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gEOL: A Gradient-based End-of-Life Criterion for Power Semiconductor Modules

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***Abstract*—This letter proposes a gradient-based end-of-life (EOL) criterion for power semiconductor modules under power cycling tests. It significantly improves the consistency in determining the cycle-to-failure of testing samples compared to the widely used absolute-value-based EOL criterion, such as the percentage change of on-state saturation voltage of IGBTs. Both analytical analyses and experimental results are presented to explain and verify the feasibility and superior consistency of the proposed one. Additionally, the testing data of the power cycling has been made publicly available (https://dx.doi.org/10.21227/ksrt-zq09).**

***Index Terms*—Degradation, end-of-life criterion, power cycling test, reliability, power semiconductor modules.**

I. INTRODUCTION

A crucial yet long-neglected challenge in power semiconductor modules' reliability is how to define or judge a tested device as end-of-life (EOL) or "dead". The standard AQG 324 identifies a 5% on-state saturation voltage increase as an EOL criterion [1]. Despite this criterion being widely accepted, the existing literature has some debates on it. For instance, by testing a novel IGBT module in [2], Zhang et al. reveal that even after reaching the 5% EOL criterion, the device continues to operate normally for over twice the EOL-determined lifetime, indicating that this EOL criterion is not reflective of true failure. Moreover, in a more comprehensive review study in [3], approximately one-third of the examined studies employ a 20% on-state saturation voltage increase as the EOL criterion rather than the standard 5%. Beneath these disputes lies a fundamental research gap: the existing studies or standards lack a sufficient theoretical basis for these EOL criteria, which thus demands a dedicated investigation.

The significance of the EOL criterion mainly lies in ensuring the effective utilization of the device. Typically, the semiconductor module experiences failure upon reaching its destruct limit, for example, dielectric breakdown due to over-voltage or an open circuit caused by overheating [4]. At this operation point, it can be considered that the device is being utilized to its fullest potential. However, this carries a high risk of leading to unforeseen catastrophic accidents. As a precaution, a specific margin is allocated, and the determination of EOL is governed by predefined criteria [5].

A good EOL criterion offers timely warnings prior to catastrophic failure while maximizing the utilization of devices. Apart from achieving this trade-off, ensuring consistency of utilization among different devices and conditions is equally important. In our prior conference work [6], the power cycling test results reveal that the standard EOL based on a 5% voltage increase has a significant inconsistency of the obtained cycle-to-failure among different testing samples and conditions. Yet, the underlying theoretical cause of this inconsistency remains unclear. To address the aforementioned challenges, this letter has two-fold contributions:

1) Our experimental case study reveals that the standard EOL criterion of 5% voltage increase can cause the tested results to have up to 30% inconsistency of utilization. Furthermore, we establish a physical degradation model to elaborate on the root cause of the inconsistency. The standard EOL criterion tightly couples with more factors related to the module characteristics and testing conditions apart from the module aging, which leads to under-performance.
2) Based on the established physical model, we propose a novel but simple EOL criterion based on the gradient of the measured on-state saturation voltage. The proposed one inherently mitigates the interference from these factors unrelated to aging, and its adoption reduces inconsistency.

II. EOL DETERMINATION AND LIMITATION OF THE CURRENT CRITERION

A. Power cycling test and requirements of EOL determination

This study utilizes the power cycling test to carry out the following analysis. During the testing procedure, the generation of thermal stresses, as presented in Fig. 1, is achieved through cyclic activation and deactivation of the power cycling current (I_{heat}), and promotes the aging process. Furthermore, the on-state saturation voltage under I_{heat} corresponding to the maximum junction temperature (T_{jmax}) in each cycle is recorded to characterize the health status [4]. The case study presented in this letter focuses on top-side contacting degradation (bond wires lift-off and metallization layer reconstruction), which is one of the common failure mechanisms [3]. When all bond wires lift off, it will cause an open circuit and is primarily characterized by a sharp rise in the on-state saturation voltage, resulting in a high magnitude.

Before discussing the selection of criterion, three concepts are proposed to clarify the requirements for EOL determination. They are explained in detail below and marked on the degradation curve, as shown in Fig. 1.

- *Actual cycle-to-failure*: the number of cycles when the tested module has open-circuited.

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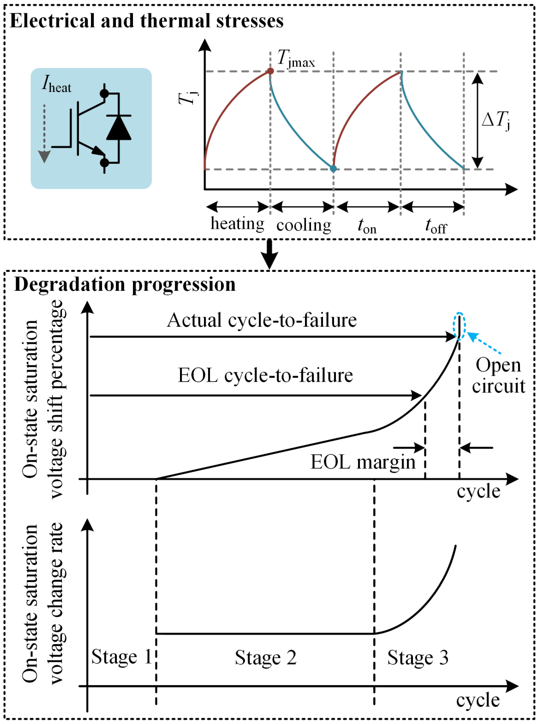

Fig. 1. Power cycling test and degradation curve.

- *EOL criterion based cycle-to-failure*: the number of cycles when the on-state saturation voltage meets the EOL criterion.
- *Cycle-to-failure margin*: it is the difference between the actual cycle-to-failure and the EOL-criterion-based one.

Typically, the selected EOL criterion should determine the high and consistent EOL criterion based cycle-to-failure, which indicates that all modules are being fully and efficiently utilized.

B. Limitation of the existing percentage-based EOL criterion (i.e., 5% increase of on-state saturation voltage)

This part presents a case study of a power cycling test to illustrate the limitation of the existing EOL criterion, with the samples, testing conditions, and actual cycle-to-failure shown in Table I. The on-state saturation voltage of each of the IGBT testing samples along the test is measured and the junction temperature is estimated based on the V_{CE} (T) [1]. The measured on-state saturation voltage data are further processed to compensate for the effect of junction temperature increase during the power cycling test [7] since the focus is on the degradation effect. Moreover, $V_{CE,sat}$ is susceptible to fluctuations due to measurement noise, typically, there is a data processing procedure before further analysis, namely data filter [8]. In this study, smoothing spline within the curve-fitting tool of MATLAB is adopted. For the sake of EOL criterion based cycle-to-failure analysis, Fig. 2 shows the increase of processed on-state voltage (%) along the normalized cycles. The x-axis is normalized with respect to the actual cycle-to-failure of each testing sample, therefore, the actual cycle-to-failure is always 100%. The three aforementioned concepts are illustrated when taking condition 1-sample 2 as an example. If the widely used percentage-based EOL criterion is applied, for example, 5% increase of on-state saturation voltage, the obtained EOL criterion based cycle-to-failure are 68.83%, 76.93%, 81.62%, 82.28%, 94.27%, 96.67%, and 99.59%, respectively. It can be noted that there is a maximum of 30% variance among the seven testing samples and the inconsistency is obvious. Additionally, there is one module, which has failed before meeting the EOL criterion.

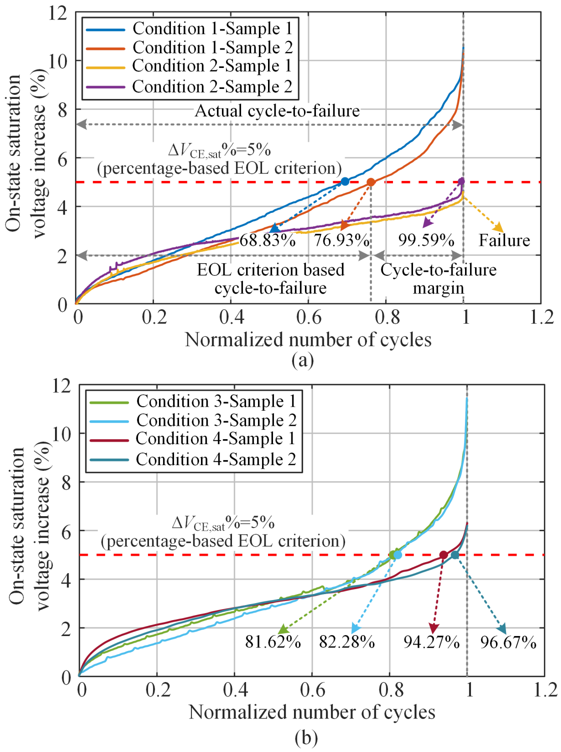

Fig. 2. Percentage of on-state saturation voltage increase with the normalized number of cycles under the testing conditions stated in Table I (The number of cycles is normalized with respect to the actual cycle-to-failure of each testing sample, on the x-axis, 0 indicates the healthy device, and 1 indicates the completely failed device), (a) condition 1 and 2; (b) condition 3 and 4.

TABLE I
DETAILS OF TEST CONDITION AND ACTUAL CYCLE-TO-FAILURE.

No.	Test condition	Actual cycle-to-failure
Condition 1-sample 1	$\Delta T_j = 100K, T_{jmax} = 150°C$	51341
Condition 1-sample 2	$t_{on}=t_{off}$=1.5s	49542
Condition 2-sample 1	$\Delta T_j = 50K, T_{jmax} = 150°C$	764566
Condition 2-sample 2	$t_{on}=t_{off}$=1.5s	785041
Condition 3-sample 1	$\Delta T_j = 100K, T_{jmax} = 125°C$	86793
Condition 3-sample 2	$t_{on}=t_{off}$=1.5s	70866
Condition 4-sample 1	$\Delta T_j = 100K, T_{jmax} = 150°C$	23890
Condition 4-sample 2	$t_{on}=t_{off}$=20s	20419

III. Theoretical Analysis of Inconsistency

On-state saturation voltage is a parameter closely related to degradation, current, and temperature. Temporarily disregarding the impact of temperature, all $V_{CE,sat}$ in Fig. 2 are decoupled to

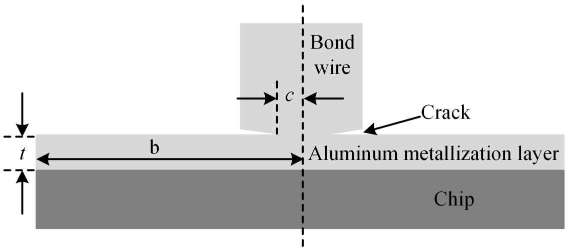

Fig. 3. Schematic diagram of the equivalent connection of the top-side contacting.

a common reference temperature. When the module is healthy, $V_{\text{CE,sat}}$ can be expressed as follows

$$V_{\text{CE,sat}} = V_{\text{ce0}} + i_{\text{c}} R_{\text{ch}} + i_{\text{c}} R_{\text{con}} \tag{1}$$

where V_{ce0} indicates the on-state zero-current forward voltage, i_{c} is the collector current, which is identical to I_{heat} in power cycling test. R_{ch} and R_{con} present the equivalent resistance of chip and package connection, respectively.

Following the underlying failure mechanism, the on-state saturation voltage primarily reflects the degradation of the topside interconnection, which mainly focuses on two locations [9]. In the case of bond wires, the stresses lead to the formation of cracks at both the heel and tip of the bond. These cracks propagate as aging progresses, eventually resulting in bond wire lift-off [10]. Regarding the metallization layer, as documented in [11], this aging process induces deviations from the original regular structure and results in surface roughening. These aging will cause the package connection resistance (R_{con}) to increase and further reflect on $V_{\text{CE,sat}}$. And [12] has proposed an analytical model that effectively characterizes the entire degradation process, and the model's parameters hold specific physical meanings. The increase of $V_{\text{CE,sat}}$ can be described using the following analytical expressions, and it can be regarded as a function of the variables c and w.

$$\begin{aligned}\Delta V_{\text{CE,sat}}\left(c,w\right) =& \frac{i_{\text{c}}\rho}{2}\left[\frac{1}{2c}+\frac{w}{\pi t}\left(\frac{b^2}{b^2-c^2}\ln\left(\frac{b}{c}-\frac{1}{2}\right)\right)\right]- \\ & \frac{i_{\text{c}}\rho}{2}\left[\frac{1}{2c_0}+\frac{1}{\pi t}\left(\frac{b^2}{b^2-{c_0}^2}\ln\left(\frac{b}{c_0}-\frac{1}{2}\right)\right)\right]\end{aligned} \tag{2}$$

where c indicates the equivalent radius of the contact area of the bond wires and gradually decreases with crack propagation, c_0 is the initial value of c. b is the equivalent radius of the aluminum metallization layer, and t represents its thickness, as shown in Fig. 3. w is used to reflect the increase in resistivity (ρ) caused by the reconstruction. (4) and (5) describe the evolution of the two failure mechanisms separately. $k_1 \sim k_5$ are the parameters to be determined, which are related to the test conditions.

$$c = c_0 - k_1\left(cycle\right)^{k_2} \tag{3}$$

$$w = k_3\left[1-exp\left(-\left(\frac{cycle}{k_4}\right)^{k_5}\right)\right]+1 \tag{4}$$

Then, the shift percentage of $V_{\text{CE,sat}}$ can be quantified as (5) and (6). s_{p} is a variable related to the degradation, and its value is between 0 and 1, the larger s_{p} means the higher degradation level and the smaller cycle-to-failure margin. w_1 is the specific values of w corresponding to s_{p}.

$$\Delta V_{\text{CE,sat}}\% = \frac{\Delta V_{\text{CE,sat}}\left(Eq_1, w_1\right)}{V_{\text{ce0}} + i_{\text{c}} R_{\text{ch}} + i_{\text{c}} R_{\text{con}}} \tag{5}$$

$$Eq_1 = \left(1 - {s_p}^{k_2}\right)c_0 \tag{6}$$

These variables in the aforementioned equations can be categorized, as shown in (7). It can be summarized that the existing EOL criterion is influenced by three factors: the inherent module characteristics including the chip and package levels, the degradation level (or cycle-to-failure margin), and the test conditions.

$$\Delta V_{\text{CE,sat}}\% = f\left[\left(V_{\text{ce0}}, R_{\text{ch}}, R_{\text{con}}, c_0, b, t, \rho\right), \left(s_p\right), \left(i_{\text{c}}, k_1 \sim k_5\right)\right] \tag{7}$$

For modules of the same type, the first factor theoretically remains the same, but it may exhibit variations due to module heterogeneity, which is primarily influenced by production tolerance. Comparing two samples in condition 1, different EOL criterion-based cycle-to-failure (68.83% and 76.93%) is presented. In other words, if the same degradation level is selected, the percentage criterion will be different. The second factor is dependent on the designer, the smaller the cycle-to-failure margin, the larger the shift percentage. Although degradation is caused by test conditions, the last factor is not anticipated, particularly current which often changes to meet specific requirements. For example, different fluctuation of junction temperature is primarily achieved through changing current in the power cycling test, particularly when the gate voltage has already been determined. Different degradation quantification results will be observed even at the same level of degradation according to (5). And this variability in turn can affect the determination of the EOL criterion based cycle-to-failure or result in different criteria. Consequently, the percentage-based criterion has limitations in determining EOL.

IV. GRADIENT-BASED END-OF-LIFE CRITERION

For power semiconductor modules, the trend of health indicators along the degradation process is commonly monotonic. The prevailing approach in EOL criteria selection primarily emphasizes the impact of degradation on parameter shifts. However, apart from this quantitative indicator, as mentioned in [5], it is possible that determining EOL can be done with the help of the change rate of the health indicator. The degradation curve typically is a combination of one or more of the three stages, as shown in Fig. 1. During stage 1, the parameter predominantly exhibits minimal variations and maintains a consistent value. Subsequently, in stage 2, the parameter presents a linear progression, and in stage 3, a pronounced acceleration in its increase becomes evident. Moreover, a distinguishing characteristic among these three stages is the change rate, i.e., zero, constant and gradually increasing values. This crucial information embedded in the precursor presents an opportunity to explore a fresh perspective in defining the EOL criterion.

Selecting an absolute value is impractical due to the substantial difference in orders of magnitude in the actual cycle-to-failure especially under different test conditions. In this study, the EOL criterion is defined as the increase factor (g) of the change rate in stage 3 relative to stage 2. Next, the feasibility of this gradient-based EOL criterion formulation is demonstrated through the proposed degradation model. The quantification of the new criterion can be expressed in (8)-(10), where s_r is used to determine that degradation is in stage 2. w_2 and w_1 are the specific values of w corresponding to s_p and s_r respectively. $f_1(x, y)$ is a function with independent variables x, y. The proposed EOL criterion can also be simplified to (11).

$$g = \frac{\left.\dfrac{d\Delta V_{\mathrm{CE,sat}}}{dcycle}\right|_{\mathrm{stage\ 3}}}{\left.\dfrac{d\Delta V_{\mathrm{CE,sat}}}{dcycle}\right|_{\mathrm{stage\ 2}}} = \frac{1}{2}\left(\left(\frac{s_p}{s_r}\right)^{(k_2-1)}\right)\frac{f_1\left(Eq_1, w_1\right)}{f_1\left(Eq_2, w_2\right)} \tag{8}$$

$$f_1\left(x, y\right) = -\frac{1}{2\left(x\right)^2} + \frac{y}{\pi t}\left(\frac{2xb^2}{\left(b^2-\left(x\right)^2\right)^2}\ln\left(\frac{b}{x}\right) - \frac{b^2}{b^2-\left(x\right)^2}\frac{1}{x}\right) \tag{9}$$

$$Eq_2 = \left(1 - {s_r}^{k_2}\right)c_0 \tag{10}$$

$$g = f\left[\left(c_0, b, t\right), \left(s_p\right), \left(k_1 \sim k_5\right)\right] \tag{11}$$

According to (11), the g-value is also influenced by module characteristics, degradation level (or cycle-to-failure margin), and test conditions. However, comparing (7) and (11), as convincingly demonstrated, there are obvious improvements, primarily evident in the following: the proposed EOL criterion exhibits less dependence on the inherent characteristics of the module and test conditions compared to the existing one. On the one hand, by retaining solely the package information linked to the degradation locations, the potential heterogeneity of the chip and the remaining package connections can be disregarded. On the other hand, the aforementioned current serves as the primary driver for altering the test conditions and is particularly removed. Therefore, it can be inferred that the proposed EOL criterion effectively mitigates the influence of these potential factors on inconsistency, possibly making improvements in EOL determination.

It is obvious that the change rate of stage 2 is not a unique value, therefore, the average of the change rates is selected, and this value is computed using the least mean square method. Then it is selected as the basis for the normalization of the change rate of on-state saturation voltage. Fig. 4 depicts the normalized change rate of $V_{\mathrm{CE,sat}}$ alongside the normalized number of cycles. The change rate exhibits a general trend of remaining constant and then increasing. In conditions 2 and 4, a saturation-like shape is presented in the preliminary stage of the on-state saturation voltage curve, and this results in a decreasing trend of the change rate of the on-state saturation voltage, thus making it inappropriate to consider the point in time corresponding to the first fulfillment of the criterion as the EOL. When a g-value, 3, is selected, the obtained EOL criterion-based cycle-to-failure is 95.83%, 95.85%, 97.11%, and 97.00%, 91.10%, 90.68%, 94.99%, and 94.82%, respectively, for the eight testing samples. It is obvious that this value of all devices is higher than 90%, these values are consistent and the inconsistency is reduced. Certainly, different g-values can be chosen, wherein higher g-values result in increased cycle-to-failure while maintaining better consistency. As shown in Table II, the inconsistency is within 4% (from 95.90% to 99.58%,) when the g-value is 6. Therefore, compared to the results obtained using the percentage-based EOL criterion, the gradient-based one presents greater consistency and higher cycle-to-failure even when different values of the parameter g are chosen.

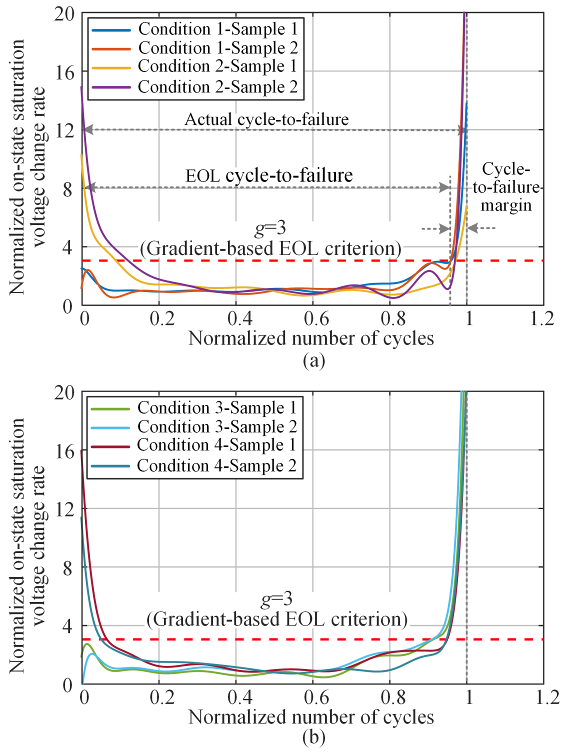

Fig. 4. Normalized on-state saturation voltage change rate with the normalized number of cycles (The number of cycles is normalized with respect to the actual cycle-to-failure of each testing sample, and the change rate of on-state saturation voltage is normalized with respect to the average of change rates corresponding to stage 2, on the x-axis, 0 indicates the healthy device, and 1 indicates the completely failed device), (a) condition 1 and 2; (b) condition 3 and 4.

It is important to note that for different types of modules, even with the same cycle-to-failure margin, another g-value may be chosen due to changes in c_0, b, and t caused by the internal connection characteristics of the module. Moreover, it becomes apparent that the new criterion solely pertains to the geometric interconnection of the package at the failure location, independent of the impact of the packaging material. This indicates its potential applicability to novel bonding materials

TABLE II
EOL CRITERION BASED CYCLE-TO-FAILURE UNDER DIFFERENT CRITERIA.

No.	Percentage-based EOL criterion ($\Delta V_{\text{CE,sat}} = 5\%$)	Gradient-based EOL criterion (g=3)	Gradient-based EOL criterion (g=6)
Condition 1-sample 1	68.83%	95.83%	98.35%
Condition 1-sample 2	76.93%	95.85%	97.38%
Condition 2-sample 1	*	97.11%	99.58%
Condition 2-sample 2	99.59%	97.00%	97.83%
Condition 3-sample 1	81.62%	91.10%	96.72%
Condition 3-sample 2	82.28%	90.68%	95.90%
Condition 4-sample 1	94.27%	94.99%	97.23%
Condition 4-sample 2	96.67%	94.82%	96.97%

* indicates that the module has failed before meeting the EOL criterion.

like copper.

V. DISCUSSION

To the best of our knowledge, this letter introduces, for the first time, the concept of a gradient-based EOL criterion and explores its practicality in wire bonding power silicon modules. In principle, this criterion exhibits the possible applicability whenever a degradation curve features stages 2 and 3, and it is worthy of extension for application to a broader range of power devices for EOL characterization. For example, building upon the available test data for wire bondless modules, double-sided cooling module [13], [14] and flip-chip module [15], the similar trend in the gradient of on-state saturation voltage or thermal resistance is presented. Moreover, the established physics-based degradation model enhancing the theoretical foundation of the proposed EOL criterion solely addresses package aging, overlooking chip-related aging, a pertinent factor in silicon carbide devices. Therefore, the effectiveness of the proposed criterion in the context of other types of devices still requires comprehensive validation.

VI. CONCLUSION

The letter proposes a novel EOL criterion for power semiconductor modules to solve the inconsistency problem of cycle-to-failure determination under power cycling tests, which is found experimentally when the percentage-based EOL criterion, a 5% increase of the on-state saturation voltage, is adopted. Not only this limitation is solved, as demonstrated the inconsistency of EOL criterion-based cycle-to-failure up to 30% is reduced within 4%. But also the root cause of the inconsistency is revealed with the help of the proposed physical degradation model. Compared with the proposed one, the standard criterion tightly couples with more factors related to the module characteristics and test conditions, which inevitably leaves the EOL determination subject to the heterogeneity of modules and variability of test conditions. However, these influences can be decoupled by the proposed straightforward mathematical transformation, i.e., the gradient of $V_{\text{CE,sat}}$. Additionally, the theoretical applicability of the proposed criterion extends to emerging bonding materials, such as copper. And the concept of the gradient-based EOL criterion shows promise for potential application to other types of modules, but it still necessitates thorough validation.

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