SUPERCAPACITOR LIFE ESTIMATION

I. Factors Affecting Supercapacitor Life

- **1.1 Supercapacitor Electrode Materials** The structural stability, specific surface area, and bonding strength of the electrode materials are the intrinsic factors determining the shedding of active materials and structural fatigue during the cycling process, directly affecting the long-term cyclic reliability of the capacitor.

- **1.2 Electrolyte** The chemical stability, temperature and voltage resistance, and ion conduction characteristics of the electrolyte determine its decomposition rate under high-temperature and high-pressure conditions, which are the core causes of calendar aging and cycle aging.

- **1.3 Temperature** Temperature is the core accelerating factor for supercapacitor aging, following the Arrhenius aging law; the higher the operating temperature, the exponentially the decomposition of the electrolyte and the aging rate of the electrode increase.

- **1.4 Operating Voltage** The closer the operating voltage is to the rated upper limit, the more intense the side reactions at the interface between the electrode and the electrolyte, the faster the oxidative decomposition of the electrolyte, and the supercapacitor's life is shortened by multiples.

- **1.5 Charge and Discharge Rate** High-rate charging and discharging will generate significant Joule heat and electrode polarization, exacerbate ion transmission loss and active material fatigue, substantially increase the cycle aging rate, and shorten the service life.

II.Supercapacitor Life Estimation Model

In the field of energy storage, supercapacitors have attracted much attention due to their high power density and fast charging capabilities. However, their service life is a key factor affecting their widespread application. This paper will introduce a supercapacitor life estimation model and elaborate on its principles and applications.

The supercapacitor life estimation model proposed in this paper is based on experimental data and mathematical modeling methods. First, we conducted a series of experiments, including charge and discharge tests at different charge/discharge rates, temperatures, and cycle numbers. Then, we analyzed and processed the experimental data, extracted key parameters, and established the supercapacitor life estimation model.

This model considers the following factors:

1. **Charge and discharge rate**: The charge and discharge rate has a significant impact on the service life of supercapacitors. Experimental results show that the faster the charge and discharge rate, the shorter the service life of the supercapacitor. This is because, at high charge and discharge rates, the diffusion speed of electrolyte ions accelerates, leading to aggravated electrolyte decomposition and loss of electrode active materials.

2. **Temperature**: Temperature also has an important impact on the service life of supercapacitors. Experimental results show that the higher the temperature, the shorter the service life of the supercapacitor. This is because at high temperatures, the decomposition speed of the electrolyte accelerates, and the loss of electrode active materials is also aggravated.

3. **Cycle number**: The number of cycles is an important indicator for measuring the service life of a supercapacitor. Experimental results show that as the number of cycles increases, the service life of the supercapacitor gradually shortens. This is because during the cycling process, electrolyte ions continuously diffuse and intercalate, leading to electrolyte decomposition and loss of electrode active materials.

The life of supercapacitors is affected by operating voltage and operating temperature, conforming to the following equation:

$$\mathbf{L = L_0 \times 3.25 \frac{T_0 - T}{10} \times 1.52 \frac{V_0 - V}{0.1}}$$

L : Refers to the theoretical life at the operating temperature;

L_0 : Refers to the working life at the maximum operating temperature;

T : Refers to the actual operating temperature;

T_0 : Refers to the maximum rated operating temperature;

V : Refers to the actual operating voltage;

V_0 : Refers to the maximum rated operating voltage.

Explanation and Supplement to the Service-Life Calculation Formula

The calculation is based on the basic nominal life (L0) of the capacitor under maximum rated conditions.
L_0: Basic nominal life (typically 1000 hours for standard series).
End-of-Life (EOL) Criteria: Capacitance change rate ≤ +30% of the initial value; Internal Resistance (IR) ≤ twice the specified initial value.
T_0: Maximum rated operating temperature (e.g., 65 ℃).
V_0: Maximum rated operating voltage (e.g., 3.0V).
T: Operating temperature under actual working conditions (℃).
V: Operating voltage under actual working conditions (V).

1. Explanation of Linear Variation Coefficients
In this model, the coefficients are not exponential bases, but linear variation multipliers based on the basic life L0:
Temperature coefficient (3.25): For every 10 ℃ change in operating temperature, the impact multiplier for service life is 3.25.
Voltage coefficient (1.52): For every 0.1V change in operating voltage, the impact multiplier for service life is 1.52.
2. Calculation Scenarios and Corresponding Formulas
Depending on actual application working conditions, the calculation of service life (L) is divided into the following scenarios:

Scenario A: *Operating under maximum-rated conditions (T=T0 and V=V0). When both the actual operating temperature and voltage equal the maximum-rated limits, no variation factor shall be applied, and the expected service life is the nominal service life specified in the specification sheet.*

$$L = L_0$$

(Note: If the capacitor has a maximum temperature resistance of 65 ℃ and a maximum voltage rating of 3.0V, its expected service life will be 1000 hours when operated under the conditions of 65 ℃ and 3.0V.)

Scenario B: *Only the voltage changes (the temperature reaches the maximum limit, T=T0). When the operating temperature reaches the rated maximum value while the actual operating voltage decreases, the service-life calculation formula is only related to voltage variation.*

$$L = L_0 \times 1.52 \times \frac{V_0 - V}{0.1}$$

Scenario C: *Only the temperature changes (the voltage reaches the maximum limit, V=V0)*
When the operating voltage reaches the rated maximum value while the actual operating temperature decreases, the service-life calculation formula is only related to temperature variation.

$$L = L_0 \times 3.25 \times \frac{T_0 - T}{10}$$

Scenario D: *Mixed Operating Conditions and Out-of-Specification Usage (Linear Superposition Method). Under normal circumstances, it is not recommended to operate capacitors under over-voltage or over-temperature conditions. However, in practical engineering applications, if one parameter exceeds its limit while another parameter is derated (e.g., over-temperature with reduced operating voltage), this model evaluates the final service life by separate calculation and linear superposition. The estimated life L is the sum of the voltage-contributed life (LV) and the temperature-contributed life (LT):*

$$L = L_V + L_T$$

$$L_V = L_0 \times 1.52 \times \frac{V_0 - V}{0.1}$$

$$L_T = L_0 \times 3.25 \times \frac{T_0 - T}{10}$$

(Note: If the actual parameter exceeds the rated upper limit, the calculation result for this item will be a negative number, representing the deduction to the base service life.)

III.Impact of Series Modules (2-Series / 3-Series / 4-Series to Multi-Series) on Lifespan

2-series, 3-series, 4-series to multi-series supercapacitor series modules will significantly change the individual cell aging rate, greatly affecting the overall life of the module. The more series connections, the higher the risk of life attenuation; the core impacts are as follows:

1. **Voltage Imbalance (Core Impact)** There is natural discreteness in capacity, ESR, and leakage current among individual cells, leading to uneven voltage division after series connection, with some cells operating under over-rated voltage for a long time. According to the life model, for every **0.1V** overvoltage, the life is reduced to 1/1.52, causing overvoltage cells to age rapidly, forming a "wooden barrel effect," directly leading to the premature failure of the module.

2. **Uneven Temperature Field Distribution** 3-series, 4-series to multi-series modules have larger volumes and longer heat dissipation paths, prone to local hot spots. For every **10°C** increase in temperature, the life is reduced to 1/3.25, and the aging rate of hot spot cells is much higher than that of other cells, accelerating the end of the module's overall life.

3. **Failure of Charge and Discharge Synchronization** Cells with weak parameters are fully charged first and fully discharged first, forced to withstand overcharge and overdischarge stresses; the depletion rate of electrodes and electrolytes doubles, and the aging speed is much faster than that of independent cells.

4. **Stress Superposition Effect** The more series connections, the more obvious the stress superposition brought by electrical connections and mechanical vibrations, accelerating the aging of seals and structural damage to electrodes, further shortening the module life.

IV.Precautions for the Use of Series Modules (2-Series / 3-Series / 4-Series to Multi-Series)

1. **Configure Voltage Equalization Solutions** 2-series, 3-series, and 4-series modules can use passive equalization; 3-series, 4-series, or multi-series modules can use active equalization according to different operating conditions to ensure that the individual voltage difference is ≤ **0.02V**, eliminating the risk of overvoltage from the root.

2. **Strict Screening and Pairing of Individual Cells** Individual cells within the same module must meet: capacity deviation ≤ **±3%**, ESR deviation ≤ **±5%**, and leakage current deviation ≤ **±10%**, to reduce consistency differences.

3. **Derated Use of Module Voltage** The overall operating voltage of the module should be derated by **5%** to **10%** from the rated value to reserve a voltage safety margin and avoid instantaneous overvoltage of individual cells.

4. **Ensure Uniform Heat Dissipation and Rate Limitation** Optimize the temperature field design to avoid local high temperatures; keep the charge and discharge rate at ≤ 1C to reduce Joule heat and polarization loss.

5. **Regular Parameter Inspection** Detect individual cell voltage, capacity, and ESR every 3 to 6 months, and replace abnormal cells in a timely manner to block the expansion of the short-board effect.

V. Statement on the Universality of Life Estimation for Series Modules

Core Conclusion For 2-series / 3-series / 4-series to multi-series modules, the direct universal calculation of the original individual cell life estimation model is not applicable. The original model can only be used as a basic calibration benchmark and cannot be directly substituted with the module's average parameters for life evaluation.

Core Reasons for Non-Universality

1. **Mismatched Model Premise Assumptions** The original individual cell estimation model is built on ideal conditions of constant voltage, uniform temperature, and no parameter discreteness; series modules experience uneven voltage division, temperature field differences, and individual cell discreteness, completely breaking the foundational assumptions of the model.

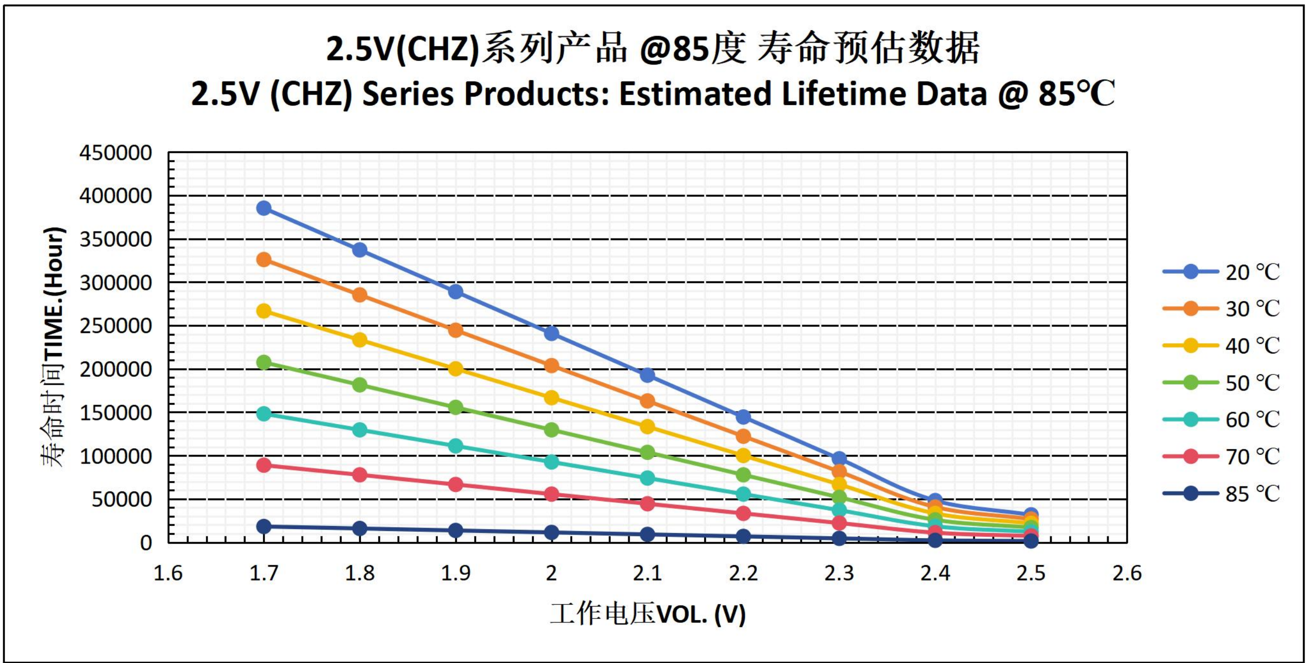
2. **Different Life Determination Logic** Individual cell life ends with its own performance attenuation; series module life ends with the attenuation of the worst cell within the module. The original model does not include the wooden barrel effect and cannot calculate the overall failure time of the module.

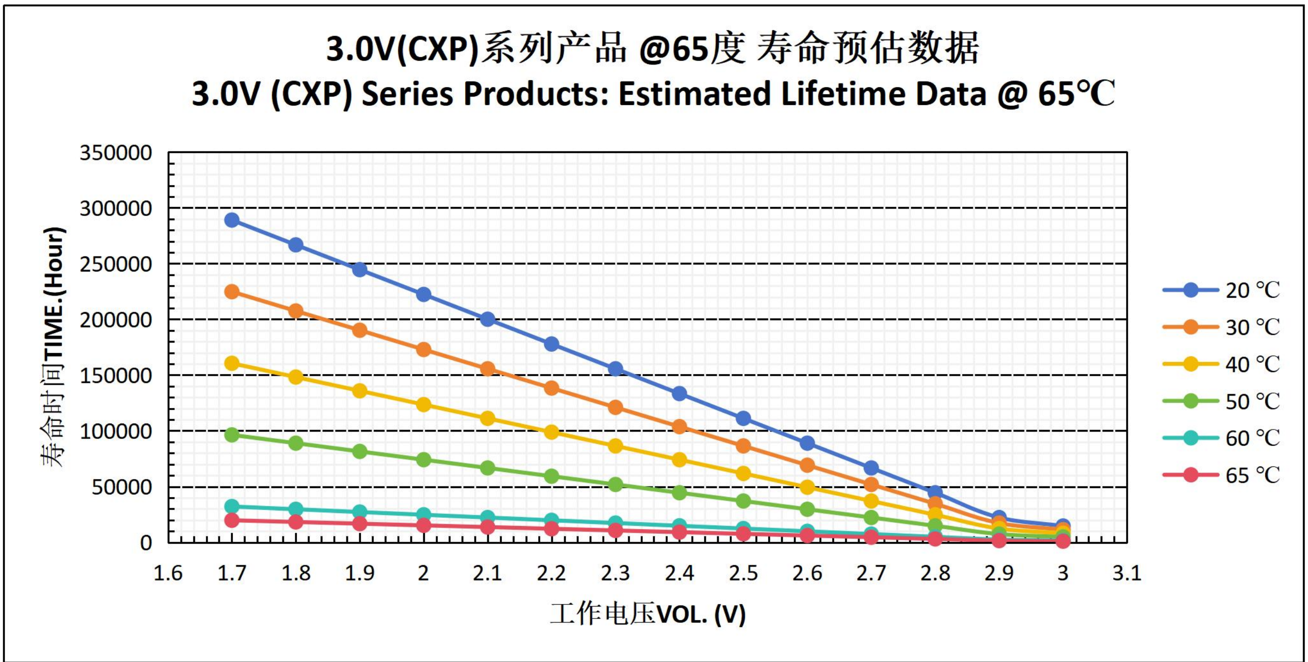
3. **Conflicting Parameter Substitution Rules** In the original model, V is the actual operating voltage of the individual cell, not the total / average voltage of the module. After series connection, individual cell voltages are discrete, and there is no unified value that can be directly substituted; direct calculation will produce massive deviations.

Rules for Module Calibration and Use Under the premises of effective voltage equalization, qualified cell pairing, and a uniform temperature field, the highest individual cell voltage and highest operating temperature within the module can be extracted and substituted into the original model to calculate the theoretical life of the worst cell, serving as a reference upper limit for the module's life. At this point, the original model is merely a calibration tool and does not possess direct universal application conditions.

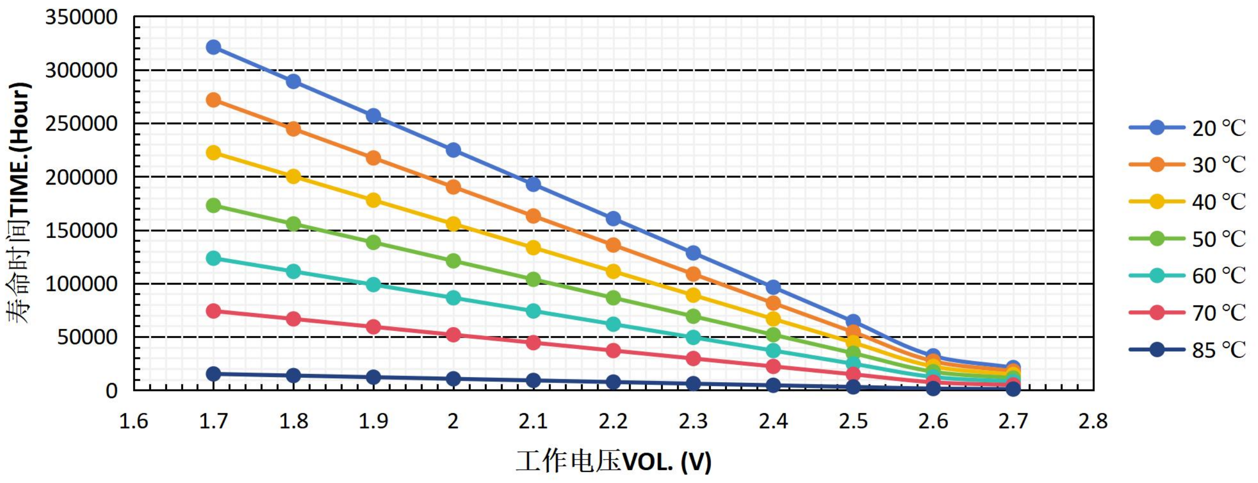
VI.Application Example

First, based on the technical parameters and actual application scenarios of the supercapacitor, set conditions such as different voltages, temperatures, and cycle durations. Then, use this model to fit the conditions to obtain corresponding model parameters. Finally, use this model to estimate the service life of the supercapacitor. Please note that the life estimation results inferred by this model are all theoretical reference values, derived from laboratory standard conditions and mathematical models, and do not represent the actual service life in a real working environment.

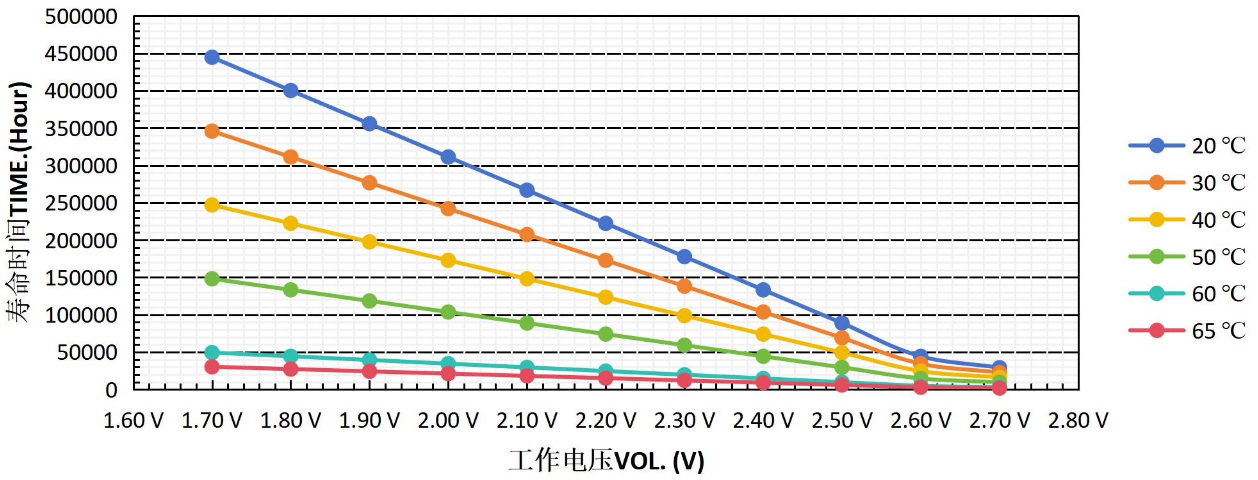




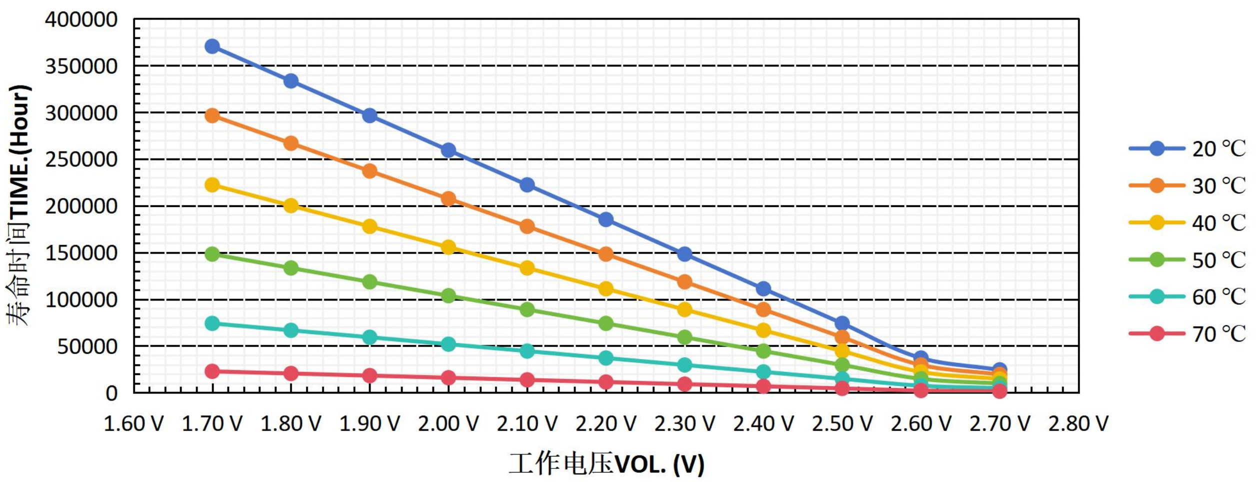
2.7V(CHW)系列产品 @85度 寿命预估数据
2.7V (CHW) Series Products: Estimated Lifetime Data @ 85℃

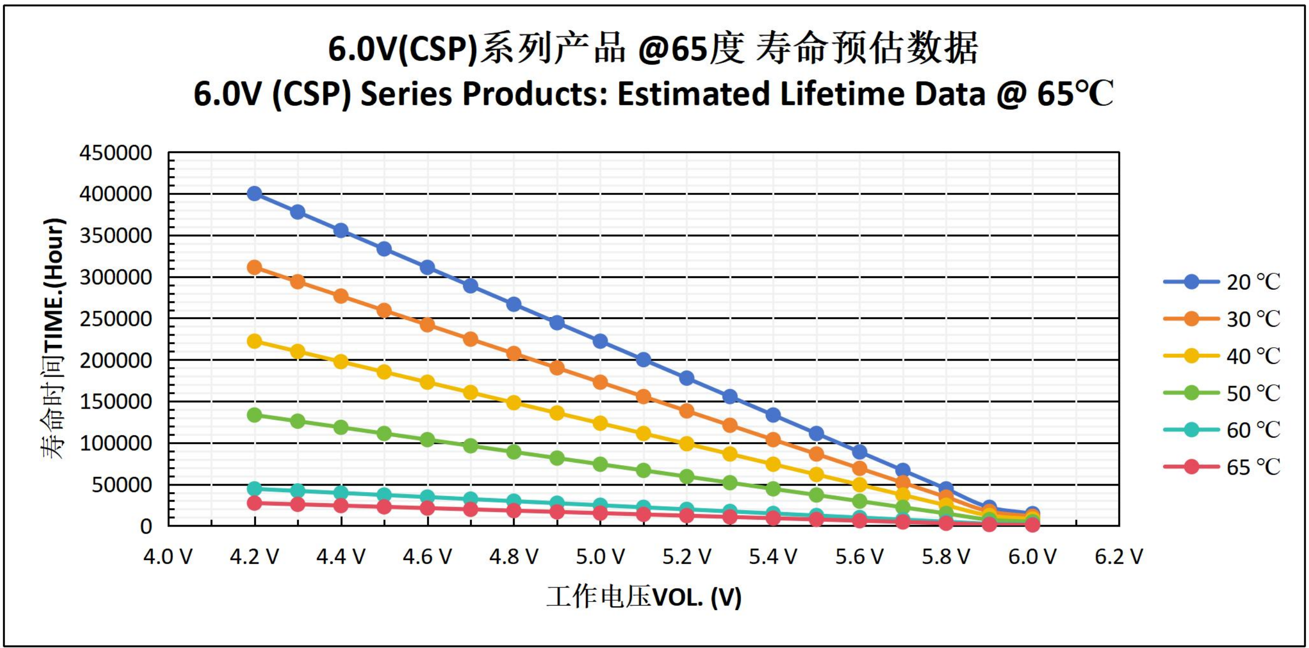


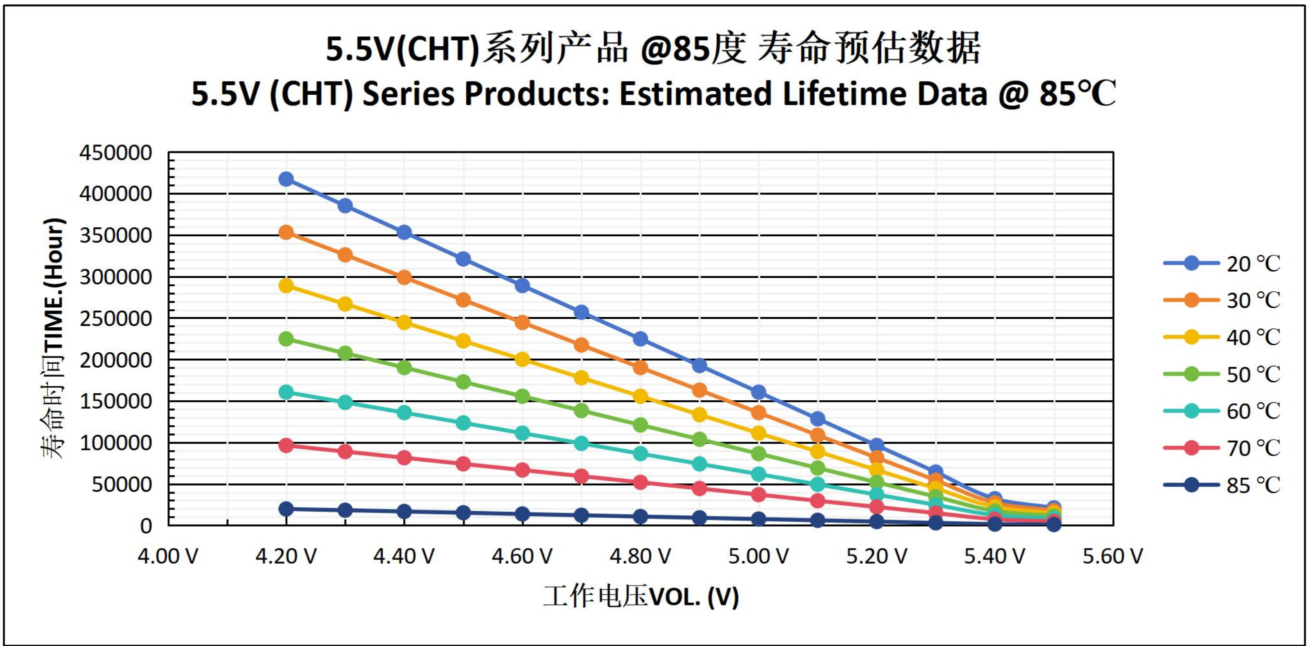
2.7V(CHV)系列产品 @65度 寿命预估数据
2.7V (CHV) Series Products: Estimated Lifetime Data @ 65℃

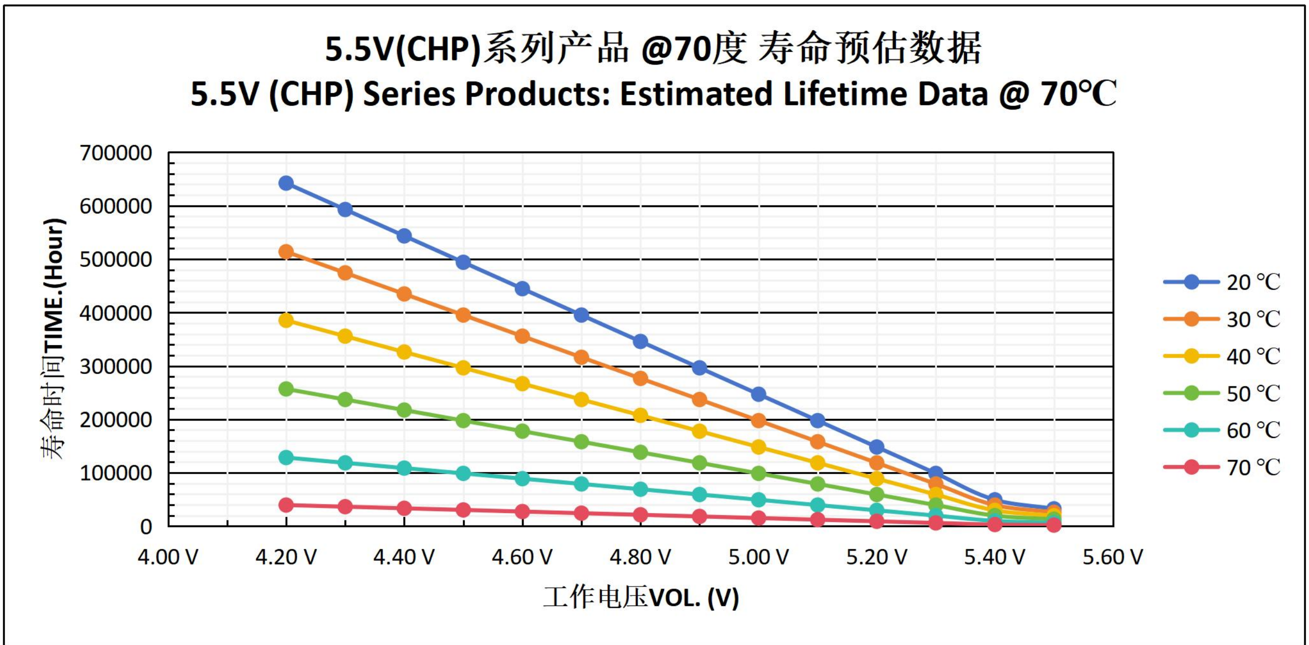


2.7V(CXHP)系列产品 @70度 寿命预估数据
2.7V (CXHP) Series Products: Estimated Lifetime Data @ 70℃

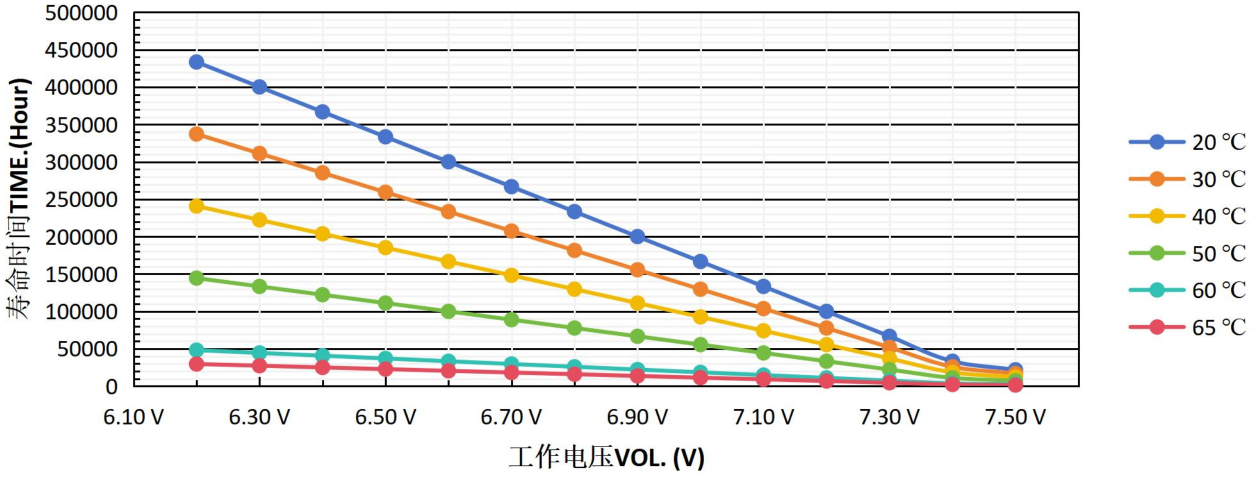



6.0V(CSP)系列产品 @65度 寿命预估数据
6.0V (CSP) Series Products: Estimated Lifetime Data @ 65℃
寿命时间TIME.(Hour)
工作电压VOL. (V)
20 ℃
30 ℃
40 ℃
50 ℃
60 ℃
65 ℃

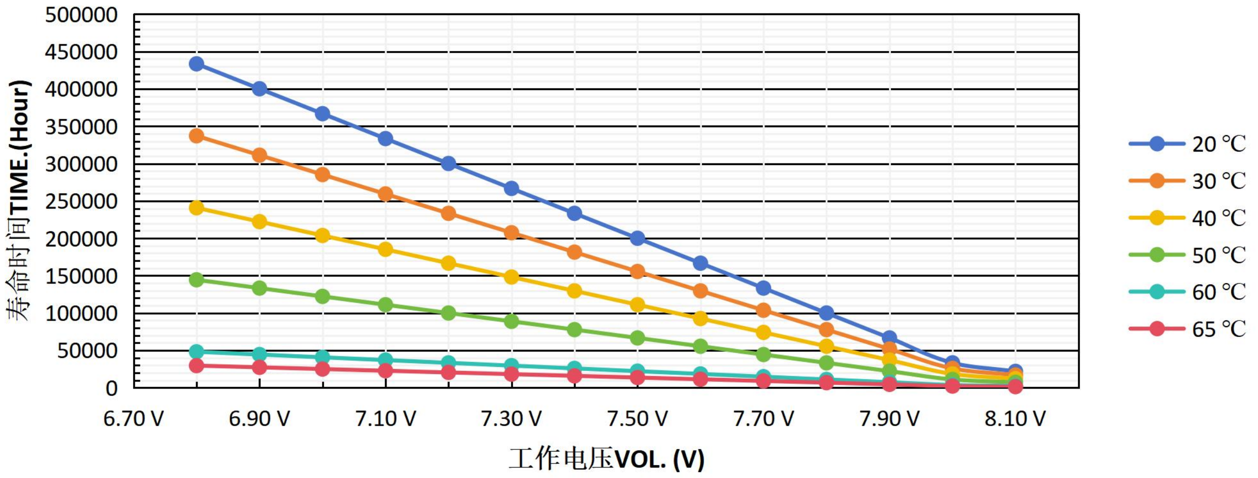

5.5V(CHT)系列产品 @85度 寿命预估数据
5.5V (CHT) Series Products: Estimated Lifetime Data @ 85℃
寿命时间TIME.(Hour)
工作电压VOL. (V)
20 ℃
30 ℃
40 ℃
50 ℃
60 ℃
70 ℃
85 ℃


5.5V(CHP)系列产品 @70度 寿命预估数据
5.5V (CHP) Series Products: Estimated Lifetime Data @ 70℃
寿命时间TIME.(Hour)
工作电压VOL. (V)
20 ℃
30 ℃
40 ℃
50 ℃
60 ℃
70 ℃

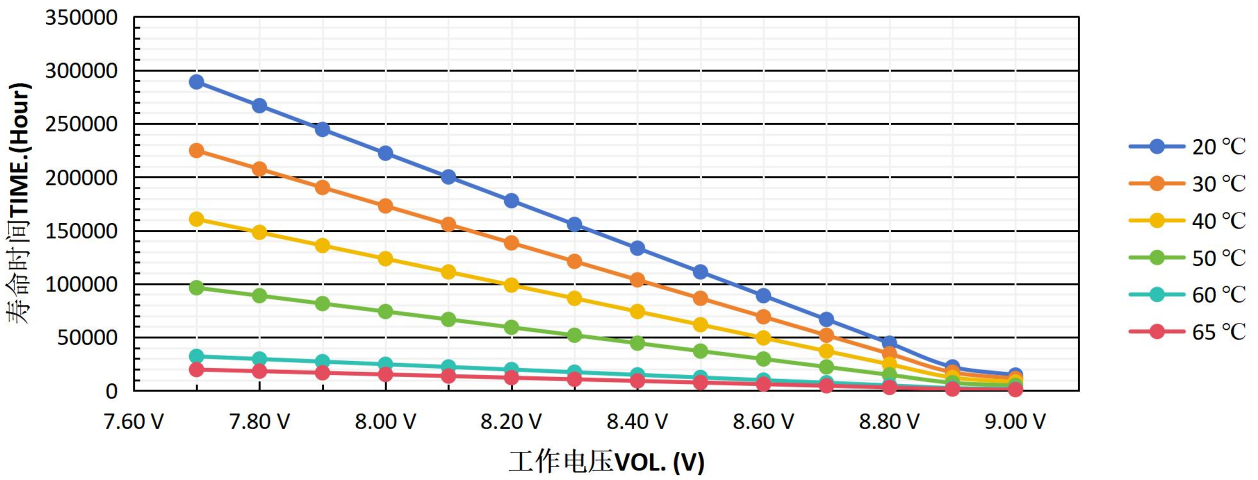
7.5V(CZP)系列产品 @65度 寿命预估数据
7.5V (CZP) Series Products: Estimated Lifetime Data @ 65℃



8.1V(CZP)系列产品 @65度 寿命预估数据
8.1V (CZP) Series Products: Estimated Lifetime Data @ 65℃



9.0V(CZP)系列产品 @65度 寿命预估数据
9.0V (CZP) Series Products: Estimated Lifetime Data @ 65℃



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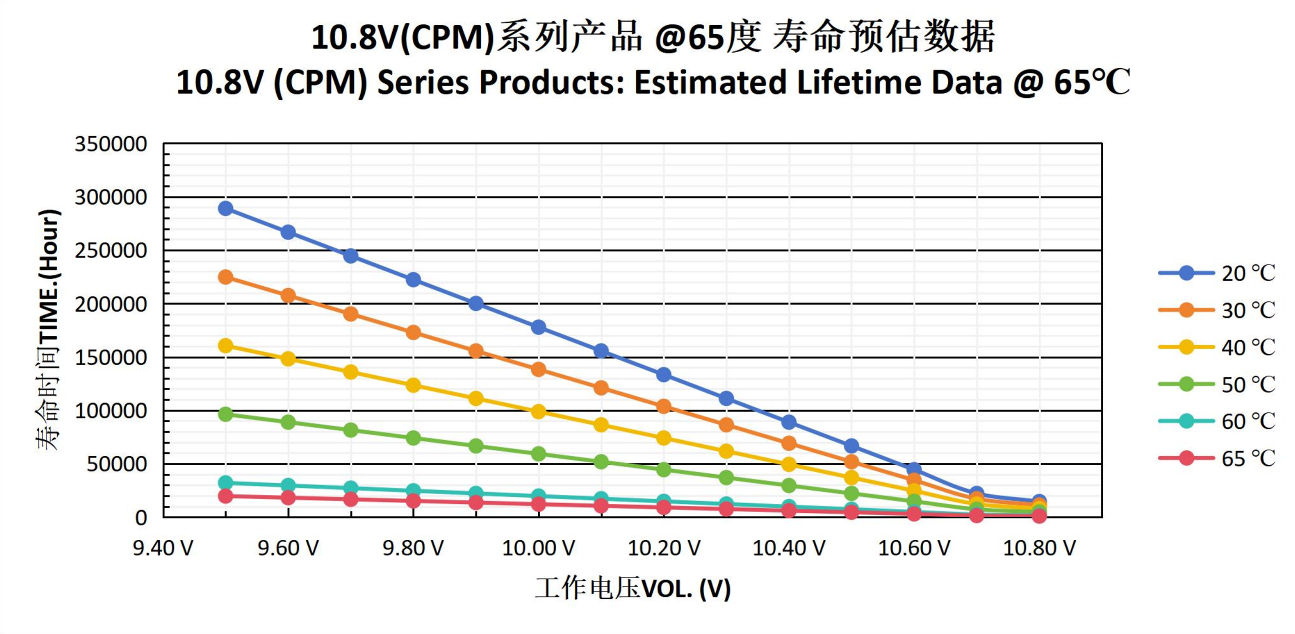
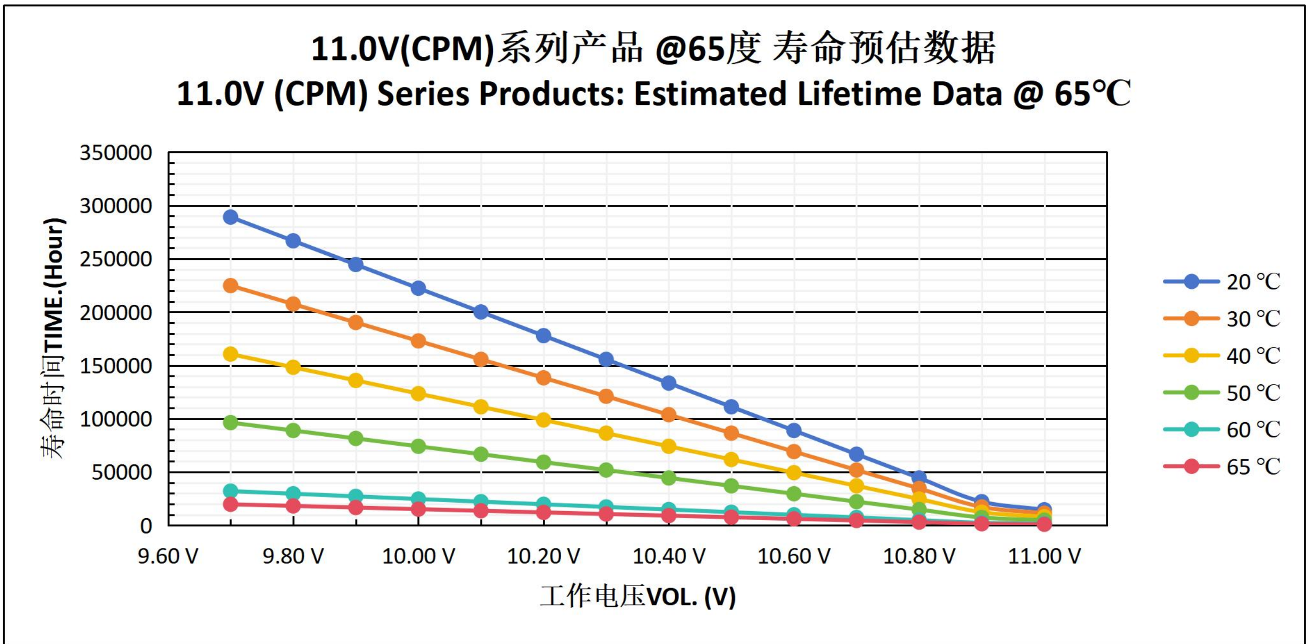
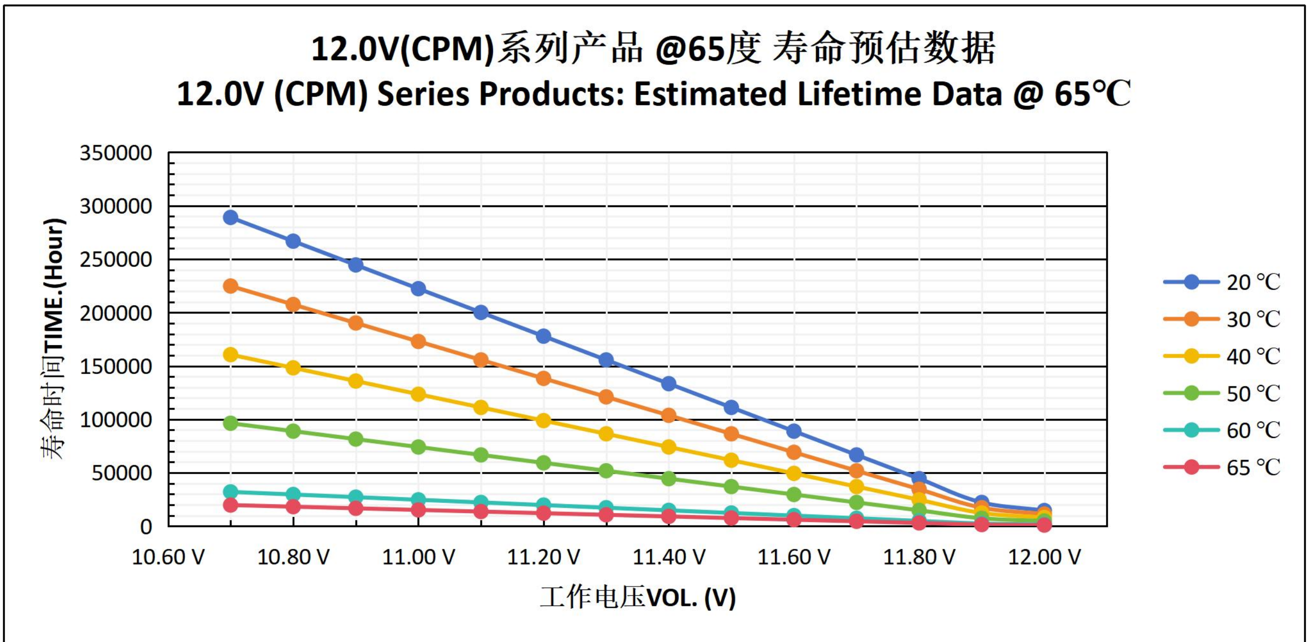






VII.Conclusion

This paper proposes a supercapacitor life estimation model based on experimental data and mathematical modeling, which considers the impacts of charge/discharge rate, temperature, cycle number, and operating voltage on lifespan. Verified by experiments, this model has high precision and strong practicality, providing an important reference for the design and application of supercapacitors.

2-series, 3-series, 4-series to multi-series modules will have their lifespans affected by uneven voltage, temperature field differences, and parameter discreteness. Measures such as voltage equalization, pairing, and derating are required to guarantee lifespan; the original individual cell life estimation model cannot be directly universally applied and must undergo consistency calibration before serving as a reference benchmark.

VIII.Future Outlook

Although we have established a relatively accurate supercapacitor life estimation model, there are still some challenges and areas for improvement in practical applications. For example, our model is mainly based on experimental data, and for new supercapacitor materials or manufacturing processes, re-experimentation and validation may be needed. In addition, the model assumes that all supercapacitors have the same charge/discharge rate, temperature, and cycle numbers, whereas these conditions often change dynamically during actual use. Therefore, during actual use, one should refer to the supercapacitor instruction manual or consult Zhi Feng Wei (CDA) for precise guidance.

In addition to this, the model can be further optimized through the following methods:

1. Add more experimental data from various working conditions to improve the model's prediction accuracy and generalization ability;
2. Introduce more influencing factors such as electrode materials, electrolyte types, and series consistency to enhance the comprehensiveness of the model;
3. Establish complex mathematical models such as neural networks and support vector machines to improve predictive capabilities under dynamic conditions.

In summary, as an important energy storage device, the life estimation of supercapacitors is of great significance for practical applications. We will continue to research and optimize, creating more precise, reliable, and practical life estimation models to assist in the development of energy storage technologies.

IX.Important Declarations

1. All life estimation results in this document are theoretical reference values, derived from laboratory standard conditions and mathematical models, and do not represent the actual service life in a real working environment.
2. Actual life is affected by multiple variables such as temperature fluctuations, voltage disturbances, charge and discharge strategies, mechanical stress, maintenance levels, series-parallel configurations, and usage environments; it is normal for deviations from the estimated values to exist.
3. For shortened lifespans caused by non-compliant operations such as failing to configure voltage equalization as required for series modules, lack of screening/pairing, or over-temperature / over-voltage / over-current usage, the related responsibilities shall be borne by the user.

This estimation is merely intended as a reference for engineering selection and does not constitute a product quality commitment, basis for warranty, or the sole standard for operation and maintenance.

Supplementary Guideline: Supercapacitor Life Degradation Mechanisms and Process Protection Specifications

As energy- storage devices with electrochemical systems, supercapacitors are highly susceptible to damage to their service life and performance caused by temperature, voltage and manufacturing processes. In practical application and production procedures, an in- depth understanding of how these stressors impact device parameters (rated Capacitance and Equivalent Series Resistance, ESR) is critical to ensuring long- term equipment reliability.

Part 1: Aging Mechanisms of Core Parameters — The Double- Edged Sword of Temperature
Ambient temperature stands as the most decisive factor governing supercapacitor service life. High and low temperatures exert distinctly different physical and chemical effects on devices.

1. High- Temperature Conditions: Irreversible "Chemical Damage" (Capacitance Drop and Resistance Rise)
Under high- temperature or excessive thermal stress, supercapacitor degradation is absolutely irreversible and follows a clear unidirectional deterioration trend:

- Rated Capacitance (unidirectional negative deviation / decline): High temperatures accelerate undesirable chemical side reactions of the electrolyte. Generated polymers permanently block the micropores of activated- carbon electrodes, reducing the effective energy- storage area of the electric double layer.
- ESR (unidirectional positive deviation / sharp increase): High temperatures directly trigger electrolyte dry- out and block ion- conducting pathways. Meanwhile, gas generated by electrolyte decomposition raises internal pressure and impairs physical contact between electrodes and current collectors.

2. Low- Temperature Conditions: Fully Reversible "Physical Freeze- Up"
At extremely low temperatures (e.g. - 40℃), device parameters fluctuate drastically (soaring ESR and sharp capacitance reduction), yet these are physically reversible phenomena.

- Mechanism: Low temperatures drastically increase electrolyte viscosity, approaching solidification in severe cases. Ion mobility becomes extremely low, and the electric double layer cannot be established rapidly.
- Recovery: Upon returning to room temperature (e.g. 25℃) and standing, parameters can recover nearly 100%. Extreme low temperatures do not shorten service life; instead, they deliver a "preservation effect" by slowing reaction rates (note voltage drop risks during cold startup).

Part 2: Storage and Life Models — Static Storage versus Dynamic Operation
The lifecycle of a supercapacitor consists of static "Shelf Life" and dynamic "Load Life".

1. Latent Aging Caused by Expired Storage
Under normal conditions, the typical shelf life of supercapacitors is 2 years. Even stored with zero applied voltage (0 V), expired devices undergo natural aging of rubber sealing rings, allowing gradual ingress of ambient moisture and minor electrolyte volatilization.

- Electrical "Avalanche Effect": Infiltrated moisture undergoes electrolysis under applied voltage to produce hydrogen and oxygen gases, causing instant bulging or liquid leakage of capacitors. Elevated ESR induced by volatilization generates severe self- heating during operation and triggers accelerated high- temperature aging.
- Response Recommendations: Expired devices must not be directly put into service. Room-temperature ESR sampling inspection is mandatory. If deployment is required, perform gentle pre-activation via minimal- current pre- charging, and operation under derated voltage is recommended.

2. Dynamic Operation and Life Consumption
After sustaining high-temperature thermal shock from soldering (remaining service life is no longer brand - new), supercapacitor degradation rate is jointly determined by operating voltage and ambient temperature.

- Voltage- driven damage: Terminal voltage acts as the electrochemical driver for side reactions; higher voltage speeds up electrolyte decomposition.
- Physical acceleration by high temperature: High temperatures serve as accelerants for side reactions. The combination of "high temperature plus full rated voltage" represents the harshest operating

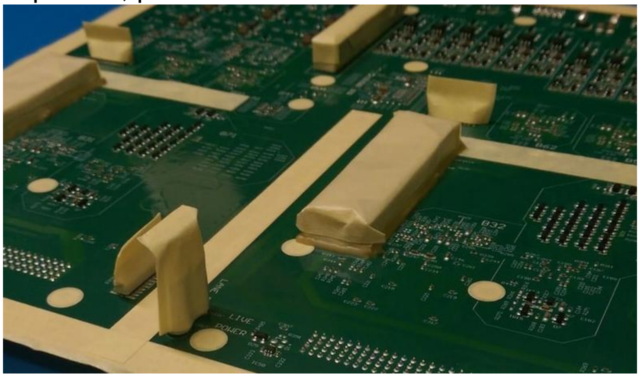
condition.

Part 3: Production Process Protection Specifications (Conformal Coating, Baking and Reinforcement)

Since vulnerabilities of supercapacitors as chemically‑ based sealed devices are often overlooked during circuit‑ board manufacturing processes (such as conformal coating, high‑ temperature baking, and ESS test reinforcement), the devices are highly prone to near‑ failure states before delivery from the factory.

1. Red‑ line Rules for Conformal Coating Process

Strict No-Coating on Device Body: Never apply conformal coating onto the supercapacitor body (including the top explosion‑ proof valve and bottom rubber plug). The cured paint film will block the pressure relief channel and cause device explosion; paint solvents will corrode the bottom‑ side sealing ring.



Need protection: Only the parts that truly require protection.
Operation: Must wait until completion.

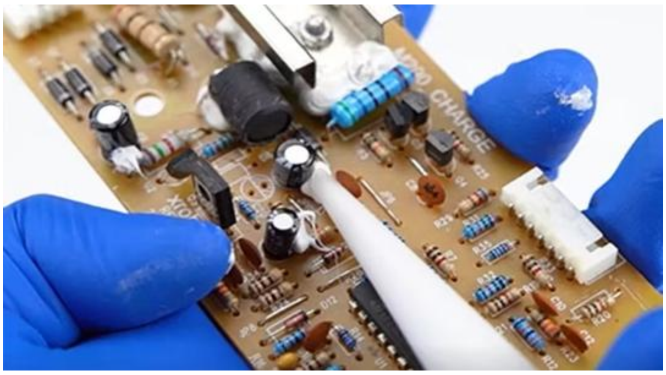
2. "Thermal Abuse" Caused by Washing and High‑ Temperature Baking

If the factory adopts prolonged baking at a high temperature of 90℃ and above, it constitutes severe thermal abuse for capacitors rated at 65℃/85℃. Boiling residual moisture forces water vapor into the interior, and vaporized electrolyte also impairs the compactness of the rubber plug, resulting in irreversible severe capacitance drop and resistance rise (ESR is expected to surge by more than 10%-30%).

Rectification suggestions: For supercapacitors, adopt manual soldering or selective wave soldering after conformal coating and baking; or require the conformal coating to use a low‑ temperature (<65℃) curing process.

3. ESS Environmental Test and Dispensing Reinforcement Specification

To pass environmental stress screening (ESS) such as random vibration, physical reinforcement via dispensing shall be performed on large‑ size components, yet the dispensing position and adhesive selection require careful consideration:



No dispensing glue on the top: Never apply glue to the top cross‑ shaped explosion‑ proof valve.
Partial bottom fixation: Do not apply full‑ fill glue between the bottom and the PCB (this will block pressure relief and cause tearing due to thermal stress). Only apply glue at the capacitor waist where it connects to adjacent large components, or place 2‑ 3 small glue dots on the outer diagonal edges of the bottom.
Glue selection: Hard epoxy resin or acidic silicone rubber is prohibited. Neutral room‑ temperature‑vulcanized silicone rubber (neutral alcohol‑ eliminating RTV type) must be used.