APPLICATION NOTE PRD-06379

ENVIRONMENTAL CONSIDERATIONS FOR POWER ELECTRONICS

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Mitigating moisture within electronics systems is crucial for extending their lifetime and preventing premature failures. These considerations are especially important in systems with high operating voltages such as power conversion. Careful consideration of the surrounding environment and cooling techniques must be observed. Operating in high-temperature, high-humidity environments allows for moisture and contaminants to diffuse into the encapsulating gel, which can reduce its dielectric strength and result in corrosion of the substrate. It also increases the risk of condensation in the module during light-load conditions. Even in mild-humidity environments, excessive cooling of the heatsink can create condensation that contributes to device failure. Considerations of these factors are necessary for operating power modules in rugged and robust applications.

CONTENTS

1. INTRODUCTION

The reliability of power electronics systems is largely determined by their operating conditions and environment. For example, moisture can degrade system lifetime through corrosion and reduction of dielectric strength. The semiconductor chips are particularly vulnerable to the influence of moisture due to the thermal cycling and high electric fields they are subjected to. Maintaining proper conditions and control of heating and cooling cycles can extend system lifetime and prevent premature failures. This document will describe the influence of moisture on the operation of Wolfspeed case modules, provide recommendations and mitigation techniques, and describe the equations necessary to determine environmental moisture conditions as defined by IEC standards.

1. DEFINITIONS

1.1 Case Modules and Environment

Case modules are a subset of power modules in which the semiconductor chips are protected by an encapsulate, generally a cured silicone-based gel, which is retained by a plastic case or housing. A notional diagram of a case module with a baseplate is shown in Figure 1. The semiconductor chips are mounted to a ceramic material that provides electrical insulation while remaining sufficiently thermally conductive to allow heat transfer to the baseplate. For baseplate-less modules, such as the FM3 and GM3 series [1], the ceramic insulator attaches directly to the heat sink with a thermal interface material. The analysis in this document applies to both types of case modules. The inside of the module is not hermetically sealed; air molecules can pass freely inside and outside of the module to maintain equilibrium with the surrounding environment. This environment depends on how the system is implemented, such as within a cabinet, a climate-controlled building, or exposed to open air.

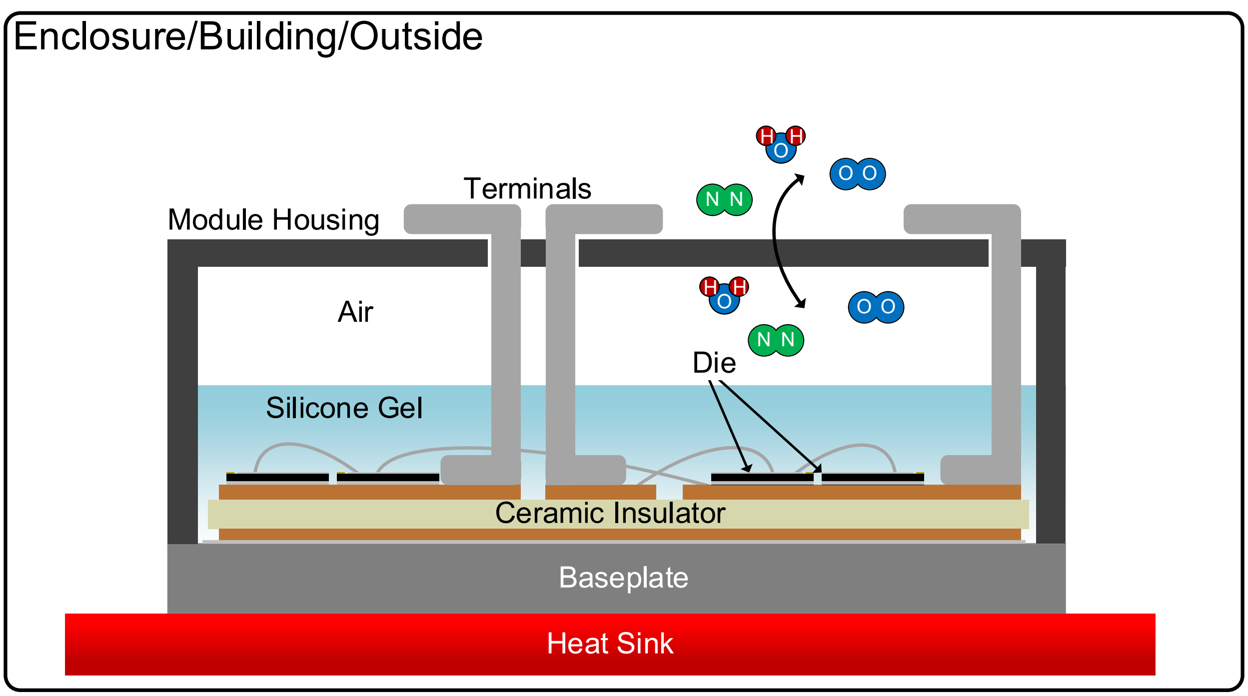

Figure 1: Notional case module diagram and description

1.2 Humidity

The most common mechanism by which power modules are exposed to moisture is through water vapor in the surrounding air. Humidity describes the concentration of water vapor diffused air and can be expressed in absolute or relative terms. **Absolute humidity (AH)** describes the density of water molecules in the air, often in units of grams per cubic meter (g/m^3). **Relative humidity (RH)** describes the ratio of water in the air to the saturation point in the given air mass, often expressed as a percentage. At a relative humidity of 100%, gaseous vapor in the air will condense into liquid water.

More formally, relative humidity is described as the ratio of vapor pressure to the saturation vapor pressure, as described in equation (1) below. The **vapor pressure (P_{ACT})** of water describes the pressure exerted by molecules of water vapor, and the **saturation vapor pressure (**PS**)** is the point at which water vapor is in an equilibrium state between liquid and gas forms. When vapor pressure is above the saturation pressure, water vapor will condense, and when vapor pressure is below the saturation pressure, liquid water will evaporate. The saturation vapor pressure is a function of temperature and is an important quantity for determining the relationship between temperature, absolute humidity, and relative humidity, which ultimately describe the atmospheric conditions for device operation.

The formulations for calculating the saturation vapor pressure above 0 °C and below 0 °C are provided below in equations (2) and (3), respectively, where *T* is in °C. These equations are approximations of the physical behavior described in [2]; other formulations exist [3], but these provide excellent accuracy across a broad temperature range and are simple to implement. Equations (2) and (3) were evaluated across temperature and compared to empirically measured values, the results of which are provided in Figure 2. The saturation vapor pressure can be used to relate absolute humidity and relative humidity per equation (4). The relationship between AH and RH using these equations is shown in Figure 3. As temperature increases, the required density of water molecules (AH) increases to achieve the same relative humidity.

$$RH = 100\frac{P_{ACT}}{P_s}\ (\%) \quad (1)$$

$$P_s = \frac{\exp\left(34.494 - \frac{4924.99}{T + 237.1}\right)}{(T + 105)^{1.57}}\ (T > 0°C)(Pa) \quad (2)$$

$$P_s = \frac{\exp\left(43.494 - \frac{6545.8}{T + 278}\right)}{(T + 868)^{2}}\ (T \leq 0°C)(Pa) \quad (3)$$

$$AH = \frac{RH}{100} * \frac{P_s}{461.5 * (T + 273.15)}\ \left(\frac{g}{m^3}\right) \quad (4)$$

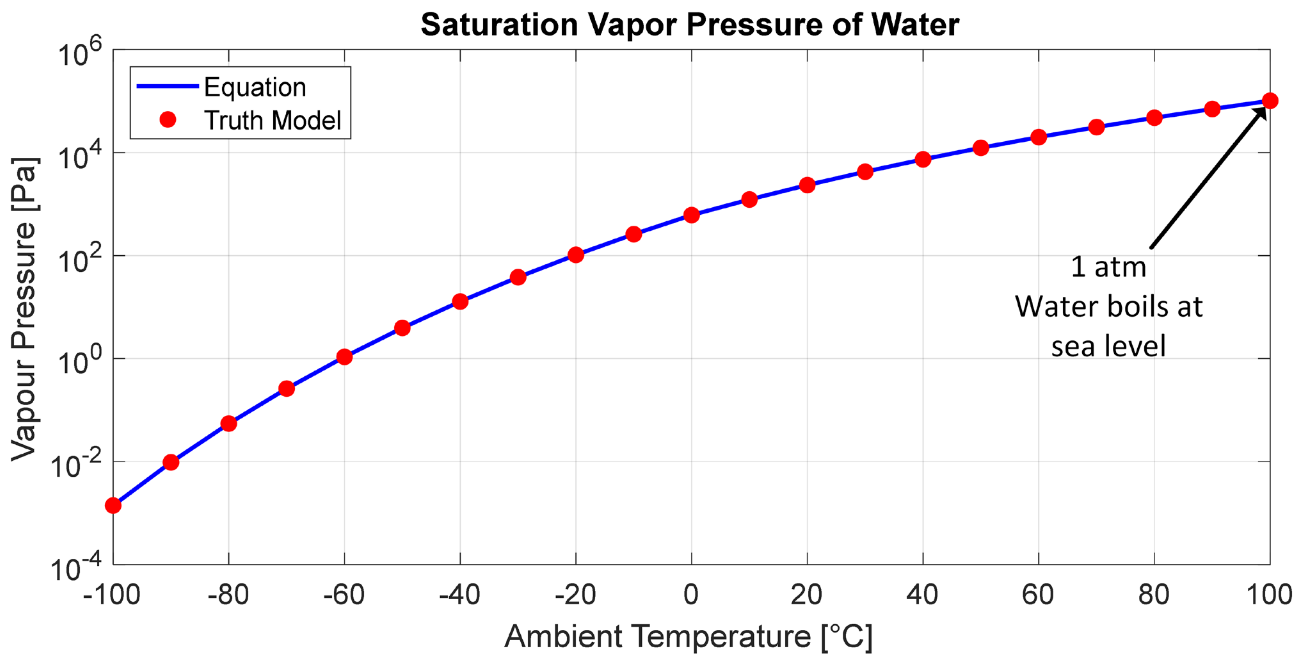

Figure 2: Saturation Vapor Pressure of Water

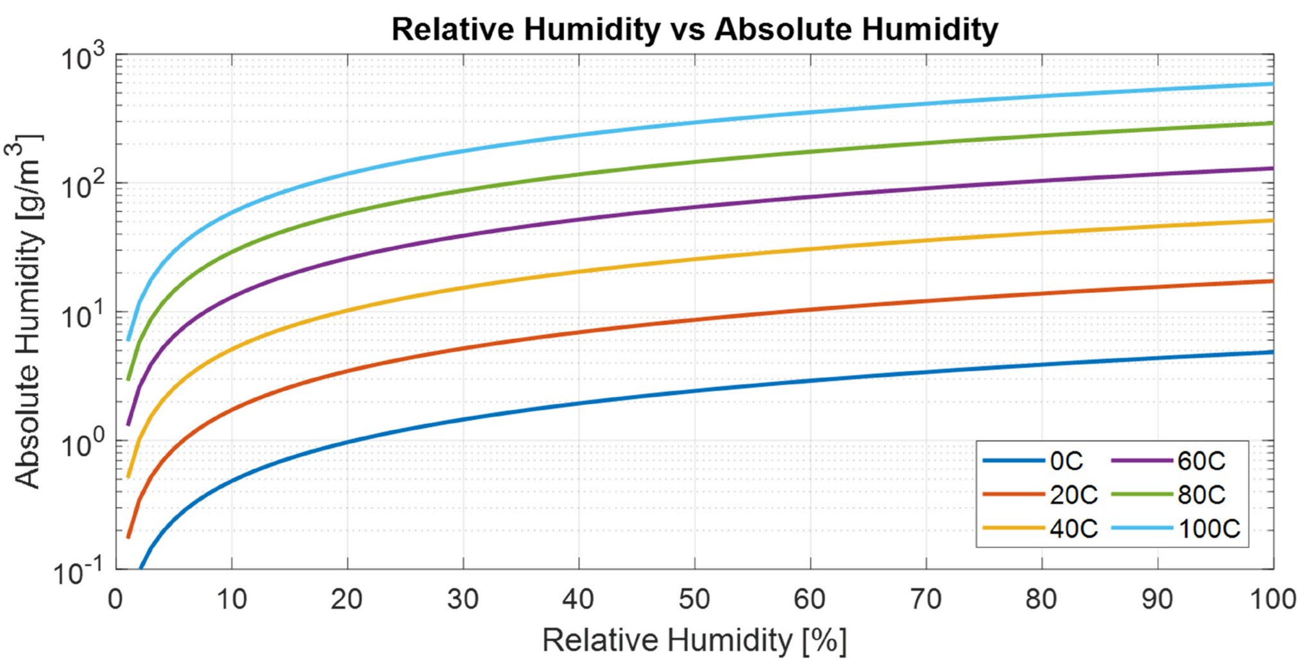

Figure 3: Relationship between relative humidity and absolute humidity at atmospheric pressure

1.3 Condensation and Dew Point

Liquid water formation due to condensation on the power module substrate or terminals poses a significant risk to device reliability. The **Dew Point (DP)** is defined as the temperature at which water vapor will condense into a liquid. In general, moisture in the air will condense onto a surface at or below the dew point of the surrounding air. Dew point is expressed in terms of temperature and several formulations are available to estimate the relationship between temperature, relative humidity, and the dew point. One such formulation is provided in equations (*5*) and (*6*). The constants *a* and *b* are 17.625 and 243.04, respectively. When combined, the complete expression shown in equation (*7*) relates temperature and RH to the dew point. It should be noted that these equations are only valid at atmospheric pressure and will differ at higher altitudes. Figure 4 evaluates equation (*7*) from 0 °C to 50 °C with relative humidity conditions from 10 % to 100 %. As the relative humidity and air temperature increase, so does the dew point temperature. At these conditions, condensation can more easily occur, increasing the risk to the module.

$$\alpha(T, RH) = \ln\left(\frac{\mathrm{RH}}{100}\right) + \frac{\mathrm{aT}}{b+T} \tag{5}$$

$$DP = \frac{b * \alpha(T, RH)}{a - \alpha(T, RH)} \tag{6}$$

$$DP = 243.04 * \frac{\ln\left(\frac{RH}{100}\right) + \frac{17.625T}{243.04+T}}{17.625 - \ln\left(\frac{RH}{100}\right) + \frac{17.625T}{243.04+T}} \tag{7}$$

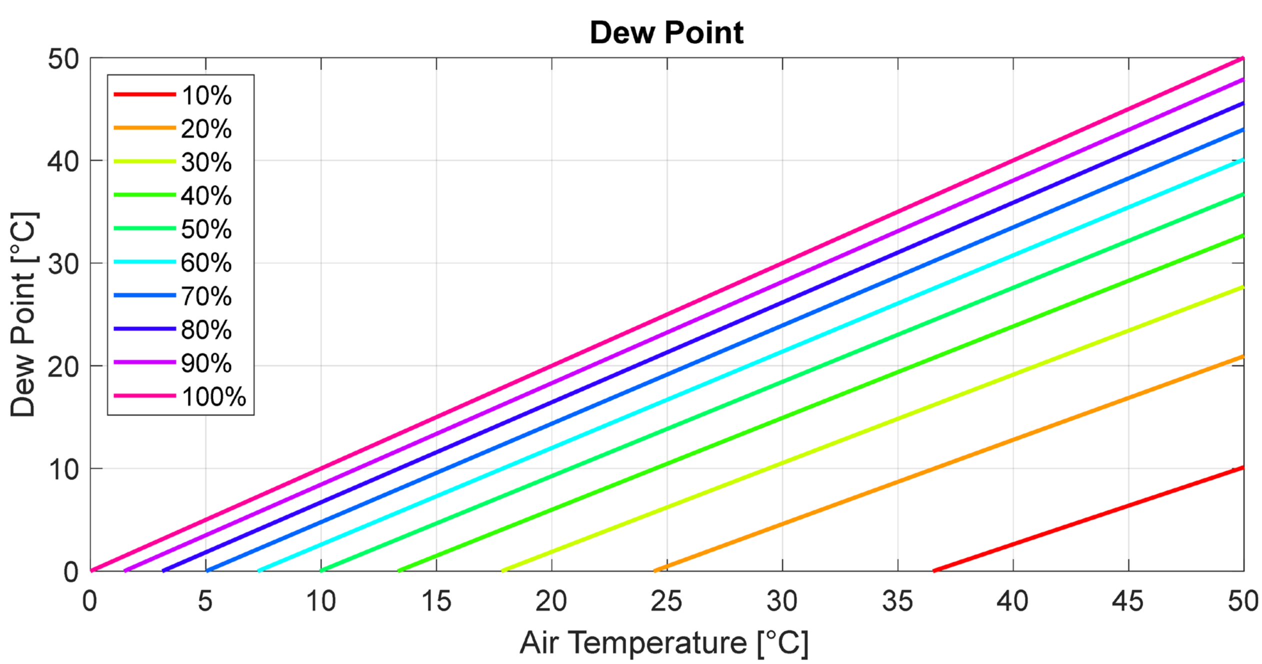

Figure 4: Relationship between air temperature and dew point relative humidity conditions between 10 % - 100 % at 1 atmospheric pressure

1.4 Standards

Currently, no widely accepted standards define a maximum allowable condition for the environment in which semiconductor power modules can operate. However, IEC 60721-3-3 provides guidance on climatic conditions within which general electronics devices should be designed to operate. The standard defines several classes based on the operating environment of the device. One such class, Class 3k22, applies to temperature-controlled enclosed locations with no humidity control, which is a common operating environment for power modules. Class 3k22 defines an air temperature between 5 °C to 40 °C, an absolute humidity between 1 g/m^3 to 25 g/m^3, and a relative humidity between 5 % to 85 %. This region of operation is defined by the dashed gold boundary in the climatogram provided in Figure 5. In terms of temperature, power modules are often designed to operate well beyond this range. An alternative operating region between -40 °C to 85 °C (with the lower limit of AH reduced to 0.05 g/m^3) is defined by the solid purple boundary.

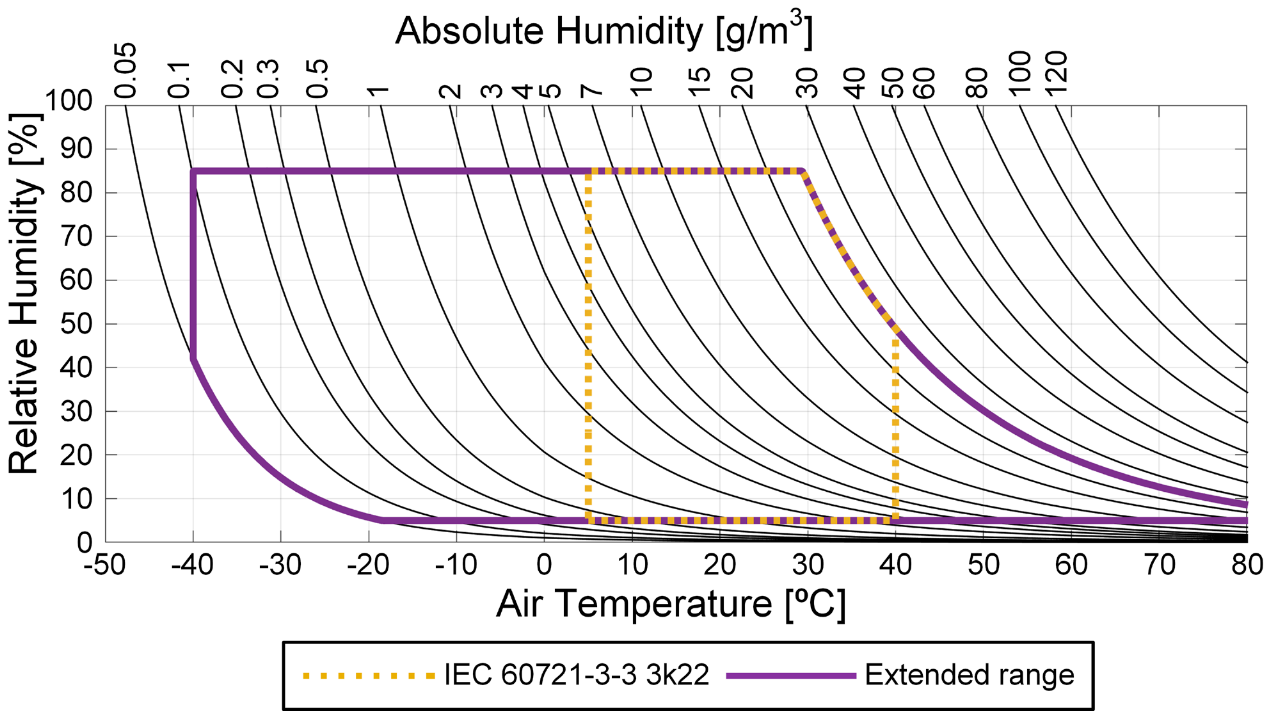

Figure 5: IEC 60721-3-3 3k22 short-term environment range climatogram

2. INFLUENCE ON CASE MODULES

As mentioned, moisture can cause detrimental effects to the reliability and lifetime of the module and can cause premature failures. The mechanisms by which moisture collects within the module and how the failures or degradations occur vary. In general, degradation occurs near the semiconductor chips within the silicone gel. The silicone gel contains diffused air, and water molecules can propagate through the silicone gel over time, as shown in Figure 6. Moisture can then cause several problems that can lead to a sudden device failure through the following mechanisms:

Dielectric Breakdown: During operation, moisture will accumulate in the silicone gel. When the load decreases and the heatsink cools, the moisture-carrying capacity of the diffused air within the gel will also decrease. Some moisture will diffuse back into the surrounding air, but some will also adhere to the cool substrate and semiconductor chips of the module. The water molecules will then align with the electric field due to their polarity and decrease the blocking voltage of the device at the chip edges, which may result in a sudden device failure.

Corrosion: Breakdown of the semiconductor chip passivation is a well-known failure mechanism for power modules [4]. Moisture on the module substrate in conjunction with high voltage biases results in corrosion at metallic interfaces within the module, distorting the electric field and increasing leakage current [5]. Module reliability with respect to corrosion is typically measured using high-humidity, high-temperature, high-reverse-bias (H3TRB) testing. This testing accelerates the penetration of moisture into the gel and operates at up to 80 % of rated blocking voltage to study the long-term aging.

Void Formation: A lesser-known failure mechanism is the formation of gas bubbles or voids within the encapsulating gel. This occurs when moisture condenses on the module substrate and then expands into gaseous water vapor, exerting pressure on the encapsulant and creating a void within the silicone gel [6]. Without the high dielectric strength of the protective encapsulant, the affected areas may be unable to block voltage, increasing the risk of device failure. While uncommon, this phenomenon has been documented in within a SiC power module encapsulant [7].

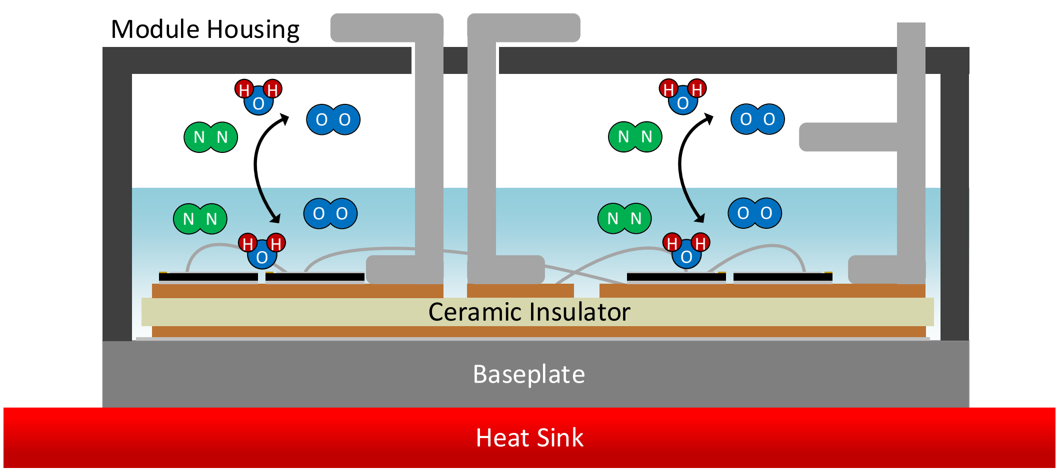

Figure 6: Diffusion of air and water vapor into and out of silicone gel encapsulant

2.1 Embedded Sensor Testing

In general, the temperature and moisture content of an encapsulant will reach equilibrium with the surrounding environment through diffusion. However, the rate at which diffusion occurs within an encapsulant is not well understood. To observe the diffusion rate of an encapsulated power module, two CAS175M12BM3 power modules with two embedded temperature sensors and two embedded relative humidity sensors were built. A picture of the assembled modules is shown in Figure 7. The sensors are mounted on the substrate region near the die and submerged in the silicone gel. The sensor leads protrude from the top of the gel for measurement purposes. The temperature sensor (TS-TMP37) is capable of measuring temperatures from -40ºC to 125ºC, and the relative humidity sensor (HIH-5030) is capable of measuring relative humidity between 0% to 100%. The integrated sensor of the HIH-5030 is covered with a hydrophobic filter which allows it measure relative humidity while submerged in silicone encapsulant. These sensors are capable of measuring the range of temperature and relative humidity of the environments in which the modules are operated.

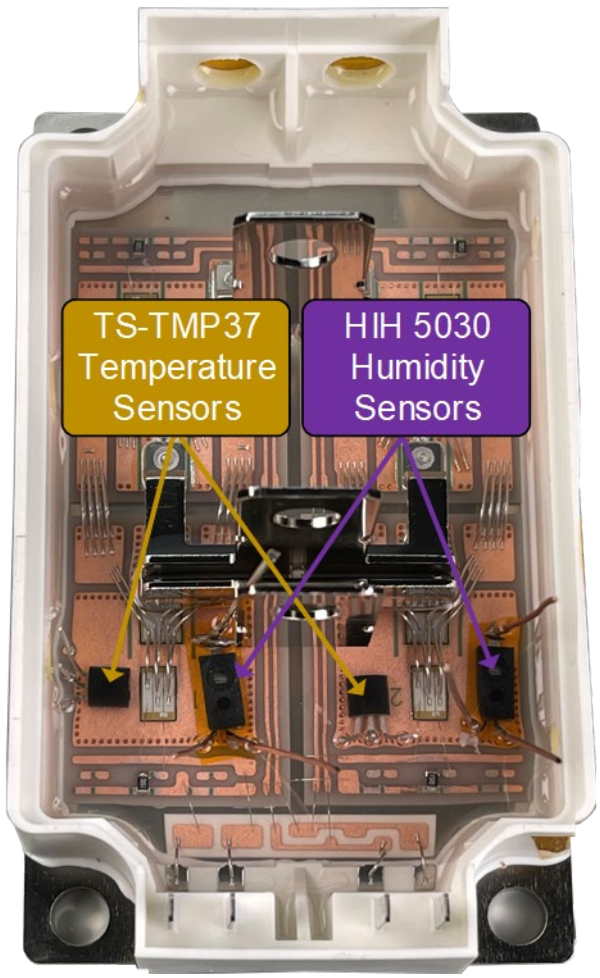

Figure 7: Encapsulated CAS175M12BM3 module with embedded temperature and RH sensors [6]

The CAS175M12BM3 power modules with the embedded sensors were placed inside an environmental chamber that can precisely control relative humidity and temperature. A picture of the modules inside the environmental chamber is shown in Figure 8. The modules were mounted to a cold plate to allow for sub-ambient cooling. An HTM2500 temperature and humidity probe was placed inside the chamber to measure the conditions during testing. Measurements of each sensor were collected every seven seconds using a Keithly DMM6500 digital multimeter. The individual sensor measurements within the gel were averaged to produce a final result.

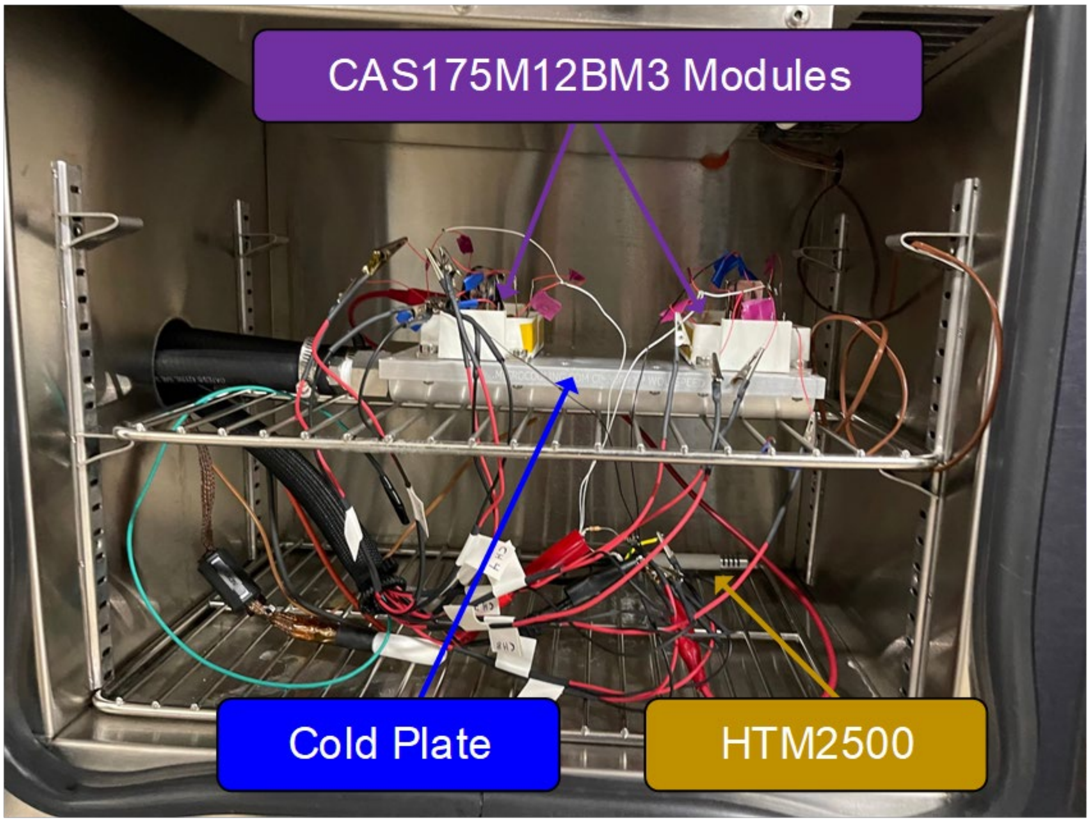

Figure 8: Environmental chamber setup with CAS175M12BM3 power modules mounted to a cold plate [6]

Using this configuration, two tests were performed. For the first test, the chamber temperature and relative humidity were increased to 35 °C and 70 %, respectively, for 40 hours before being returned to ambient conditions. These conditions represent potential weather conditions in humid climates during the summer months. No coolant flowed through the cold plate during this testing. The measurement results in Figure 9 show that the gel responds very slowly to changes in environmental moisture; the initial increase from 20 % RH to 55% RH takes 10 hours, and only a small increase (<10 %) occurs between 10-40 hours. On the other hand, the temperature of the gel responds much faster, and reaches the environmental conditions after only one hour. One consequence of this is that the module may change temperatures quickly in response to environmental changes while retaining moisture from the prior condition. This can be observed in Figure 9 when the chamber temperature and humidity return to ambient conditions; the RH of the gel momentarily spikes above the RH of the chamber due to its decrease in temperature. The increase in RH above the ambient conditions represents a risk of condensation that could be caused by rapid changes in weather or by transitioning from an outdoor to an indoor environment. However, these risks are low, and assume that the module is in a low-load condition.

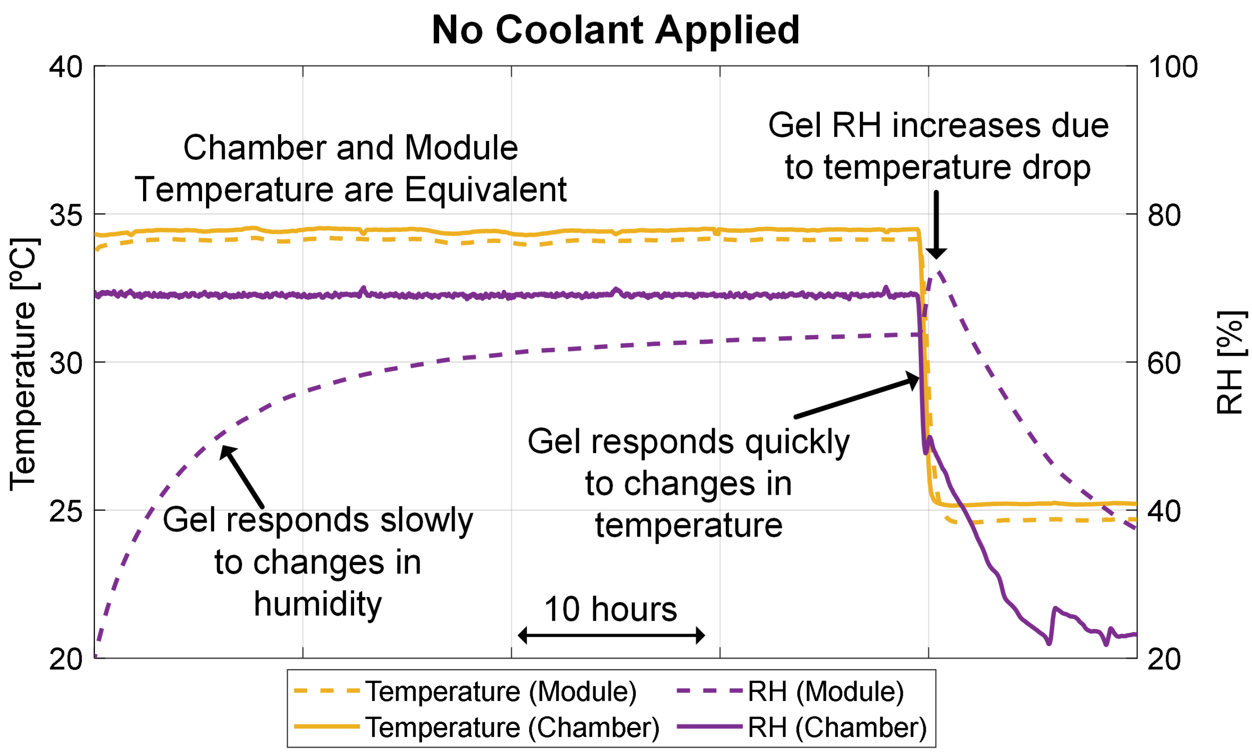

Figure 9: Module gel response to 35 °C, 70 % RH with no coolant applied [6]

For the second test, the chamber temperature and relative humidity were again increased to 35 °C and 70 %, respectively, for 40 hours. However, 25 °C coolant flowed through the cold plate during this test. The results in Figure 10 show a significant difference in the response of the gel with the coolant applied. First, the gel temperature remained close to ambient throughout the test, as expected. Second, because the module is cooler than the ambient air, the gel RH increases rapidly, and exceeds the relative humidity of the chamber after only five hours. By the end of the 40-hour soak, the module RH is near condensation, at around 95 %. However, the sudden decrease in chamber temperature during the return to ambient conditions causes the RH of the module to reach 100 %, where condensation occurs.

This testing demonstrates that sub-ambient cooling significantly increases the risk of condensation forming on power modules. In addition, it shows that the encapsulant is not susceptible to short-term moisture accumulation. However, if modules are operating at low-load conditions with sub-ambient cooling for prolonged periods, the moisture inside the gel can become excessive and increase the risk of failure.

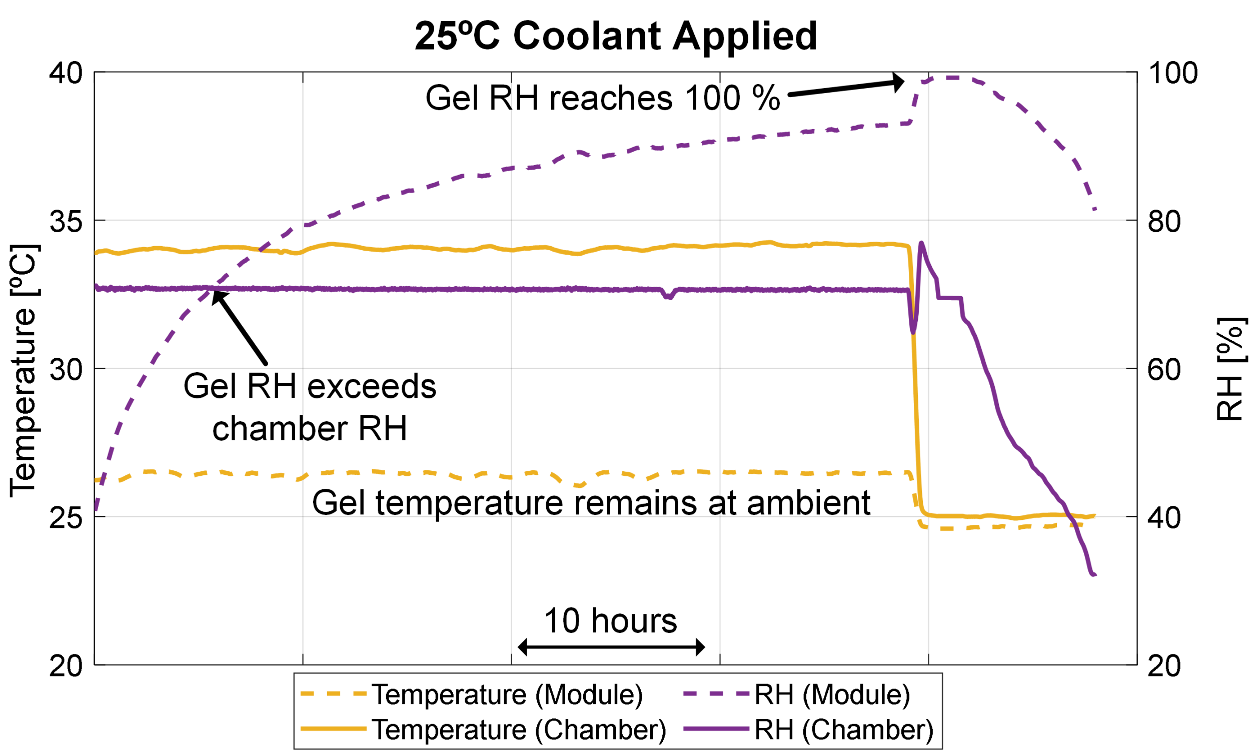

Figure 10: Module gel response to 35 °C, 70 % RH with 25 °C coolant applied [6]

2.2 Device Failure Example

Figure 11 demonstrates a device failure due to moisture-induced void formations. Several case modules were placed on a cold plate at 30 °C in a chamber at 85 °C with 85 % relative humidity. Figure 12 shows one such module with visible condensation that has accumulated on the module terminal surfaces. During this condition, water molecules can condense on the substrate inside the module, shown in Figure 11 (a). However, this moisture is not visible on the substrate or semiconductor chips. The modules were then removed from the chamber and subjected to a heavy load condition. As the substrate heats up, the water evaporates and forms small cavities of water vapor at nucleation sites on the substrate that appear as bubbles within the gel, shown in Figure 11 (b). If the amount of moisture, change in temperature, or duration is excessive, the cavities can completely remove the protective gel from the surface of the die, shown in Figure 11 (c). In this condition, premature failure of the module is much more likely during operation.

The mechanism of this failure relates to the rapid change in states between the high-humidity, cool condition in Figure 11 (a) and the sudden change to the low-humidity, high-temperature conditions in Figure 11 (b) and (c). This testing simulates a common scenario in systems where a module rests in an inactive state for several hours before a heavy load is applied. Techniques to mitigate this issue are discussed in Section 3.

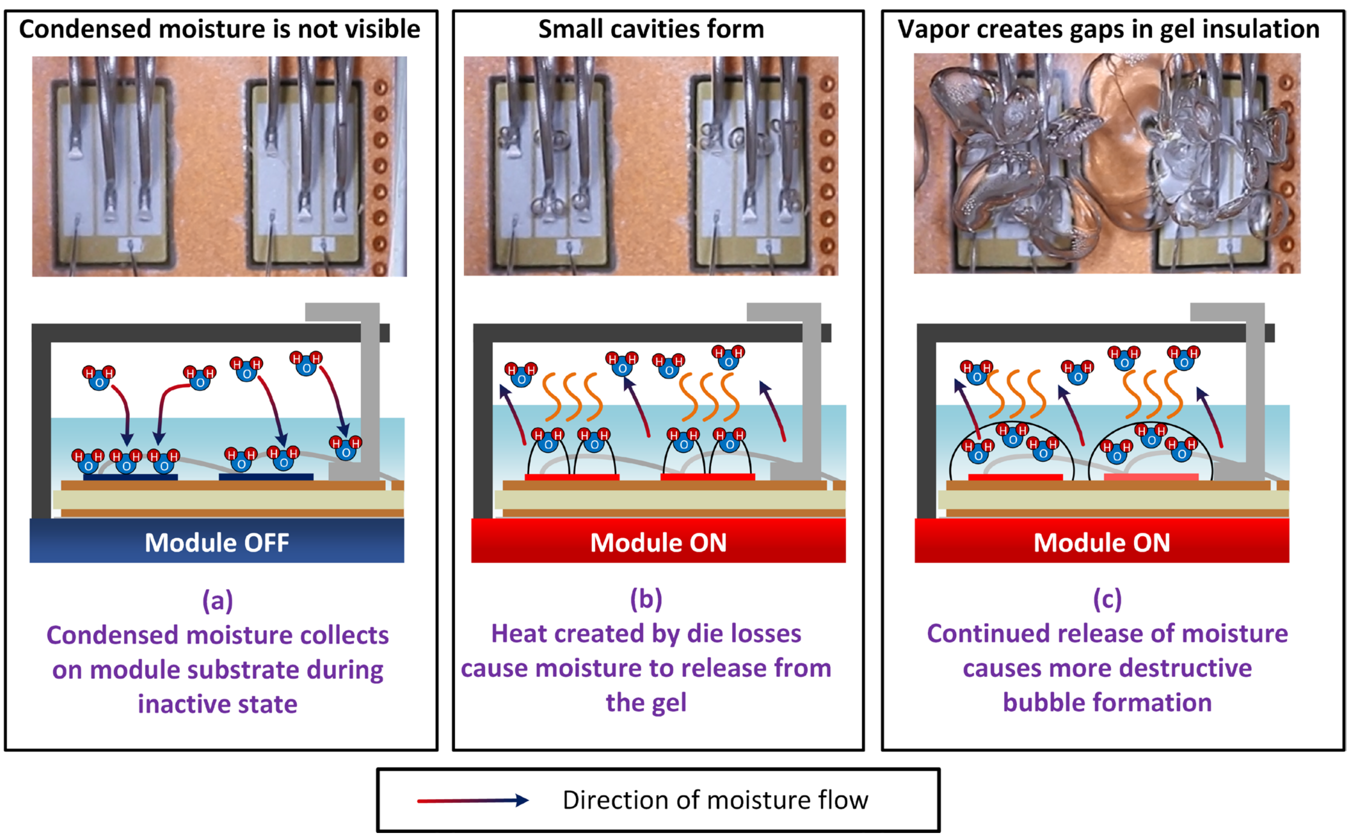

Figure 11: Example of water vapor bubble formation within silicone gel

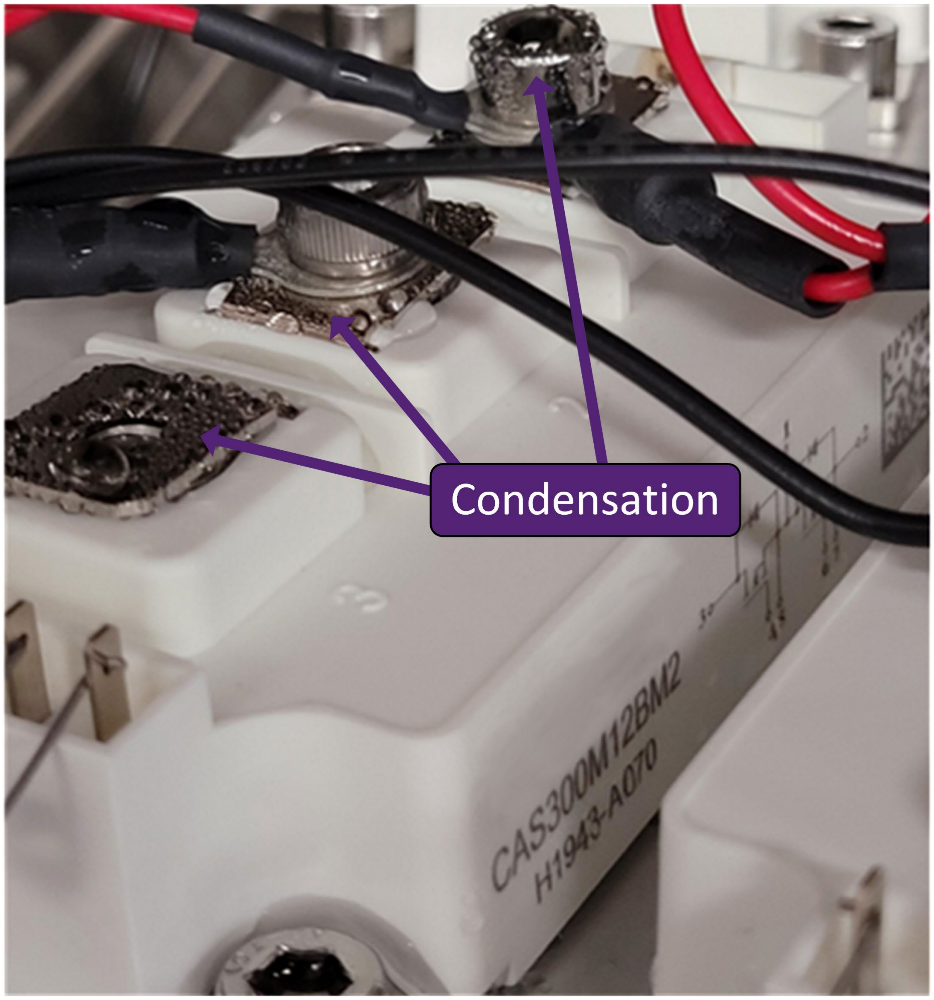

Figure 12: Accumulation of condensation on power module terminals when attached to a cold plate

3. MITIGATION TECHNIQUES

Several techniques may be employed to minimize or reduce the risk of device failures and aging due to moisture. These include climate-controlling the operating environment, limiting the minimum coolant temperature, considering sudden changes in load conditions, removing voltage from the DC terminals during inactive periods, and employing drying techniques when moisture has accumulated on or in the module. These techniques will each be described in the following sections.

3.1 Operating Environment

Climate-controlling the environment surrounding the module with heaters or dehumidifiers can work to reduce relative humidity. While this is the most effective method, it comes with several disadvantages. First, it can only be employed in a hermetically sealed enclosure, which is not applicable or practical to implement for many systems. Second, it increases the system complexity significantly by requiring specialized sealed cabinets, climate-control equipment, and humidity/temperature sensors. However, if implemented correctly, a climate-controlled system can greatly improve the lifetime of the module and reduce the need for other mitigation techniques. In general, the relative humidity should not exceed 85 %, especially at temperatures 85 °C and above. For additional precautions, limit the absolute humidity to 25 g/m3 per the IEC 60721-3-3 3k22 standard from Figure 5.

3.2 Liquid Cooling

A primary cause for moisture retention within the modules is the coolant temperature during light-load conditions. **At a minimum, the coolant temperature should never be lower than the dew point of the surrounding air**. Ideally, ensuring that the temperature of the heat sink does not fall below the enclosure air temperature will provide an additional buffer against condensation. Temperature and/or humidity sensors within the enclosure can be used to create a closed-loop control system with the coolant heat exchanger to ensure that this condition never occurs. In environments with rapid changes in the surrounding moisture, a heating element can be added to the coolant loop to increase the coolant temperature when necessary. While this increases the system complexity, it is crucial that moisture does not condense on the module, or failures such as the failure mode described in Figure 11 can occur. Surrounding equipment may also drip moisture onto the module if the equipment's temperature falls below the dew point. If a module is exposed to condensation or high-humidity conditions for several hours, drying techniques such as those discussed in Section 3.5 can be employed.

3.3 Operating Conditions

A primary cause of moisture build-up within a power module is the presence of large temperature differentials between the module and the surrounding air. Changes in the day/night cycle, load conditions, inactive periods, and fault conditions can all lead to sudden changes in temperature and humidity that can produce condensation. For example, consider the operation sequence described in Figure 13. The module begins in an inactive state, in which the heat sink and module are at a similar temperature to the enclosure air. The module then begins operation under heavy load and rapidly increases the temperature of the heat sink, the module, and the surrounding enclosure air. During this state, moisture within the module may transfer out of the silicone gel into the enclosure. After some time, the module enters another inactive state, in which the liquid coolant rapidly decreases the temperature of the heat sink to its initial set temperature. However, the heat sink and module cool much faster than the surrounding air, and a temperature differential occurs between the surrounding air and the module. Because the module is cooler than the surrounding air, there is a risk of condensation in this state. Reducing temperature differentials and the occurrence of rapid changes in operating states is important for mitigating the risk of moisture. Primarily, when operation changes from a heavy load condition to a light or no-load condition, it is important to keep the module from cooling below the ambient enclosure temperature.

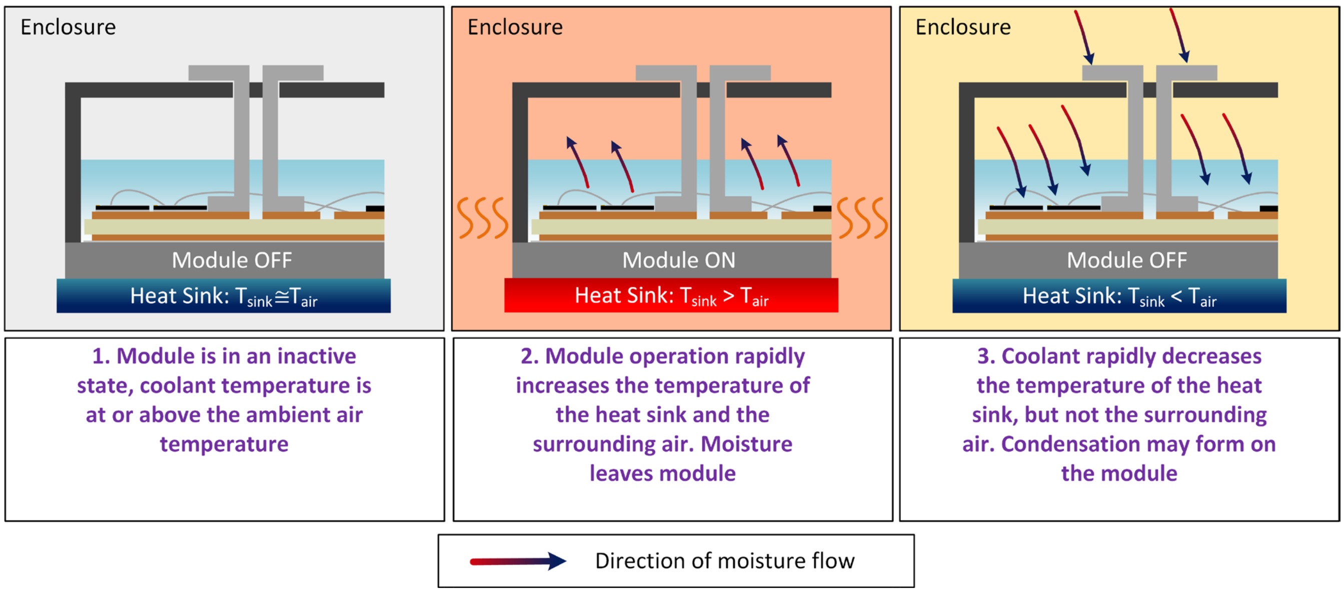

Figure 13: Example of condensation risk due to system operation and temperature change

3.4 DC Voltage Removal

Corrosion of the semiconductor metallization is caused by the simultaneous presence of moisture and high voltage biases. In applications where modules have long periods of inactivity, disconnecting the DC bus voltage can extend the lifetime of the module by reducing long-term corrosion effects. Because modules are most likely to retain moisture during inactive periods, discharging the DC voltage during these times will greatly reduce the time spent in high-voltage, high-moisture conditions. However, implementing a system to discharge the bus during these periods will increase system complexity, and may stress other components in the system due to cycling of the electric field.

3.5 Moisture Removal

Moisture accumulation most often occurs during light-load or inactive conditions during which the module temperature is low. When the system resumes operation, rapid changes in temperature and strong electric fields in conjunction with high moisture content will accelerate module degradation and increase the risk of failure. In situations where modules have been exposed to high humidity in a light-load or inactive state for several hours, it is recommended to remove moisture within the module before applying high voltage. This can be achieved with module cabinet heaters or by increasing the coolant temperature to above the ambient air temperature until the moisture content has been reduced.

While desiccants can also be used to remove moisture, they are not practical for systems during operation as they will quickly saturate in an open environment. However, when transporting modules or systems in high-humidity environments, they can be used to reduce the humidity of the sealed packaging and reduce module moisture accumulation during the inactive period.

4. SUMMARY

If not properly managed, moisture can significantly reduce the lifetime and reliability of gel-encapsulated power modules through corrosion, reduction of dielectric strength, or void formation within the encapsulant. Mitigating moisture in both its gaseous and liquid states is critical for extending module lifetime and preventing premature failures. Understanding the relationship between temperature, absolute humidity, and relative humidity yields several opportunities for mitigation techniques that can be implemented at the system level. This document provides the equations necessary to calculate these relationships and describes several mitigation techniques with regards to moisture. Most critical for preventing significant moisture accumulation within the module is to ensure that the module temperature remains higher than the dew point, the temperature at which condensation will occur.

Revision History

Date	Revision	Changes
July 2022	1	Initial Release
September 2023	2	Added embedded sensor moisture and humidity testing

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