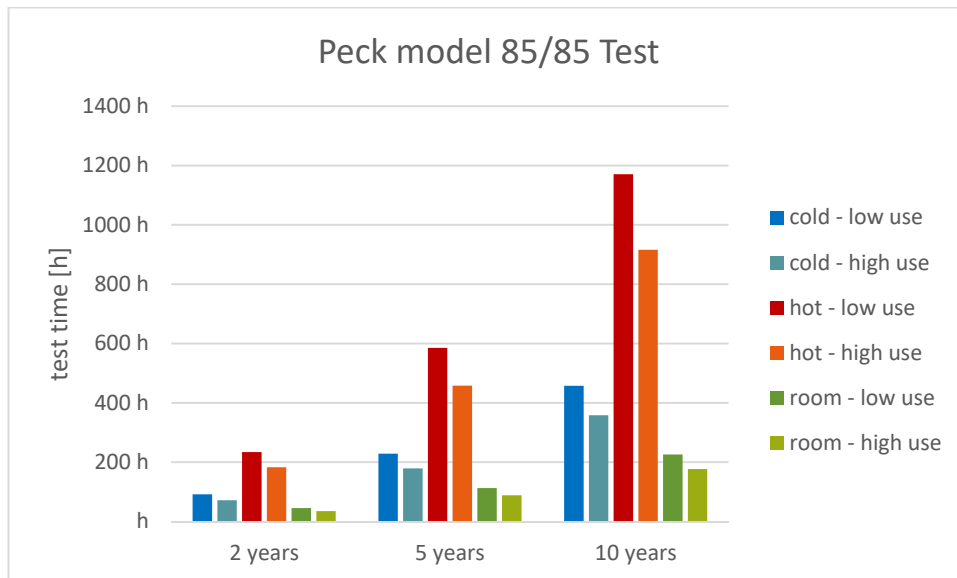


Figure 16: Television - test duration humidity-temperature storage test

The chosen worst case scenarios, like the hot humid shack or the humid cellar, are most likely not typical use cases for a television. These environments are not very comfortable to the user and while the occasional extreme weather condition may cause such scenario at the usual television position, this should be more of an exception.

The result of the test duration for the temperature storage test can be seen in Figure 17.

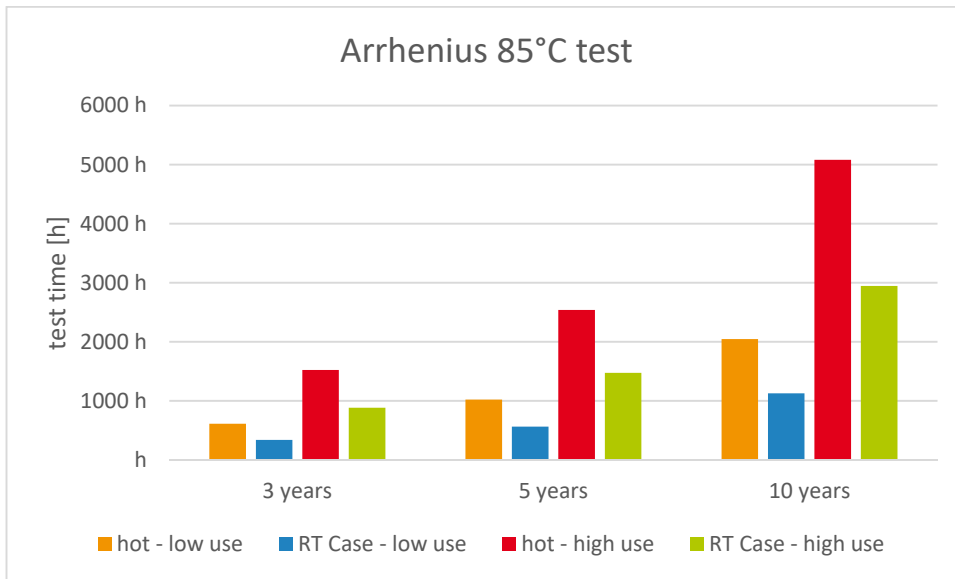


Figure 17: Television – test duration temperature storage test

Besides the impact of the environment it can be seen that the duration of use has a major impact on the test duration. The acceleration between test and a hot environment combined with a high use intensity leads to a relatively small acceleration and causes a high test duration, especially for a high lifetime (e.g. 10 years).

The number of temperature cycles to be tested can be seen in Figure 18. The number only depends on the number of cycles per day during use, as these determine how many thermal cycles due to power loss are happening during lifetime.

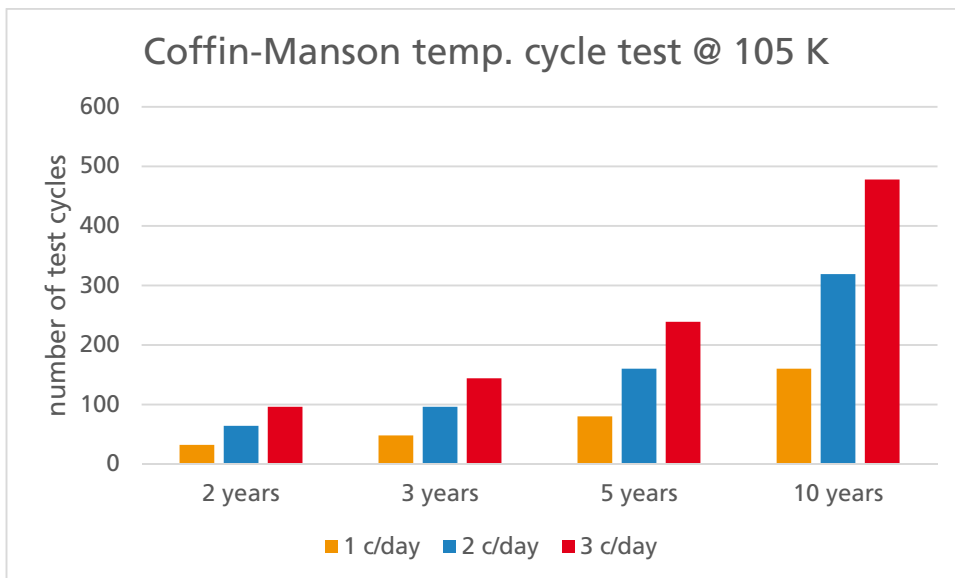


Figure 18: Television – test cycles for temperature cycle test

Similarly to the washing machine, a daily temperature change of 10K leads to 11 cycles during test after 10 years of use. Therefore the longer the lifetime or the higher the amount of daily cycles, the less relevant the environmental cycles become.

Since all tests include temperature conditions as a component, a certain overlap between tests can lead to over testing. To minimize this over testing, the time at extended temperatures during the humidity and temperature cycle test will be subtracted from the temperature storage test.

For the temperature cycling test a dwell time of 15 minutes per cycle is assumed to transform the number of cycles into hours at high temperature.

Due to the fact that all three tests are to be carried out at the same high temperature (85°C), the time at elevated temperatures can simply be subtracted from the temperature storage test without recalculation with the help of an acceleration factor.

The new test time for the temperature storage test calculates as follows:

- $TS_{\text{test_new}} = TS_{\text{test}} - HTS_{\text{test}} - TC_{\text{time}}$

For the television with a lifetime of 10 years the test durations/cycles for the most critical cases are shown in Table 10.

Table 10: Calculated test duration / number of cycles for a television and 10 years of lifetime

Scenario	TS	TC (3 cycles / day)	HTS
Hot, high use	4046.5 h	478	916 h (1171 h for low use)
Average room, high use	2650.5 h	478	177 h (226 h for low use)

Due to the high temperatures and long usage time as well as low humidity during use, temperature storage is much more relevant compared to the washing machine. While temperature cycle tests and humidity-temperature storage tests reduce the time for temperature storage, it still remains the longest test duration.

As mentioned, the chosen worst case mission profile conditions probably only occur in exceptional circumstances for televisions. Therefore the test conditions should consider a more probable environment somewhere in-between the worst case and 'average' room condition. This means a decision is necessary about the question what coverage is necessary for the test. Should all kinds of users be covered or just the average user? Based on the results the following test procedure is derived for the television, see Figure 19. The suggested duration is a range between the average room and the worst case scenario and is still to be determined.

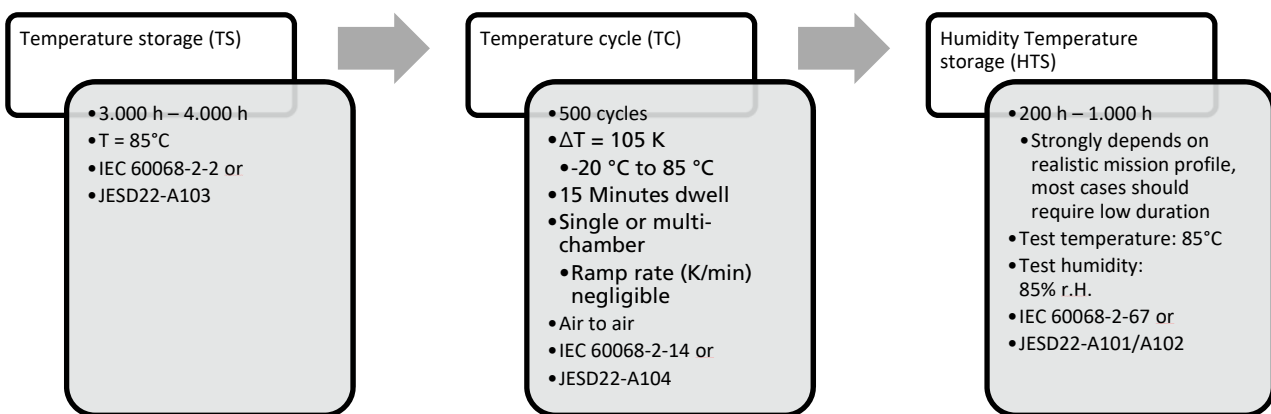


Figure 19: Suggested test procedure for the television

3.3 Summary and Conclusion

Mission profiles for different scenarios were considered and tests have been defined with the help of ageing models. While the method developed here seems feasible, some concerns remain. The current approach generalizes all specimen of a product group to be the same. Realistically, individual differences of products will change stressors in the system during use. It may be possible to measure some of these stressors in an unassembled system and do a recalculation using our method, which could be done very easily. Nonetheless, other factors like unknown real parameters for ageing models or mission profiles remain. For the mission profiles it is more or less necessary to decide on a worst case user, which should still be capable to operate the product with a full lifetime. It is not feasible to determine parameters of ageing models as these change with technology development and can vary largely between different products. Often the manufacturers themselves do not have this kind of information as an analysis would be very time and cost intensive. Currently the calculations have been done with parameters from JEDEC industry standards, which cover general electronic failure mechanisms. Overall the results can be seen as an estimate to show the impact from different parts of a mission profile. Also the recommended range of tests can be derived. The results could be used for example to decide on a minimum criteria that should be tested for.