Thermal mission profile build up with Monte Carlo simulation

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I. INTRODUCTION

Failure mechanism-based endurance tests are usually used for industrial products qualification. JEDEC test standard is used for semiconductor products qualification. The standard is the reference for applications like cellphone, personal computer, electronic gadgets etc. The electronic components working condition is more severe in automotive field thus a dedicated test standard AEC-Q is used as reference for automotive application. This standard is defined by Automotive Electronics Council [1] for qualification propose. Semiconductor products, which can successfully pass AEC-Q test, can be automotive graded. In the standard, the components are classified into different families in respect of their electronic characteristic and applications. Specific tests and test flows are defined to each component family [2].

The thermal stress is one of main reliability factors. It is taken into consideration in test standards. The related tests include, but not limited to, high temperature operation, power thermal cycling, and temperature humidity bias. These tests are explained below.

A. *High temperature operating life (HTOL)*

This test aims at reproducing the thermal aging phenomena in materials. Thermal aging refers to long-term, irreversible changes in the structure, composition, and morphology of materials exposed to temperatures that they are likely to encounter in service. For semiconductor products, the mechanisms like crystal defect (edge dislocation), junction deterioration, electromigration, compound generation between metals etc.,[4] are thermal aging failure mechanisms. Thermal aging can be activated and accelerated by thermal energy received by the materials. It is practical to link the lifetime to the temperature aging with Arrhenius model. The acceleration factor can be calculated with this model and the activation energy in the model depends on the failure mechanisms. [5]

B. *Power thermal cycling test*

This test aims to ensure the function of the device/component despite of the cumulated thermal mechanical fatigue in materials. For metallic materials in electronic components, the component lifetime achieves when the cracks are initiated then propagated in the metallic connections until the increased electrical resistance reaches the tolerable threshold. For this failure mechanism, the lifetime links to the amplitude of temperature variation with Coffin-Manson type model. The acceleration factor can be calculated with this model.[5]

C. *Temperature humidity bias test*

This test is for accelerated stress testing with respect to corrosion and other humidity driven degradation mechanisms. Temperature and humidity are accelerating factors. Peck model can be used for acceleration factor calculation. [6] For IGBT, the applied voltage should also be considered. [7]

To determine the acceleration factors, the knowledge about the infield thermal stress is necessary. For a given component, the thermal stress depends on its self-heating, surroundings, and the climate conditions. This stress is temporal and varies with the user. The standardized test has its specific test conditions, test duration and sample number. Logically, the reliability coverage of the test varies with the choice of referent client. The thermal mission profile is needed to define the referent client, and it is also an element of reliability target setting.

The thermal mission profile is processed from the temperature data. The temperature of a device/component can be measured by embedded sensors then stored locally or sent into cloud. These data arrive years after the component development cycle. This strategy requires extract storage capacity and data maintenance. The implementation is costly. A timely and less expensive solution is required.

In this paper we attempt to address these issues by presenting a thermal mission profile build up method with MCMC simulation. The method is applied on an underhood ECU. The simulated thermal profiles and their interpretations are presented.

II. METHODOLOGY

The temporal temperature simulation is composed by two steps. At first, MCMC simulation is used to create life state evolution versus time. Secondly, the life state evolution is used as an input of a mathematical model to derive temperature evolution.

A. *Life state evolution build up*

One important hypothesis in this study is that the life state evolution has Markov chain property. The probability that a life state to be reached at step n+1 depends on the life state at step n. Under this condition, the Markov Chain simulation can be used to create life state evolution versus time.

If N is the number of life states and the life states are ordered from 1 to N. Then the life state can be represented by a vector of dimension 1 x N. As the life state can be either valid or not valid and only one life state can be valid at a time, so in a life state vector, only the element of which the index equals to the order of the valid life state equals to 1. Other elements are 0.

Markov formula (Equation 1) can be used to calculate the life state probability vector at each step. This vector contains the probabilities with which a life state can happen at each step. This vector is an important element to conduct Monte Carlo simulation.

$$P(n) = S(0) * A^{n} \qquad (1)$$

P(n): the vector of life states probability at the n-th step
S(0): the initial life state vector
A is the transition matrix

The transfer matrix is a matrix of size N x N. It contains the probability of the states switching.

The output of the equation is the life state probability vector. It is a 1x N vector. This vector is to be used to define the life state of n-th step.

To define the life state, the valid life state order should be known at first. The valid life state order is defined randomly. Draw a number from 0 to 1 then find its nearest number in the life state probability vector. The index of finding number equals to the order of the valid life state.

B. *Temperature modeling basing on life state evolution*

Thermal management is to make the heat generated by a component evacuate. Under a stable external condition, a good thermal management design can ensure the temperature of a component reach thermal steady state after a certain working duration. The stabilized temperature should be lower than the allowed maximum working temperature. More the margin there is, less there is a risk to have thermal aging related reliability issues.

When the component stops working, its self-heating stops. The temperature tends to converge to the surrounding air temperature. Basing on these observations, the following model (Equation 2) is proposed to describe the component temperature evolution with time.

$$T(t) = T(t-1) + \Delta T(t) * \left(1 - 0.1 * \frac{\Delta \mathrm{t}}{\tau}\right) \quad (2)$$

T(t) is the component temperature at t

ΔT(t) is the temperature difference between the temperature at moment t and the stable temperature that the chip can reach in actual life state.

Δt is a step (one minute for actual study)

τ is the thermal inertia (time needed for temperature stabilization)

The parameters in the equation are to be deduced with thermal management design data.

III. APPLICATION

In this chapiter, the method is applied on an underhood ECU. To build the thermal stress, the first step is to build the life state evolution. In the actual example, the ECU life state happens to be synchronized with the engine state. So, the problem is translated to create a vehicle temporal life situation for different virtual clients.

A. *Underhood ECU life state build up*

A vehicle is either in motion or in parking. The driving conditions, e.g. driving on highway or in traffic jam, have a significant effect on the temperature under the hood. The reason is that in different driving conditions, the energy dissipation is different. One client can drive often in the city while another client drives more often on highway. At the end of a trip, the vehicle will be parked. The thermal stress can be very different from one client to another.

In this study case, the life state of a vehicle includes : Highway driving, Trafic jam, City, National road, Mountain driving, and Parking. These life states can be represented by numbers from 1 to 6 respectively.

The transition matrix gives the probability of driving condition switching and the probability to park the car after a certain driving condition.

Here below is one transfer matrix used in this study case. All elements in the colon of Highway equal to zero. This means the matrix represents a population which never drives on highways. The sum of each row is one, so it is a right stochastic matrix.

$$\begin{array}{l|cccccc|}
 & \text{Highway} & \text{Traffic} & \text{City} & \text{County} & \text{Mountain} & \text{Parking} \\
\text{Highway} & 0 & 0 & 0 & 0 & 0 & 1 \\
\text{Traffic} & 0 & 0.2 & 0.04 & 0.008 & 0.005 & 0.63 \\
\text{City} & 0 & 0.085 & 0.034 & 0 & 0.004 & 0.878 \\
\text{County} & 0 & 0 & 0.004 & 0 & 0 & 0.995 \\
\text{Mountain} & 0 & 0.022 & 0.005 & 0.001 & 0 & 0.973 \\
\text{Parking} & 0 & 0 & 0 & 0 & 0 & 1
\end{array}$$

There are ten transition matrices ordered from 1 to 10. They represent ten types of clients. The proportion of each type of clients is described by a probability weights vector. The client weight vector is a 1 x 10 vector.

Clients can use their vehicle with different frequencies on daily basis. The duration of each trip can also be various. The lognormal distribution is used to describe daily trip number and the duration of each trip. The distributions are available for populations of different commercial regions (Europe, America, China etc.).

The flow chart below shows the procedure to build the life states evolution of the ECU.

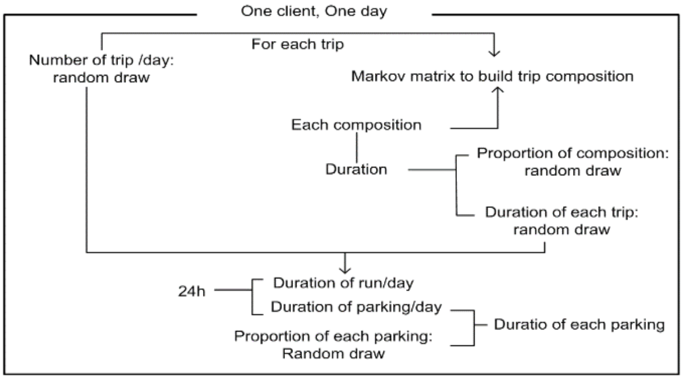

Fig. 1. Flow chart of life state build up

1) *Client type decision and transfer matrix choosing selection*

The transfer matrix, which describes the client driving preference, should be chosen randomly. To do so, draw a number from 0 to 1 then find its nearest number in the client probability weights vector. And the finding number's index equals to the order of client type. The corresponding transfer matrix should be used for this client life state simulation.

2) *Define the trip number per day for the random client*

To compute the trip number per day, the client severity is defined as a random number from 0 to 1. With the inverse function of lognormal distribution, the trip number can be computed.

3) *Simulation of the life states in each trip*

Random process is used to simulate the life state evolution in one trip. The process is about using the method in the section 2.1. A hypothesis is taken for the initial life state. We consider the trip always starts in city, so the initial life state vector is [0 0 1 0 0 0]. Increment the step number in Equation 1, and the iteration stops until the Parking state is reached.

The output of the process will be the trip composition and ends with parking state. For example, a trip is composed by city driving, traffic jam, national road and ends with parking, its life state vector is [3 2 4 6].

The duration of each trip is decided randomly with the inverse function of lognormal distribution of trip duration. In the trip, the proportion of each life state is considered randomly distributed. Knowing the proportion of each life state during driving and the trip duration, the duration of each life state in a trip can be deduced.

For example, having the life state vector [3 2 4 6], its driving state vector is [3 2 4]. Create a vector which has the same size of the driving state vector and filled with random numbers, for example [2 5 3]. Sum normalizing this vector to get the proportion vector which is [0.2 0.5 0.3]. For a given trip duration, the vector of driving state duration is Trip duration * [7,5 5 12.5].

The total parking duration can be deduced by removing the total trips duration from one day time. Considering the parking duration proportion is randomly distributed, the duration of each parking can be deduced.

Once knowing the duration of each life state, the life state evolution versus time can be built.

A simulated client one day life state evolution is plotted in figure 2.

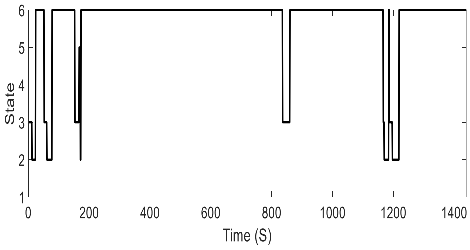

Fig. 2. One day life state evolution

B. *Central chip temporal temperature build-up*

Once the life state evolution available, knowing the temperature of a component varies with its life state, the thermal stress can be built. The relation between the temperature and the life state is quantified by equation 2. By applying the equation, the temperature versus time signal can be computed.

The flow chart below shows the flow to build the thermal stress of the ECU central chip with equation 2.

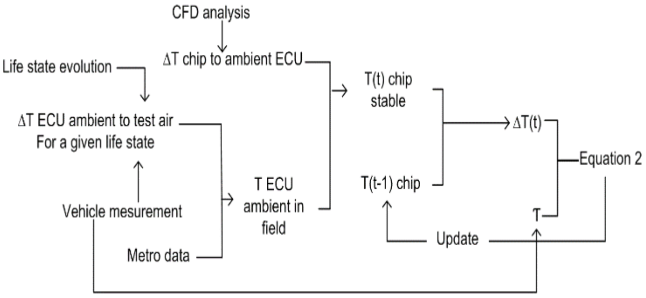

Fig. 3. Flow chart of thermal stress build up

To deduce the parameters in Equation 2, the thermal steady state characteristics of a component are necessary.

Figure 4 shows a CFD analysis of the ECU. The simulation carried out under 85°C in free air. The air flow provided by an equipped fan is considered during the simulation.

The left image is a cross section plot of the air flow rate inner the ECU. The right image is the temperature plot. In the temperature plot there is a central chip which reaches 100°C. The heat is conduced into the heatsink and dissipated by forced convection.

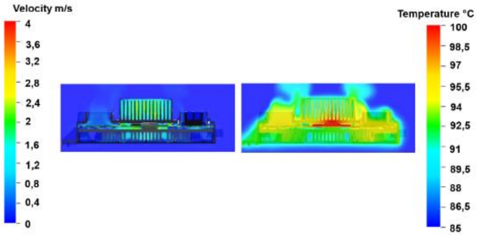

Fig. 4. CFD analysis results of the ECU

This high temperature of the central chip comes from its self-heating effect. The temperature difference between the chip and the air around the ECU (ΔT_{chip}) is 15°C.

The thermal dissipation of a chip and the cooling system activation can vary with thermal conditions. Also, the cooling strategy can impact the cooling effect so the CFD analysis is to be carried out in various scenarios to obtain the necessary elements.

The information of air temperature around ECU is from vehicle level thermal management data. Underhood architects developed temperature measurement methods to get inputs for thermal management strategy definition. The tests for measurements are carried out in a climate chamber. The air temperature is stable during the test. The vehicle will run to simulate different driving conditions (highway, traffic jam, mountain climbing etc.).

In actual study, the thermal sensors are placed around 10 cm to the ECU to take the self-heating into consideration. The information like thermal inertia and the maximum continuous temperature around ECU can be obtained (Table 1). For the cooling down stage, the thermal inertia (τ) can be taken from 90 to 120 minutes.

TABLE I. VEHICLE UNDERHOOD MEASUREMENT

	High way	Traffic	City	County	Climbing
$T_{ECU\ air}$	65	85	80	75	90
$T_{test\ air}$	45				
$\Delta T_{ECU\ to\ air}$	20	40	35	30	45
τ	25	20	20	20	15

In the field, the temperature varies with time. In different climate zone, the average annual temperature is different. The climate zones are classified into very hot zone, hot zone, mild climate zone, cold zone, and very cold zone. The air temperature data versus time can be extracted from metro website. Data from March 2008 to March 2018 was downloaded to be the data base for this study.

The figure below shows the temperature evolution in the referent cities of very hot and very cold zones from 21/03/2009 to 21/03/2018.

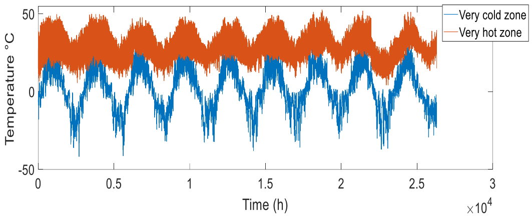

Fig. 5. The temperature evolution extracted from metro site

It is considered that the thermal gradient from ECU to air outside the car ($\Delta T_{ECU\ to\ air}$) depends only on driving conditions. For a given driving condition, the ECU ambient temperature in field can be deduced by adding the $\Delta T_{ECU\ to\ air}$ (Table 1) and the air temperature. The central chip stable temperature under a given driving condition is the addition of ECU ambient temperature in field and ΔT_{chip} from the CFD analysis. With these elements, the central chip temperature evolution in field can be computed with Equation 2.

For the first iteration, the chip temperature at the beginning of the first trip (T(0)) is the air temperature. The first trip starts in city, the central chip stable temperature under city driving (T(1)) can be calculated. And ΔT(1) is the difference between T(1) and T(0). The thermal inertia depends only on driving conditions which is available from vehicle measurement (Table 1).

Continue the iterations, the chip temperature versus time signal can be computed. Here below the central chip temperature evolution of a very hot climate virtual client. The dash line is the air temperature evolution from metro database, the data describes air temperature evolution of one day in July. The black line shows the life state evolution in a day. This client had eight trips. The parking duration between the fourth and fifth trips is very short (24 minutes). Besides city and traffic jam driving modes, there is10 minutes highway driving in the sixth trip. The solid red line shows the chip temperature which increases during each trip and cools down when de component is turned off at the end of the trip.

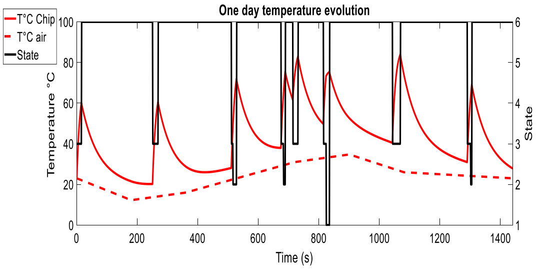

Fig. 6. Simulated central chip temperature evolution

C. Results processing and Analysis

One thousand virtual clients from a given climate zone are simulated. For each client, the temperature temporal data is processed with rain flow counting. The rain flow counting gives the thermal cycle number of a given temperature amplitude. Taking the JEDEC thermal cycling profile (-40°C to 125°C) as reference, the acceleration factors of the laboratory stress versus rain flow counted stress can be calculated with Coffin Masson model. Divide the counted cycle number at different stress levels by the respective acceleration factor to get the equivalent laboratory cycle number. After the summation of all converted laboratory cycle numbers, the result can be extrapolated to expected field lifetime.

The 15 years corresponding laboratory cycle numbers of one thousand simulated clients are plotted into histogram as following. This data plot can be fitted by lognormal distribution. The parameters of the distribution are: mln 6.23654 and sln 0.32786.

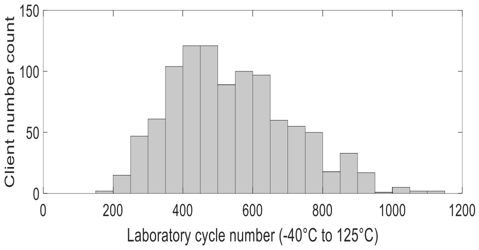

Fig. 7. Laboratory thermal cycle number distribution of very hot climate zone

To evaluate the climate impact on laboratory cycle number distribution, the same calculation is carried out with very cold climate data. The obtained cycle numbers are plotted in histogram and superposed with the very hot climate data as below (Figure 8). The graph shows that the hot climate population data has more dispersion, and the average is higher than very cold population. The very hot climate population is more critical in terms of thermal cycle number. The qualification test standards (JEDEC and AECQ), requiring 1000 TC cycles, covers 99.7% overall population.

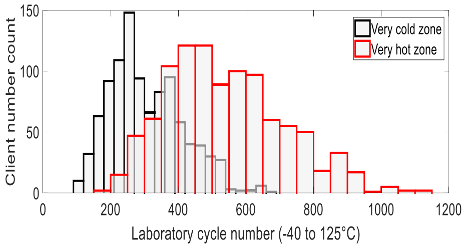

Fig. 8. Thermal cycle distribution in very cold zone and very hot zone

With the knowledge of the activation energy of the aimed failure mechanism. The temperature evolution can be converted to equivalent HTOL test duration with Arrhenius model.

For example: Considering the activation energy 0.7eV and during the test, chip case temperature reaches 125°C, the field working duration in 15 years equivalent HTOL test durations of populations from very hot zone, very cold zone and mild climate are calculated and plotted into histogram (Figure 9).

The graph suggests that the thermal aging profile of very hot zone population is much more critical than very cold zone and mild climate application.

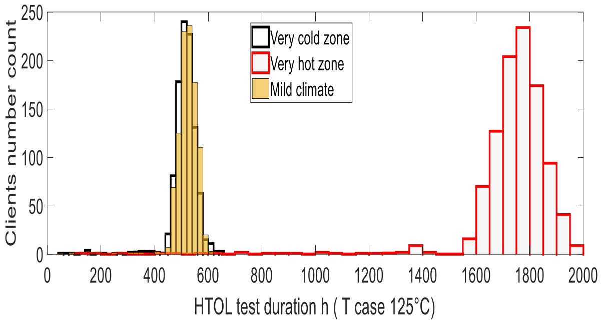

Fig. 9. HTOL test duration distribution for different climate zones

The qualification test standards (JEDEC and AECQ), requiring 1000 h HTOL test, can cover well 15 years thermal aging profile of very cold and mild climate clients for this application. It can cover 8 years use for very hot zone application.

We also plot the average percentage of working duration spent on each chip temperature level for the populations of very cold zone and very hot zone (Figure 10). The clients at very hot zone spent more time at higher temperature range.

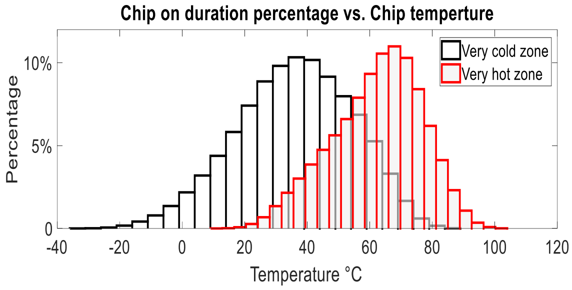

Fig. 10. Average time spent percentage at chip temperature range

IV. CONCLUSIONS AND PERSPECTIVES

This article presents a method to use MCMC simulation to build up thermal profile at chip level. The method is applied on an underhood located ECU. The application example shows that the AEC Q tests don’t cover all failure mechanisms for the entire vehicle life especially when the targeted clients located in hot climatic zone. Advantage is that this method is used far before the ECU Design Validation (DV) stage so the detected reliability risk can be revaluated in DV.

The early risk detection allows a high quality of ECU level reliability demonstration which is essential for safety relevant hardware and the product sustainability.

The method deploys existing design data. So, its implementation cost is limited.

The challenges are to get the necessary inputs like the transfer matrix and vehicle level measurement. The transfer matrix is a processed result from customer behavior data. Once it is built, it can be used for other simulations. However, vehicle level measurement is needed to be done when the underhood architecture changes.

In terms of thermal, the vehicle level input (Table 1) considered only temperature. The temperature is indeed one major thermal factor. However, the flow rate, which is also an important factor, is not considered. Taking account, the flow rate into is a challenge because it is difficult to be measured. Also, the air flow has heterogenous repartition. To tackle these difficulties, a severity/security factor, which represents the effect of convection, might be applied.

Besides thermal factors, other factors like humidity, can also be considered. Failure mechanisms perimeter can be extended.

With increasing functions provided by ECUs, the embedded systems may have more complex life states which are not synchronized with engine life state. A life state temporal study of the ECU (or a specific chip), which defines the self-heating, should be done.

Acknowledgement

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