Application Note

How to Debug RH Accuracy Issues in RH Sensors

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ABSTRACT

Relative Humidity (RH) sensors are powerful tools for capturing environmental data, however they differ significantly from other integrated circuits (ICs) and sensors types. Capacitive-based RH sensor ICs feature an open-cavity package, where the sensing element is directly exposed to the environment. This exposed sensor consists of two key components: a topside polymer layer and an underlying electrode. The polymer acts as the dielectric material for the capacitor. As moisture in the air is absorbed by the polymer, its relative permittivity changes, resulting in a measurable change in capacitance at the electrodes. This change is then internally translated to a RH output.

Due to their unique die and package construction, capacitive RH sensors require careful handling and specific guidelines to maintain their specified accuracy over time. This application note details common issues that can arise when using RH sensors, outlines methods to prevent typical sources of measurement errors, and offers techniques to mitigate performance degradation.

Communication interface issues (for example, I²C errors) and RH results from specific chemical effects are outside the scope of this document.

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1 Introduction: Why RH Sensors Appear *Out-of-Spec*

When working with RH sensors, users can occasionally observe accuracy deviations that exceed the datasheet specifications due to external factors such as environmental conditions or incorrect handling. While these sensors are designed to operate within specified RH accuracy limits, certain factors can cause the reported RH values to drift above or below the expected range. Identifying and resolving such deviations requires a systematic approach, beginning with how the sensor is integrated into the system, followed by the manufacturing process, and finally evaluating conditions in the end-use environment.

Identifying and resolving such deviations requires a systematic approach of three phases:

1. Identifying the RH errors and determining when the errors are being introduced in the production & deployment cycle.
2. Determining the source of the RH error, and understanding the impact on the performance of the RH sensor.
3. Understanding the potential root cause of the RH error source, so that the effects can be prevented or mitigated.

This document is structured to support iterative or stage-specific troubleshooting. Users are encouraged to navigate to sections relevant to the current design phase or observed issue for targeted guidance on diagnosing, preventing, and mitigating RH accuracy deviations.

1.1 Where and When do RH Errors Occur?

Figure 1-1 shows a typical design-to-deployment flow, starting with evaluation on an EVM and ending in the final application use case. At each stage in this flow, RH accuracy errors can be introduced. To effectively troubleshoot root cause for RH accuracy errors, TI recommends beginning by identifying the stage at which the error first appears, then tracing the issue backwards. For example, if RH accuracy errors are detected during evaluation with an evaluation module (EVM), then the errors must be related to environmental effects, heating effects, chemical exposure, or incorrect prototype/production testing methodology. This is because the EVM offers a known good PCB design and assembly process.

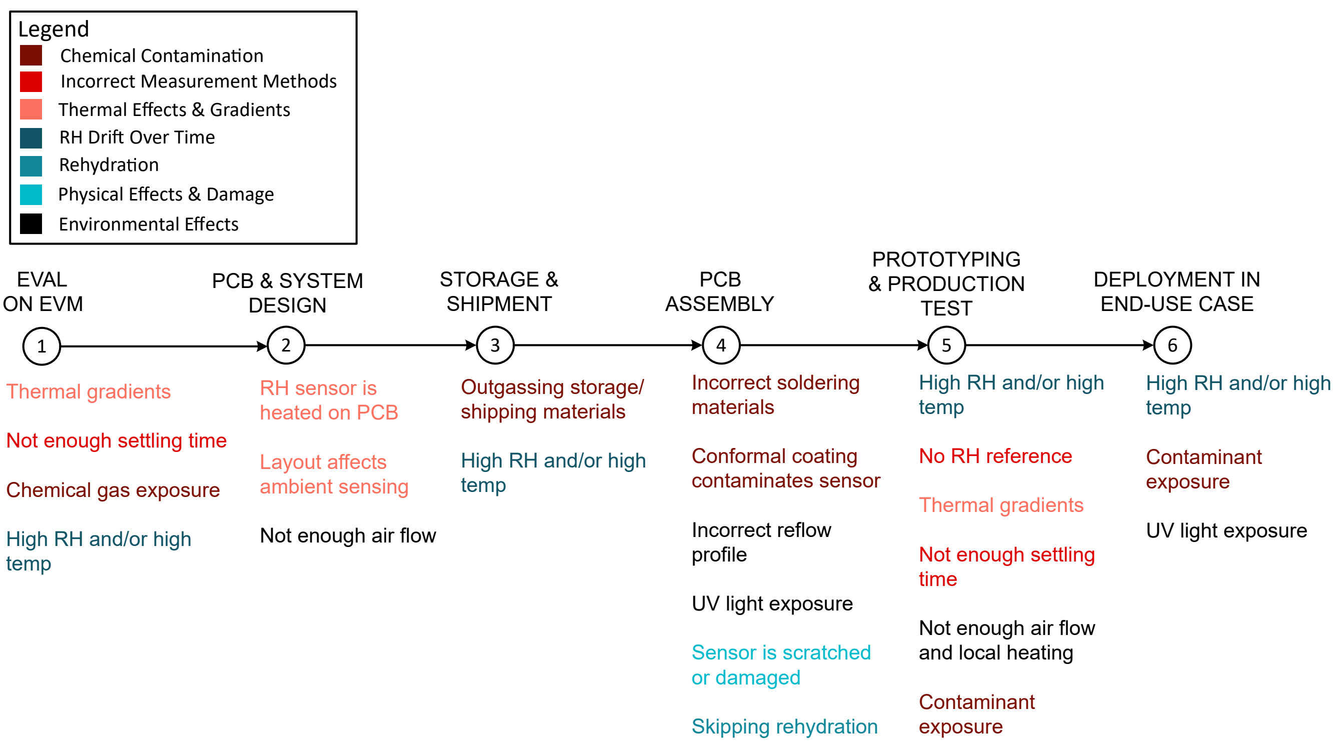

Figure 1-1. RH Sensor Design Example Timeline

The different sources of RH error are color coded in Figure 1-1, and are discussed further in the following sections of this document:

- Chemical contamination is discussed in Assembly, Soldering, and Manufacturing Processes, Storage and Handling, and Chemical Contamination.
- Incorrect measurement methods are discussed in Test Setup and Environment.
- Thermal effects and gradients are discussed in PCB and Enclosure Design Considerations, Storage and Handling, and Test Setup and Environment.
- RH drift over time is discussed in Storage and Handling and Operating Conditions: Application Environment Conditions and Effects
- Rehydration is discussed in Rehydration Post-Assembly
- Physical effects & damage are discussed in Assembly, Soldering, and Manufacturing Processes, Storage and Handling, and Chemical Contamination.
- Environmental effects are discussed in PCB and Enclosure Design Considerations, Assembly, Soldering, and Manufacturing Processes and Operating Conditions: Application Environment Conditions and Effects.

1.2 What are the Root Causes of RH Errors?

The Fishbone Diagram in Figure 1-2 provides a root-cause perspective on the most common sources of RH accuracy errors. Reading the diagram from left to right, the error sources are arranged according to category of error, several of which can occur at multiple points in the production process. For example, thermal effects on the RH sensor can occur during testing stages if temperature is not uniform in the test chamber, but also can occur due to the PCB design.

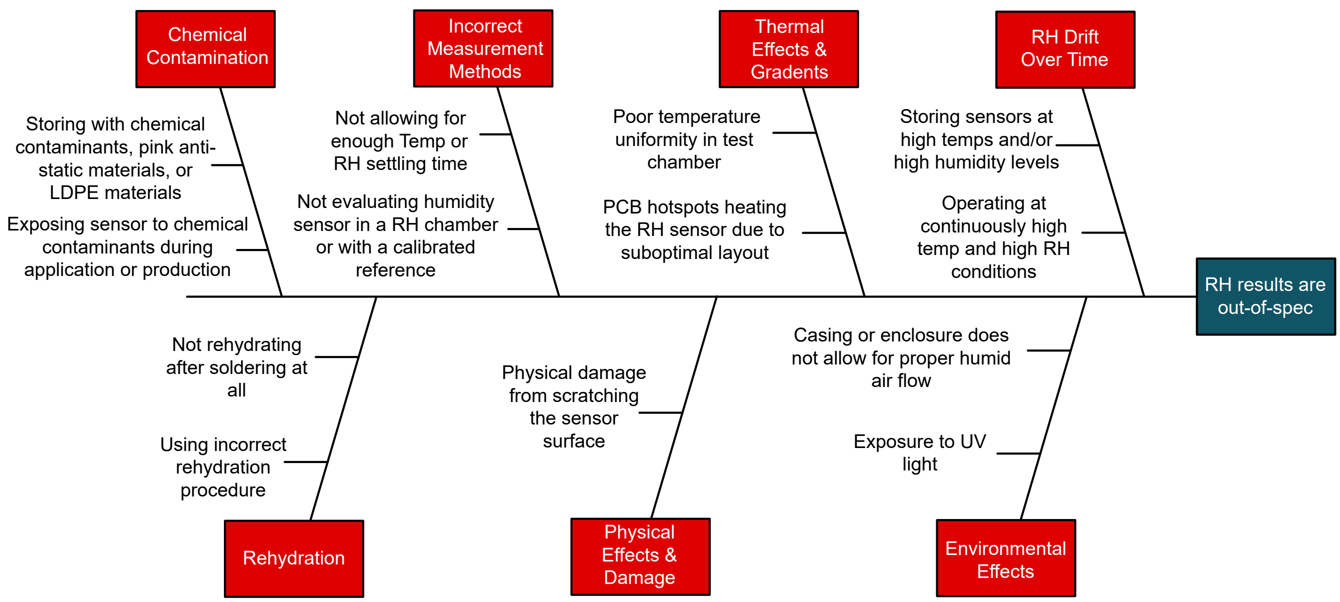

Figure 1-2. Common Root Causes of RH Error

This document categorizes these error sources into different stages of the development, production and application as well, to help users understand where the errors can occur. Furthermore, this document provides a few case studies as examples to illustrate the RH accuracy debugging process, along with a flowchart in Figure 4-11 to help guide users to a root cause.

This document examines each of the seven primary error sources in three key ways:

1. The potential impact on RH accuracy.
2. Strategies to prevent occurrence.
3. Methods to mitigate effects when prevention is not feasible.

1.3 Case Studies

This application note concludes with an appendix presenting three case studies that demonstrate how the outlined principles can be applied in practice. Each example begins with an RH accuracy issue of unknown origin. Through systematic analysis using the methods described in this guide, the root cause was identified and addressed. The selected case studies represent a range of complexities to highlight that while some RH accuracy issues are simply resolved, others require more extensive investigation and design modifications.

- **Case Study 1:** A user observed a consistent positive RH offset of approximately 3.5% RH, pushing the sensor outside of datasheet limits. The issue was later isolated to parts sourced from a specific PCB manufacturer. Root cause analysis pointed to the assembly process, due to sensor storage conditions at that facility. The affected sensors were successfully recovered through a controlled baking procedure, restoring them to datasheet specifications.
- **Case Study 2:** In an outdoor installation, users found that RH sensors initially performed as expected, but over time were unable to report 100% RH during high-humidity conditions. The maximum reported RH gradually declined, suggesting a degradation in sensor performance due to prolonged exposure to saturated environments.
- **Case Study 3:** In a gas sensing application, a customer tested two RH sensor products (HDC2021 and HDC3021) on an old PCB design and a new PCB design. The HDC2021 reported correct RH results, while the HDC3021 reported incorrect RH results. Investigation revealed that both chemical contamination and PCB layout errors contributed to the issues affecting all parts, with opposing effects masking the full extent of the RH error in the sensors.

2 Definitions: Key Terms for RH Accuracy

This section defines key terms for discussing RH accuracy. Understanding the concepts presented in this section is critical to being able to evaluate, diagnose, prevent, and mitigate RH accuracy errors with the methods presented in Section 4 of this document.

- Sensing Polymer: capacitive-based RH sensors utilize an exposed polymer to capture moisture in the air. This captured moisture fills voids in the polymer, which alters the dielectric constant of the polymer. This change in dielectric constant creates a change in capacitance for the sensing electrode beneath the polymer. Temperature and humidity conditions can also affect how the polymer senses humid air, along with other unwanted components such as other chemicals. Figure 2-1 shows a simplified sensor structure, with the polymer acting as the media which captures moisture from the air.

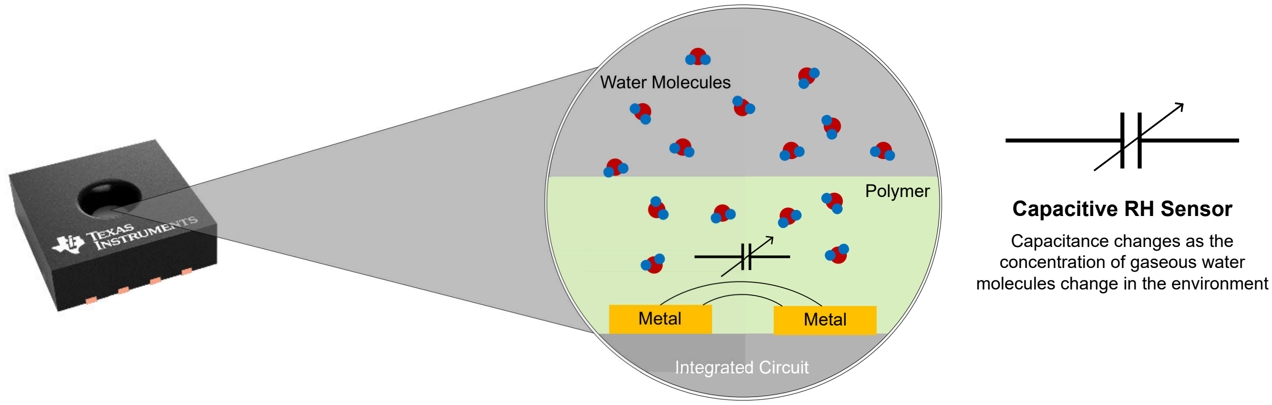

Figure 2-1. Sensing Polymer Example

- **RH Error**: the difference between the RH sensor's humidity measurement and a calibrated reference.
- **RH Hysteresis:** the difference between the *up curve* (RH error as ambient RH increases) or *down curve* (RH error as ambient RH decreases) and the centered average of the up and down curves. Positive RH hysteresis is the gap between the centered average and the down curve, negative RH hysteresis is the gap between the centered average and the up curve. Hysteresis occurs because the sensing polymer has a memory of the humidity conditions this has seen before. Hence the RH sensor's RH error will be slightly negative when previously exposed to low RH conditions, and slightly positive when previously exposed to high RH conditions. The exact shape of the RH hysteresis can change with different ambient temperatures. Figure 2-2 shows two different views of the "up & down" curves, one for RH error vs reference RH ,and the other shows measured RH vs reference RH.

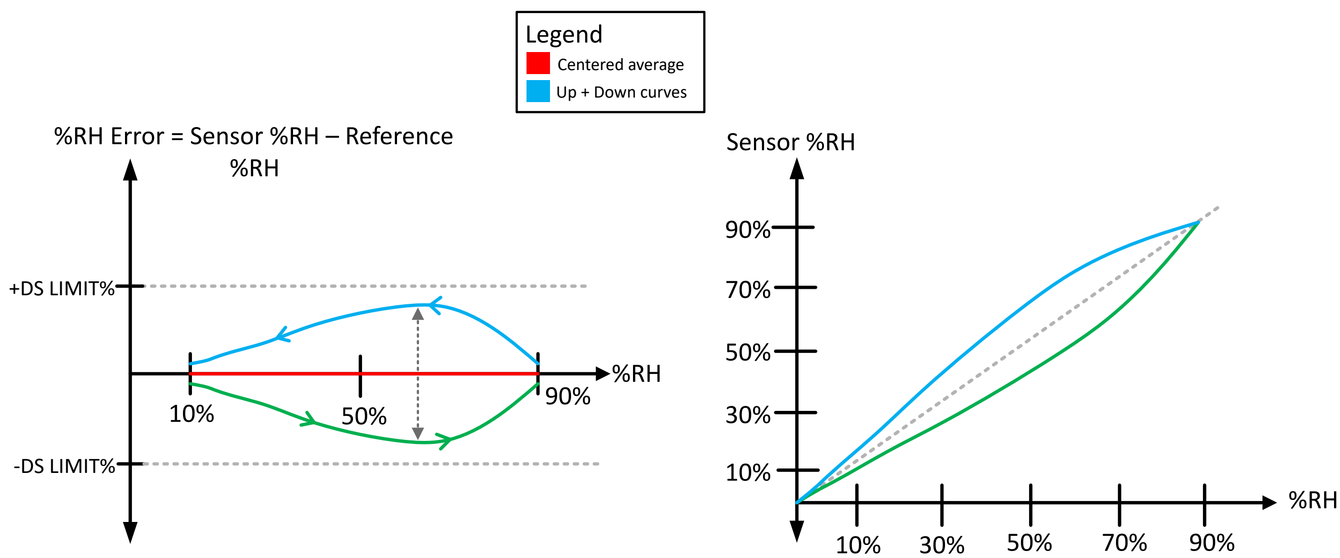

Figure 2-2. RH Hysteresis Example

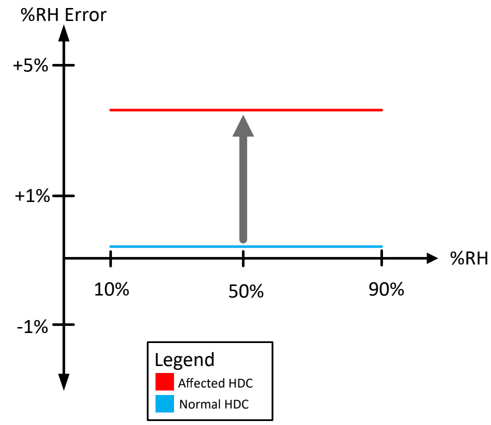

Figure 2-3. RH Offset Error Example

- **RH Offset**: refers to a positive or negative shift in RH error that is constant over different ambient RH levels and temperatures. Figure 2-3 demonstrates how %RH error can flatly increase across RH levels.
- **RH Gain**: refers to a shift in RH error that is not constant over humidity; for example, a positive RH gain may have low RH error at low humidity and a high RH error at high humidity, while a negative RH gain may have high RH error at low humidity and low RH error at high humidity. Figure 2-4 shows two examples of RH gain. On the left is an example of negative RH gain, and on the right an example of positive RH gain. Note how at low RH levels the effects of gain shift can be minimal, but as RH increases the effects become more pronounced. In many real-world cases, RH offset and RH gain can be combined.

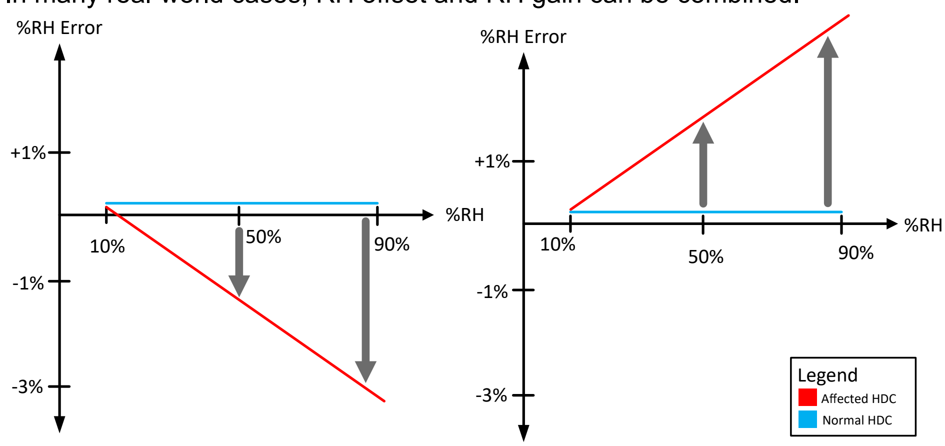

Figure 2-4. RH Gain Error Example

- **VOCs:** Volatile Organic Compounds. VOCs are organic chemicals, often human-made, that have a high tendency to vaporize into the air, otherwise known as "off-gassing". VOCs can negatively impact RH accuracy by interfering with the normal operation of the sensing polymer. Because VOCs can vaporize into the air at ambient conditions, they are a common source of chemical contamination for polymer based humidity sensors.
- **MSDS**: material safety data sheet. The MSDS for a given product (for example, a particular conformal coating, shipping foam, solder paste, and so on) can detail most if not all of the chemicals in the product. Obtaining and reading the MSDS is key to avoiding potential chemical contaminants, so that user's can choose products that minimize impact to RH accuracy.
- **SEM:** Scanning electron microscopy. Used to take high resolution images of sensing polymer, can be useful in identifying deposited chemical contaminants
- **EDX:** Energy dispersive X-ray spectroscopy. A failure analysis technique that shows the chemical composition through spectroscopy of a spot on the sensing polymer. Very useful to determine the nature of a chemical contaminant. This is considered destructive failure analysis because of the thin layer of metal deposition required, so no further RH testing can be done on a unit that undergoes EDX.

3 Initial Troubleshooting Steps

Before attempting to diagnose or improve the RH accuracy of a sensor, it is essential to first confirm that an actual RH accuracy issue exists. While this document focuses on systemic and environmental factors that affect RH accuracy, these initial verification steps are critical to rule out basic functional or setup issues. These verification steps can save users time by identifying that the issue was not humidity accuracy but something else.

3.1 Initial Verification Steps

1. **Perform an A-B-A Swap:** Replace the suspected sensor with a known-good unit, following all soldering precautions. If the issue persists on the same PCB, the root cause is likely related to the board or system integration. If the issue follows the sensor, the device itself may be at fault. This method is commonly referred to as the A-B-A Swap Method (see Guidelines for Returns).
2. **Check for Proper Decoupling:** Ensure a decoupling capacitor is placed as close as possible between the sensor's VDD and GND pins. Poor power decoupling can introduce noise or instability.
3. **Inspect for Physical Damage:** Conduct a visual inspection of the sensor package and exposed cavity to identify any signs of damage, contamination, or foreign material.
4. **Verify Communication:** Use the provided TI code examples on *ASC Studio within SysConfig* to confirm proper I²C communication and device initialization. ASC Studio is a microcontroller agnostic GUI-based code generator that will provide the desired example code. Check if pull-up resistors are installed for SDA & SCL pins.
   a. An additional sign of a digital communication error is if the %RH output from the RH sensor is flatly 100% or 0% RH paired with a temperature reading of 130°C or -45°C (125°C or-40°C in the case of HDC1x & HDC2x). This means the sensor is reporting 0x0000 or 0xFFFF, which means there is a digital communication error.

3.2 Diagnostic Questions

Once these basic checks confirm the device is operational and that a more systemic RH accuracy issue is present, the following diagnostic questions can help scope the problem and guide further root-cause analysis:

1. Is the RH error observed across all devices or only a subset?
2. Are all affected sensors from a specific lot or production group?
3. Are the accuracy errors static, intermittent, or progressively worsening over time?
4. Is the RH sensor reporting the right temperature result?
5. What form does the RH error take? Is there a consistent positive offset, a negative gain, or a combination of behaviors?
6. At what stage in the development or production process do the RH errors first appear?
7. What is the sensor's end-use environment? For example:
   a. Are sensors used indoors, outdoors, or in industrial environments?
   b. What temperature ranges are involved? What humidity ranges?
   c. Are sensors exposed to fluctuating humidity or relatively stable conditions over time?
   d. Does the ambient air to be sensed actually reach the RH sensor?
   e. Does the system allow for RH to stabilize?

Answers to the above questions allows the user to navigate through the Figure 4-11 in Section 4.8. This flowchart is intended as a guide to help users navigate to where their RH error source is coming from and allow for a faster debugging process. Once the user has identified the likely area of concern, navigate to the appropriate topic in Section 4.

4 Common Sources of RH Error - Prevention and Mitigation

This section discusses multiple common sources of RH accuracy errors in RH sensors. Each topic is broken down into subtopics where explanations, prevention strategies, mitigation methods, and best practices are discussed at length. The different sections are not ordered in terms of importance, severity, or likelihood of occurring. Instead these topics are presented in the order that they can occur during the engineering design process. They can be read in any order. This section provides the user the required tools to optimize their design and minimize unnecessary risks to RH accuracy.

4.1 PCB and Enclosure Design Considerations

RH accuracy can be significantly impacted early in the development process through unoptimized PCB layout or enclosure design. Key factors include thermal transfer through the PCB and airflow management within the enclosure, both of which influence the sensor's ability to accurately measure ambient humidity.

4.1.1 PCB Thermal Transfer to RH Sensor

Thermal energy conducted from other sources can interfere with the sensor’s ability to accurately sense ambient air temperature and RH. Local heating of the sensor causes the RH sensor's junction temperature to not match the ambient air temperature. Because RH is inversely related to temperature (at constant pressure), this causes lower reported RH values that do not reflect true ambient conditions. This effect manifests as a negative RH offset and gain error.

Common heat sources include nearby power-dissipating components and copper planes with high thermal conductivity. A general rule: for every 1°C increase in sensor temperature above ambient, RH readings can drop by approximately 3% RH (3%RH additive, not multiplicative). This value varies with ambient temperature & humidity levels, but is useful to grasp how much %RH can change due to temperature fluctuations. In systems that warm gradually after startup, RH readings will drift downward over time as local board temperature increases.

To prevent RH accuracy errors that are caused by the PCB design:

- Follow the layout guidelines in the data sheet to thermally isolate the humidity sensor.
- Avoid placing heat-generating components near the RH sensor.
- Do not route copper planes that extend to other parts of the PCB under or around the RH sensor footprint, as they can conduct heat to the device from elsewhere on the PCB.
- Do not directly expose the RH sensor to the sun or bright lights.

Figure 4-1 is an example of a PCB layout that is optimized to sense ambient humidity and temperature using the HDC3020.

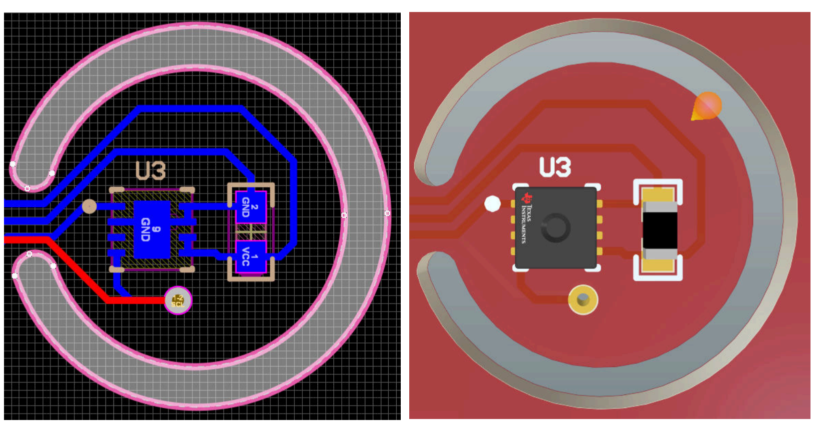

Figure 4-1. HDC3020 PCB Layout Example with Slot Cut Around HDC3020

The optimized layout example has a circular slot cut around the sensor, which prevents heat traveling through the PCB material from getting to the sensor. Heat transfers relatively poorly through air. At 25°C air has a thermal conductivity of 0.026 W/mK. Meanwhile just FR4, a common PCB dielectric material, has a thermal conductivity of 0.2 W/mK. That is a nearly 10x benefit from using PCB cutouts to thermally isolate the RH sensor.

Note there should be no copper plane beneath the sensor. Copper has a high thermal conductivity of 400 W/mK, so any shared copper plane can easily transfer heat dissipated from other components on the PCB.

Where possible, place the RH sensor at the edge or corner of the PCB, away from heat sources. A small PCB extension can further isolate the sensor and increase exposure to ambient airflow. For more guidance, see *Optimizing Placement and Routing for Humidity Sensors,* for examples of PCB design that maximize RH sensor's ability to sense the ambient temperature as closely as possible.

In Figure 4-2, the PCB designs on the left better optimize for thermal isolation because of incorporated air gaps and physical separation of the RH sensor from other components on the PCB. The PCB designs on the right side have less or no thermal isolation at all, leaving the humidity sensors vulnerable to heat sources on the PCB and hence RH errors.

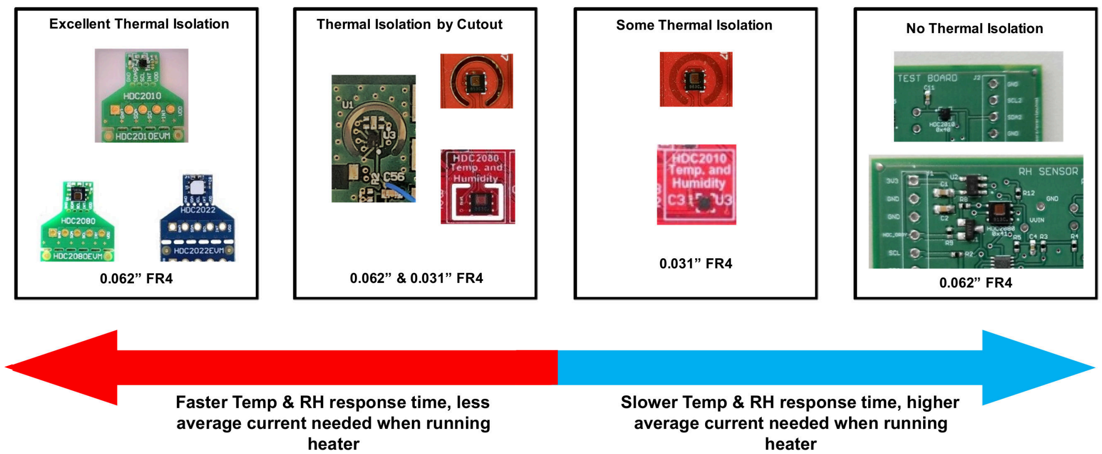

Figure 4-2. Thermal Isolation PCB Design Examples

4.1.2 Power Supply Noise and Analog RH Sensors

For analog-output RH sensors such as the HDC3120, power supply noise can introduce errors in both RH and temperature readings. This occurs because the HDC3120 is a ratiometric device, using VDD as the reference for its output DACs. Noise or ripple on the VDD line directly translates into measurement errors.

To minimize these effects:

- Place bypass capacitors as close as possible to the RH sensor's VDD pin.
- Use a clean, low-noise voltage regulator to supply VDD.
- Avoid routing VDD traces in large loops, which can act as antennas and introduce coupling.

Proper power filtering and PCB layout are essential to ensure high-accuracy analog output from RH sensors.

4.1.3 Enclosure Design & Airflow Considerations

Enclosure design plays a critical role in achieving accurate RH measurements. In many applications, the RH sensor is housed within a protective enclosure alongside the PCB to shield it from environmental elements such as water, dirt/dust, or chemicals. While this approach protects the sensor, it also requires careful attention to airflow design to ensure the sensor is exposed to ambient air and can report representative RH values.

If adequate airflow from the external environment is not established, the sensor may only sample the internal enclosure air, which can become thermally biased due to heat generated by components on the PCB. This localized heating effect reduces the measured RH, as relative humidity decreases with increasing temperature.

To minimize airflow-related RH errors:

- Include ventilation holes or air slots in the enclosure, ideally positioned as close to the RH sensor as possible.
- Avoid placing an opening directly above the sensor’s exposed cavity, as this can increase susceptibility to liquid water, dust, or chemical contaminants.
- Ensure the enclosure material and design do not trap heat or limit passive airflow across the sensor.

4.2 Assembly, Soldering, and Manufacturing Processes

Assembly and soldering processes pose significant risks to RH sensor performance, particularly because these steps are often delegated to third-party vendors or overlooked during system integration. While soldering is routine for most ICs, this represents a critical point of vulnerability for open-cavity RH sensors, and is often the earliest stage where accuracy issues are introduced.

4.2.1 Assembly Instructions: What to Avoid

Several error mechanisms can arise during assembly and every effort must be taken to avoid the following common sources of RH accuracy error during the PCB assembly (PCBA) process:

- **Thermal Stress:** Exposure to multiple high-temperature reflow cycles can lead to sensor dehydration, manifesting as a negative RH offset.
- **Chemical Contamination:** Volatile organic compounds (VOCs) from materials such as board cleaners or certain fluxes can contaminate the sensor, resulting in shifts in RH offset or gain.
- **Improper Soldering Techniques:** Use of non-recommended reflow profiles, wave soldering, or hand soldering can introduce metal particles or flux residues into the sensor cavity, degrading performance. Depositing conformal coating onto non-tape cover package options must also be avoided, otherwise the sensor cavity or filter will be smothered with the coating and the ability to sense RH will be compromised.
- **Ionic Contaminants:** Contact with ionic substances like salts or saltwater will contaminate the RH sensor and must be strictly avoided. Ionic contaminations present as a potentially large negative RH error at high ambient RH.

4.2.2 Assembly Instructions: Best Practices

To ensure proper handling during assembly, follow the detailed guidelines in the device datasheet and silicon user’s guide. Key recommendations include:

- **Assembly Sequence**
  - Mount the RH sensor as the final step in the assembly process.
- **Reflow Soldering:**
  - Always follow the IPC/JEDEC J-STD-020 standard profile with peak temperatures at 260°C.
  - Limit to one reflow pass and avoid rework.
- **A-B-A Swap Exception:**
  - If rework is necessary (e.g., for diagnostic purposes), follow these precautions:
    - Minimize handling.
    - Use a heat gun to remove the sensor cleanly, without additional flux.
    - Perform rehydration post-removal, as the sensor may have been exposed to drying heat.
- **Solder Paste and Cleaning:**
  - Use no-clean solder paste. Do not clean boards post-assembly.
  - If cleaning is necessary, use distilled water only.
  - Verify that all materials used are free of harmful chemicals (consult MSDS documentation).
  - Example: **Kester R276** is a recommended no-clean solder paste shown to be compatible with TI RH sensors.
- **Chemical Exposure Avoidance:**
  - Avoid materials that emit VOCs during baking or curing.
  - Examples of contaminants include: PCB wash chemicals, adhesives, epoxies, some conformal coatings, and outgassing byproducts.
- **UV Light Avoidance:**
  - Avoid exposing the RH sensor to UV light. UV light can damage the sensing polymer and introduce irreversible RH errors.
- **Mechanical Protection:**
  - Do not subject the sensor to high-pressure air blasts or ultrasonic cleaning.
  - Use low-pressure, oil-free dusting if needed.

- **Conformal Coating:**
  - Must not be applied directly on the sensor cavity, doing so will prevent ambient RH measurements
    - Ensure the cavity is protected during curing. Make sure to choose an conformal coating that does not outgas during or after curing to reduce the risk of gaseous chemical contamination of the RH sensor.

4.2.3 Sensor Cavity Protection During Assembly

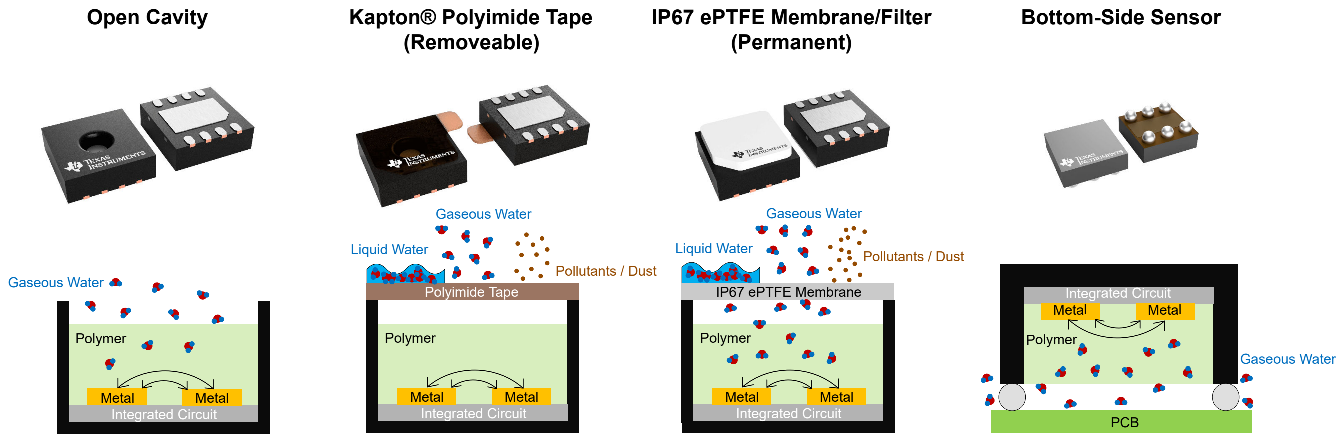

Figure 4-3. Different Package Options for HDC3x

Figure 4-3 illustrates how the polyimide tape protects the HDC3021 and how the IP67 rated filter protects the HDC3022 from chemical contaminations introduced during the PCBA process.

To protect the sensor from physical and chemical contamination during assembly:

- Use polyimide tape to cover the sensor cavity.
- Devices such as the HDC2021 and HDC3021 are shipped with factory-installed, removable polyimide tape. This tape:
  - Shields the sensor from contamination during SMT processes and conformal coating.
  - Is chemically resistant and acts as a physical barrier.

Tape Removal Instructions:

1. Remove the tape after assembly using ESD-safe tweezers.
2. Grip the adhesive-free tab at the top-right corner and peel diagonally toward the bottom-left, lifting upward to avoid contact with the sensor surface and avoid damage.

Note for Sensors without Tape Cover: For devices with no cover (HDC1x, HDC2080, HDC3020, HDC3120) and devices with an IP67 permanent filter (HDC2022, HDC3022):

- If conformal coating is required, manually apply polyimide or Kapton tape to protect the filter during the coating process.
- Ensure no coating contacts the filter, as this will block moisture ingress, resulting to inaccurate RH readings.

4.3 Rehydration Post-Assembly

Rehydration is an often overlooked and misunderstood step when using RH sensors. Rehydration is the process of recovering the RH sensors after the assembly process by re-introducing moisture into the sensing polymer. This process involves leaving the assembled sensors in a controlled RH and temperature environment for a number of days. Skipping this step can cause negative RH offset and increased hysteresis.

4.3.1 Recovering Sensor Accuracy Post-Soldering

Rehydration restores moisture to the sensing polymer that may have been lost during high-temperature assembly steps, such as solder reflow or bake. These steps dry out the sensor polymer. Without rehydration RH sensors can exhibit an increased hysteresis and negative RH offset (especially at higher humidity levels). The effect of this increased hysteresis and negative RH offset is shown in Figure 4-4 (red line).

These errors will go to zero after rehydration, ensuring the sensor performs within specification. The blue line in Figure 4-4 shows the recovered RH error after rehydration.

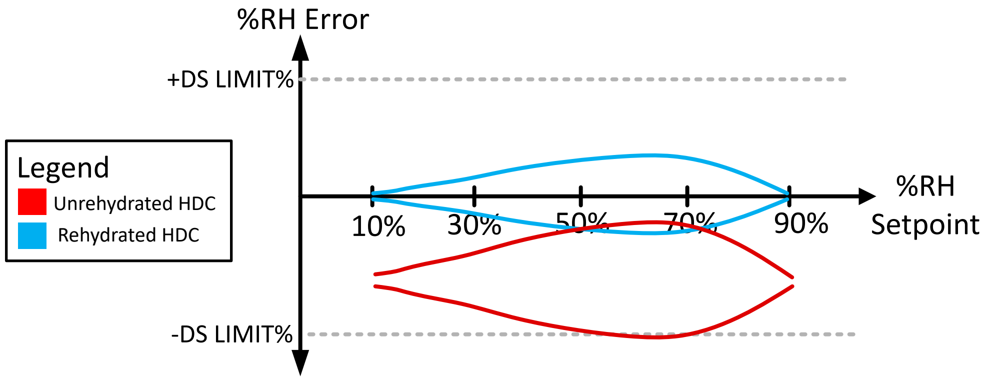

Figure 4-4. Rehydration Effects on RH Accuracy Example

4.3.2 Rehydration Procedure

Follow the data sheet's rehydration procedure without modification to ensure optimal sensor performance. Skipping or shortening the process can result in persistent negative RH error or postive RH error caused by over-correction at high RH. Rehydration should be done with the PCB powered off. This is to avoid other components on the PCB generating heat and transferring it to the RH sensor through the PCB or the air. With an elevated temperature, the rehydration profile will change and the effects on the RH accuracy are unpredictable.

Recommended rehydration conditions:

- HDC1x and HDC2x: between 20°C and 30°C, 30% RH to 40% RH for 2 to 5 days
- HDC302x: 25°C, 50% RH for 5 days
- HDC3120: 25°C, 80% RH for 2 days (48 hours)

In some cases, sensors may rehydrate naturally when deployed in environmental conditions that are least 25°C and 50%RH. Rehydration in the application may not occur when deployed into high-temp/low-RH environments (temperatures above 30°C, %RH less than 40%RH). While not recommended, this can serve as a workaround when rehydration delays are unacceptable. However, temporary negative RH shifts should be expected until the polymer fully reabsorbs moisture. Excess moisture from extremely humid environments can be mitigated by baking (e.g., 100°C for 5–12 hours) or activating the integrated heater.

4.4 Test Setup and Environment

If a user is testing at any point in the engineering process, having a test setup that can test RH sensors as accurately as possible is very important.

RH testing requires:

1. A calibrated RH & temperature reference sensor
2. A stable and controlled temperature & humidity environment
3. Adequate settling time

Without these, measurement noise and RH accuracy errors can occur.

4.4.1 RH References

Use an ISO/IEC 17025-calibrated reference (e.g., dew point mirror) and a controlled environment to validate RH sensors. In addition, use a calibrated humidity chamber to evaluate the RH sensor at different RH conditions. The humidity reference needs to be at least as accurate as the typical RH accuracy of the RH sensor under evaluation. For example, if evaluating the HDC3020, which has a typical RH accuracy of ±0.5%RH, the humidity reference needs at least ±0.5%RH accuracy. If unavailable, compare results against a verified EVM from TI. In the absence of either, consider a certified third-party lab.

4.4.2 Setup Uniformity: Controlled Environment

A controlled humidity test environment (such as a calibrated environmental chamber) allows precise regulation of both temperature and relative humidity. In contrast, uncontrolled environments (e.g., ambient indoor conditions) lack such control and are subject to fluctuations caused by temperature gradients, air currents, and other disturbances.

Even small variations, such as less than 1°C or a few percentage points of RH, can introduce significant test errors. These may falsely suggest that a sensor is out of specification or unstable, manifesting as apparent RH offsets or inconsistent readings due to shifting ambient conditions.

If a calibrated RH chamber is not available, testing in a small, controlled temperature-stable room is preferable compared to uncontrolled conditions. In such cases, placing a cover over the test setup can help stabilize the local environment. Always allow the environment to fully settle before beginning measurements.

If a controlled environment is not available, create a localized test enclosure around the setup. This enclosure should:

- Be large enough to accommodate all sensors or assemblies under test and an RH reference.
- Be small enough to allow rapid environmental stabilization.
- Adequete thermal isolation from the external environment for temperature stability.
- Include small ventilation openings to allow air exchange.
- Use a low-speed internal fan to circulate air and improve temperature and RH uniformity.
  - Keep in mind that depending on the fan and the size of the enclosure, the fan may contribute more to temperature and RH noise due to dissipating heat. Always evaluate a test setup with and without a fan to determine what is the best for the system being tested.

Controlled vs Unscontrolled Humidity Test Setup illustrates a controlled test environment vs an uncontrolled environment. The controlled setup is within a RH chamber and includes a test PCB, fan and RH reference. The uncontrolled test setup has no chamber to control the temperature and humidity, is completely exposed to environmental factors such as sunlight and changing temperature and humidity levels, and is vulnerable to external contaminants.

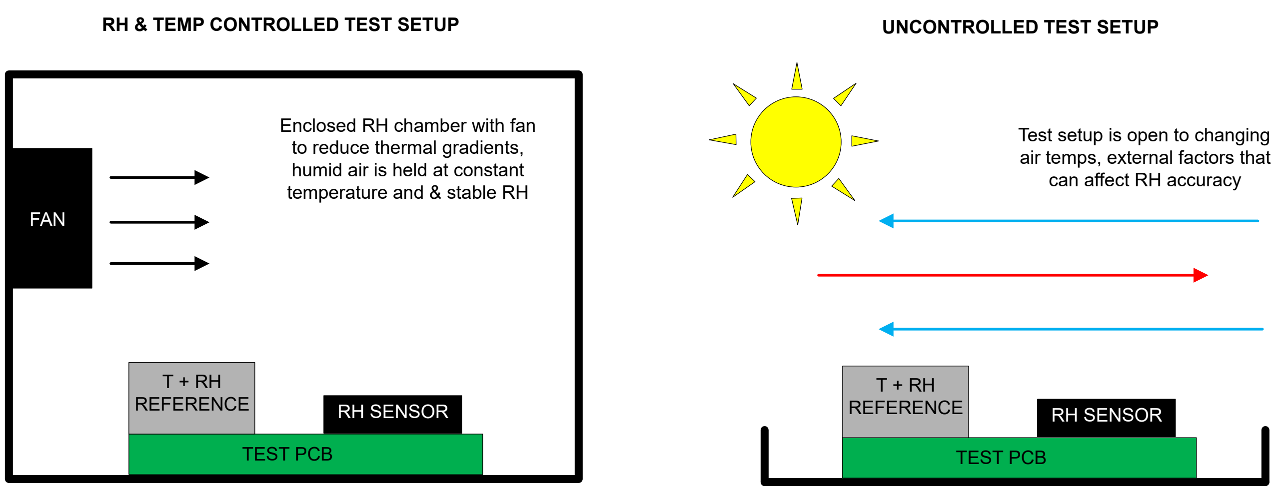

Figure 4-5. Controlled vs Uncontrolled Humidity Test Setup

4.4.3 Setup Uniformity: Thermal Gradients

Thermal gradients within a test environment introduces artificial humidity measurement errors. For example, as an environmental chamber reaches its target temperature, hot or cold spots may form due to uneven airflow or poor thermal distribution. Even minor differences (for example, a 0.2°C variation between the warmest and coolest points) can result in an apparent RH error of up to 0.8% due to RH's inverse relationship with temperature. Such discrepancies may influence whether a device passes or fails evaluation, even if the sensor itself is operating correctly. This is because the temperature gradient causes the sensor and reference to actually experience different RH conditions, causing mismatched measurement results.

While complete temperature uniformity is ideal in a RH chamber, that is often not realistic. The temperature gradient should not exceed the typical temperature accuracy of the RH sensor under test. For example, if testing the HDC3020, the typical temperature accuracy is ±0.1°C. So the maximum acceptable thermal gradient for a RH chamber would be ±0.1°C between the coolest and warmest points. This will maintain a %RH difference of no more than ±0.4%RH, which is within the ±0.5% typical RH accuracy.

Figure 4-6 shows a real-world example where thermal gradients resulted to RH errors. The error was more pronounced without airflow, and reduced (but not eliminated) when low-speed fans were added to the chamber in order to circulate air and reduce thermal gradients. Red indicates temperature, blue indicates RH.

WITHOUT FANS

-	29.79	29.84	29.81	-	-	29.84	29.83	29.87	-
29.85	29.88	29.89	29.88	29.88	29.90	29.87	29.90	29.88	29.89
29.92	29.90	29.92	29.93	29.95	29.96	29.96	29.96	29.95	29.96
-	29.95	29.96	29.93	-	-	30.04	30.04	30.05	-

-	52.12	51.90	51.89	-	-	51.91	51.82	51.73	-
51.77	51.76	51.77	51.76	51.64	51.72	51.60	51.66	51.65	51.65
51.68	51.66	51.66	51.59	51.45	51.41	51.43	51.60	51.53	51.60
-	51.61	51.54	51.52	-	-	51.31	51.28	51.20	-

Temperature differential between lowest and highest spots = 0.26°C → Resulting RH differential between lowest and highest spots = **-0.92%**

WITH FANS

-	30.66	30.71	30.68	-	-	30.71	30.72	30.75	-
30.70	30.71	30.70	30.72	30.70	30.71	30.70	30.74	30.71	30.72
30.70	30.67	30.70	30.73	30.71	30.70	30.74	30.72	30.70	30.71
-	30.71	30.71	30.69	-	-	30.75	30.73	30.72	-

-	52.01	51.67	51.64	-	-	51.63	51.48	51.45	-
51.75	51.71	51.75	51.66	51.60	51.68	51.54	51.58	51.59	51.62
51.71	51.75	51.68	51.48	51.64	51.66	51.59	51.70	51.63	51.70
-	51.81	51.65	51.69	-	-	51.58	51.56	51.52	-

Temperature differential between lowest and highest spots = 0.09°C → Resulting RH differential between lowest and highest spots = **-0.56%**

Figure 4-6. Humidity Chamber Thermal Gradients Example

To minimize thermal gradients:

- Place sensors as close as possible to the RH reference.
- Place sensors as close together as practical within the chamber.
- Use internal fans to improve air circulation and temperature uniformity.
- Limit airflow at sensor level to ≤1 m/s. If higher fan speeds are necessary to achieve mixing, place fans away from the sensors to avoid localized airflow effects.

Figure 4-7 shows a fan setup used to enhance circulation and reduce thermal variation in the chamber.

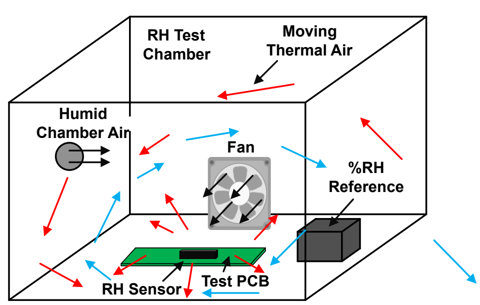

Figure 4-7. Humidity Chamber with Moving Air to Mitigate Thermal Gradients

4.4.4 Settling Time

Settling time refers to the duration a test environment, such as a humidity chamber, must remain at a stable setpoint before taking RH measurements. The required time varies based on chamber size, response characteristics (e.g., underdamped or overdamped), and the desired precision. If the chamber has not stabilized, the ambient RH may continue to drift during testing, introducing thermal gradients, noise, and artificial measurement spread across devices under test.

As a general guideline, a 20-minute %RH settling period at an already settled temperature is a reasonable starting point when no prior characterization data is available. Every humidity chamber is different, however 20 minutes will typically allow %RH overshoots and oscillations to settle while not over-exposing the RH sensor to a particular RH setpoint for most humidity chambers.

Recommended Stabilization Sequence:

1. Stabilize Temperature First: Set the desired temperature and use a moderate RH level (20–50%) to avoid condensation. Allow the temperature to stabilize to within ±0.1°C. Depending on the system, this may take several hours.
2. Stabilize Humidity Next: Once temperature is stable, adjust the RH setpoint. Since the thermal conditions are now steady, RH can typically stabilize within ±0.2% RH in approximately 20 minutes.

Regardless of the test environment (whether using a controlled chamber or not) it’s essential to allow adequate time for both temperature and humidity stabilization. While 20 to 30 minutes per RH setpoint is a good baseline, actual stabilization time may vary and should be confirmed through experimentation.

Caution: At high humidity levels (RH > 70%), limit sensor exposure during settling to the shortest time necessary. Extended exposure at elevated RH will lead to excess moisture absorption and induce a temporary positive RH offset due to the sensor's inherent hysteresis. To minimize this risk, avoid exceeding 30 minutes per setpoint at high RH levels.

4.5 Storage and Handling

Proper storage and handling are essential to maintaining RH sensor accuracy throughout the product lifecycle. Errors can be introduced by improper environmental conditions, unsuitable storage materials, or physical damage during handling.

4.5.1 Storage Temperature and Humidity Conditions

Storage guidelines apply to the sensor’s full lifespan, not just pre-deployment. Store RH sensors away from direct light, in a stable environment between 20–30°C and 30–50% RH. Prolonged exposure to >70% RH can cause temporary RH offset or gain. Severe exposure (e.g., 85°C/85% RH) can cause irreversible performance degradation.

To recover from excess humidity exposure, bake sensors at 100°C and <5 %RH for 5–10 hours, followed by rehydration per the datasheet. Baking helps mitigate, but not always eliminate, long-term RH drift or contamination effects.

4.5.2 Storage Materials

Common antistatic packaging materials like pink foam, pink polyethylene bags and LDPE (low density polyethylene) bags or packing materials may offgas VOCs, which can degrade RH sensor accuracy. These contaminants may cause offset or gain errors depending on the type, concentration, and duration of exposure. Packing materials containing antistatic agents such as ethoxylated amines or color additives like amines will also degrade the performance of the RH sensor. RH sensors should never be stored with or near any chemical that offgases.

Use sealed, metallized antistatic bags and amine-free, polyethylene/LDPE-free packing materials for storage and transport.

Figure 4-8 shows some examples of common pink foam with amine additives that must not be used with any TI RH sensor.

Figure 4-8. Pink Foam Examples

4.5.3 How Does MSL Level Relate to RH Sensors?

A common source of confusion regarding storage conditions is MSL level. MSL stands for Moisture Sensitivity Level, and is a storage rating that informs users under what conditions an IC can be stored. Table 4-1 shows the different MSL levels.

Table 4-1. Factory Floor Life at 30°C

<table>
<tr><th>MSL</th><th>Floor Life</th><th>Moisture Relative Humidity</th></tr>
<tr><td>1</td><td>Unlimited</td><td>85% RH</td></tr>
<tr><td>2</td><td>1 year</td><td rowspan="7">60% RH</td></tr>
<tr><td>2a</td><td>4 weeks</td></tr>
<tr><td>3</td><td>168 hours</td></tr>
<tr><td>4</td><td>72 hours</td></tr>
<tr><td>5</td><td>48 hours</td></tr>
<tr><td>5a</td><td>24 hours</td></tr>
<tr><td>6</td><td>Bake before use and reflow within time on label</td></tr>
</table>

TI's RH sensors are rated MSL-1, meaning the sensors can be stored indefinitely in the packaging without affecting mechanical reliability. However, MSL rating pertains only to package integrity, not sensing performance.

For example, storing a sensor at 30°C/85% RH for one year can preserve package quality, but degrade RH accuracy due to moisture ingress into the polymer. Therefore, sensors must be stored in cooler (20°C - 30°C), drier (30%RH to 50%RH) environments than the MSL rating suggests.

More information on MSL can be found in *MSL Ratings and Reflow Profiles*.

4.5.4 Handling Best Practices

The HDC302x Silicon User's Guide details the storage and handling guidelines.

Incorrect handling, such as scratching the sensor cavity with tweezers, can cause irreversible mechanical damage. Use vacuum pens whenever possible. If tweezers are necessary, avoid contact with the sensor element. Visibly damaged RH sensors should be discarded and replaced.

4.6 Chemical Contamination

Chemical contamination refers to when the sensing polymer's moisture absorption properties have been altered by an external chemical. Chemical contamination can occur at any point in the production process or the end-application, and can be difficult to identify and mitigate. The best way to protect RH sensors from chemical contamination effects is to prevent this from occurring at all. This section includes how chemical contamination affects RH sensors, common steps where this is encountered, and how to handle contamination after it occurs.

4.6.1 How Chemical Contamination Affects RH Accuracy

An RH sensor's response to chemical contamination depends on several key factors:

- The type of chemical involved
- Duration and frequency of exposure
- Concentration of the contaminant/chemical
- Which RH sensor is being used

The type of chemical can affect whether a positive or negative RH offset and/or gain is observed. Depending on the factors above, the magnitude and nature of the error will change, and may or may not be reversible. The HDC3x Silicon Users Guide Section 2.2 provides a non-exhaustive list of chemicals to avoid.

For example, exposure to pink antistatic foam for multiple days will induce a positive RH offset to the HDC302x family causing the RH accuracy to no longer be in spec. If the contamination is ionic in nature, the RH will take on a large negative gain that can begin to appear at lower RH levels (typically around 30%RH), but not show any error below that threshold.

Contaminants can be gaseous, liquid, or solid. For example, gaseous contaminants may fill the polymer's internal voids, blocking water vapor molecules and altering the polymer's relative permittivity (ε). Since the sensor's output is based on changes in capacitance linked to ε, contamination can result in inaccurate RH readings.

Solid chemical contaminants are deposited on the top of the sensing polymer. This can prevent water vapor molecules from being captured by the sensing polymer. This affects the relative permittivity of the polymer as well.

Figure 4-9 shows three chemical contamination scenarios to help visualize how contaminants affect the RH sensing polymer. The left picture shows no chemical contamination. The center picture shows a gaseous contamination. The right picture shows a solid matieral contamination.

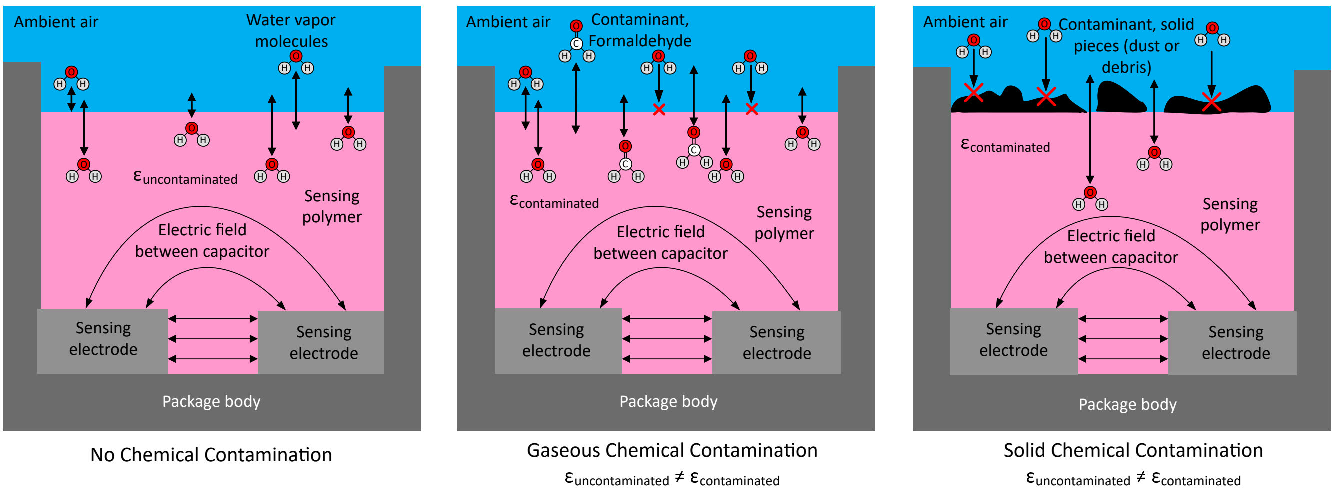

Figure 4-9. Sensing Polymer With and Without Chemical Contamination

4.6.2 Where and How are Chemical Contaminants Introduced?

Identifying potential sources of chemical contamination requires a thorough review of each step in the production, testing, and operational lifecycle.

Ask these questions when interrogating where and how a chemical contaminant could be introduced to the RH sensor:

- **Assembly & Soldering:**
  - Is the no-clean solder paste/flux low-residue and free of volatile solvents?
  - Are flux removers or board cleaners in use near the sensor?
  - Has conformal coating been applied without shielding the sensor cavity?
  - Coordinate closely with third-party assembly vendors to review **each** assembly material and process step for unintended chemical exposure.
- **Test Setup and Rehydration:**
  - Are sensors exposed to volatile chemicals in the room during testing or rehydration?
  - Is the test environment free from airborne contaminants?
- **Storage and Handling:**
  - Are sensors stored in pink foam or LDPE bags that may off-gas VOCs?
  - Are sensors in proximity to materials known to release contaminants (such as ethoxylated amines or color additives)?
- **Operating Conditions:**
  - Is the sensor used near cleaning agents, industrial solvents, or smoke?
  - In residential applications, is it exposed to air fresheners or household chemicals?
  - In industrial settings, is the sensor operating near VOC-emitting processes?

While contamination during production can often be controlled, field exposure is harder to prevent. Mitigation tools such as baking, cleaning, and protective filters may help, but recovery is not always guaranteed. The response depends on contaminant type, exposure time, and polymer sensitivity.

4.6.3 Mitigating Effects of Chemical Contamination: Bake

Baking is done to remove moisture or chemical residues affecting RH accuracy. This works because at higher temperatures, the speed at which chemical contaminants outgasses increases, meaning that the removal of chemical contaminants is accelerated. Baking can be done either on chip using the integrated heater (see Section 4.7.3 on using the integrated heater), or externally in a controlled oven.

Begin by baking the sensor at 100°C and <5%RH for 5 to 10 hours, then re-evaluate RH accuracy. As recommended in TI's RH sensor data sheets, a baking duration of up to 10 hours may be applied. After baking, rehydrate the RH sensor according to datasheet recommendations to help recover or reduce accuracy drift caused by chemical exposure. If insufficient improvements to RH accuracy are observed after baking and rehydrating, performing an additional bake can help outgass more chemical contaminants. The baking process must be done without the presence of other sources of chemical contamination because the elevated temperature may accelerate the effects of further contamination. Baking can reduce contamination-caused RH shifts in some, but not all, cases of chemical contamination.

4.6.4 Mitigating Effects of Chemical Contamination: Cleaning

Cleaning RH sensors is a delicate procedure that should only be performed by experienced personnel. It is only effective in cases of visible solid or liquid contamination on the sensing polymer; cleaning cannot remove gaseous contaminants such as off-gassed VOCs. Figure 4-10 illustrates how to use a swab to clean the top of the sensing polymer. Manual cleaning poses a risk of damaging the RH sensor, so it should not be done as the first troubleshooting step.

Cleaning a sensor manually can siginificantly improve deposited chemical contaminants, but should only be used for troubleshooting purposes. If cleaning is done on a large quantity of devices, the risk of damage to the sensor increases significantly. Cleaning should be used to identify if a deposited chemical is causing RH accuracy errors so that the chemical can be avoided in production or end-application environments.

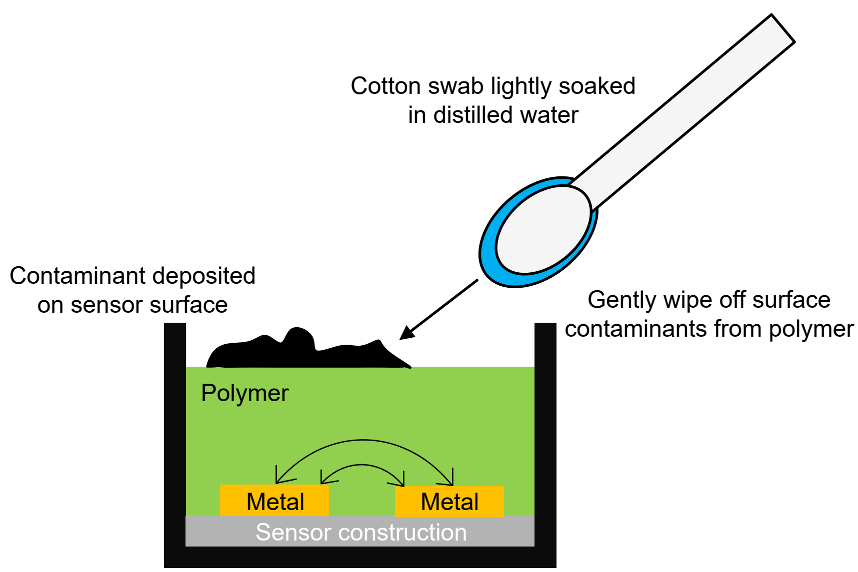

Figure 4-10. HDC Manual Cleaning Example

The following steps describe the procedure to safety clean the sensing cavity of RH sensors:

- Do not use chemical cleaning agents such as PCB wash or isopropyl alcohol.
- Lightly moisten a cotton swab with distilled water. The swab should be damp but not dripping.
- Gently clean the interior of the RH sensor cavity. Avoid direct pressure with the sensing polymer, wipe as lightly as possible.

- Ensure no residual water remains inside the cavity.
- Avoid spilling water onto the sensor's sides, which could lead to electrical shorts on the PCB.
- Dry the sensor using low-pressure compressed air directed across the surface.
- Do not use ultrasonic baths, as submersion and vibration can damage the sensor and lead to water ingress under the device, especially if the thermal pad is not soldered.
- Use a microscope to observe the sensing polymer, and observe if any solid contaminants were removed.

4.6.5 Mitigating Effects of Chemical Contamination: Enclosure Design

Enclosure design plays a critical role in protecting the RH sensor from solid and liquid contaminants. Positioning the sensor away from direct exposure, such as offsetting it from the enclosure opening, helps shield it from dirt, dust, and liquid ingress. Incorporating a filter, such as a hydrophobic PTFE membrane, over the enclosure opening provides additional protection. However, enclosures cannot prevent contamination from gaseous chemicals, as unrestricted airflow is necessary for the sensor to accurately track ambient humidity.

4.6.6 Mitigating Effects of Chemical Contamination: Device Selection

TI offers multiple generations of RH sensor ICs with enhanced protections against chemical exposure. Beginning with the third-generation HDC3x2x series, a new polymer technology improves resistance to chemical contamination and stress conditions such as 85°C/85% RH.

- **HDC2021 and HDC3021**: Equipped with a factory-installed, removable polyimide tape to protect the sensor element during manufacturing steps such as PCB was or conformal coating.
- **HDC2022 and HDC3022:** Feature a permanent IP67-rated hydrophobic PTFE filter that shields the sensor from dust, water, and PCB wash (which often contains VOCs). The microporous PTFE membrane offers 99.99% filtration efficiency down to 100nm particles.

While IP67 filter-covered devices offer significant protection against liquids and particulates, they do not block gaseous contaminants, as ambient air must still reach the sensing element. The filter may slightly slow the RH response time, but this tradeoff is often acceptable in exchange for improved sensor longevity and reliability.

Preventative measures are the most effective strategy. It is essential to identify and mitigate all potential points of exposure to chemical contaminants throughout assembly, storage, and operation of RH sensors.

4.6.7 Mitigating Effects of Chemical Contamination: Assembly Considerations

When using a RH sensor with a polyimide tape cover (whether it was factory applied or manually applied according to the instructions in Section 4.2.3), the tape provides a temporary barrier against assembly contaminants. Always ensure that the RH sensor is installed during the last step of the assembly process to eliminate the risk of additional reflow cycles and chemical exposures.

4.7 Operating Conditions: Application Environment Conditions and Effects

Even if the RH sensor is deployed without any error introduced during manufacturing or assembly, the application environment itself can still lead to accuracy issues, either temporary or permanent. Environmental stress factors such as high humidity, temperature extremes, or condensation may degrade RH accuracy. Temporary RH error induced by environmental conditions can often be reduced by using the integrated heater or by baking the device.

4.7.1 Environmental Conditions That Contribute to RH Accuracy Errors

Prolonged exposure to high humidity can cause temporary RH errors, typically seen as a positive offset and gain error. In contrast, extended exposure to low humidity and high temperatures can result in a temporary negative RH offset and gain error due to dehydration. Sustained exposure to extreme environments—such as 85°C/85% RH stress—will lead to permanent RH error. Under such conditions, moisture may condense within the polymer structure, altering its dielectric properties and reducing its ability to sense humidity changes.

The RH sensor is rated for use in non-condensing environments. If condensation or water droplets form on the sensor surface, the RH output will temporarily drop to 0% and remain inaccurate until the moisture is removed. Baking or using the internal heater will assist in recovery by evaporating liquid water on the sensor.

To summarize how sustained environmental conditions cause RH accuracy errors:

- High RH exposure, no high temp exposure → Reversible positive RH offset & possible positive RH gain shift due to excess water vapor filling sensing polymer voids
- High temperature exposure at low RH → Reversible negative RH offset & possible negative RH gain shift due to sensing polymer dehydration.
- High temperature & high RH exposure (e.g. 85°C/85%RH) → Irreversible positive RH offset and positive RH gain shift, due to water droplets forming in sensing polymer voids trapping high RH conditions into sensor.
- Condensation directly over sensing cavity → Sensor output drops to 0%RH temporarily, then will not sense RH accurately while liquid water continues to block ambient water vapor from entering sensing polymer.

4.7.2 RH Offset Mitigation & System-Level Design

For positive RH offset caused by extended high humidity exposure and condensation prevention/removal, baking is effective for removing RH offset. However it typically requires removing the sensor from the system, which is impractical for field applications. The integrated heater offers an alternative in-system method. However, prevention is the best method, especially if heating or baking is not suitable. Another strategy is to optimize enclosure design to minimize exposure to moisture and contamination. Design enclosures so that the RH sensor is not directly under any openings, reducing the risk of water droplets entering the cavity. Use sensors with IP67-rated filter membranes (such as the HDC2022 or HDC3022) to protect against water ingress and particulate contamination.

To recover from negative RH offset caused by prolonged exposure to low humidity and high temperatures, rehydrate the sensor per datasheet recommendations. Some RH sensors, like the HDC2x and HDC302x families, have programmable RH offset registers so that if the RH offset cannot be removed, it can be digitally corrected in the sensor.

4.7.3 Using the Integrated Heater

Instead of removing the RH sensor from the system for external baking, the integrated heater can be used to periodically remove excess absorbed moisture. The heater can be used to restore RH accuracy in high humidity environments and prevent/remove condensation on the sensing surface. A typical procedure involves powering the sensor at 3V or higher, activating the heater at maximum power for several minutes, and then measuring RH accuracy. Using the heater at maximum power will allow for the greatest temperature rise for a given supply voltage. Users should aim to acheive 100°C with the heater. To use the heater for RH accuracy correction, use the following process:

1. Activate heater at a power setting that will allow RH sensor to acheive 100°C (usually max power for 3.3V VDD).
2. Run heater for at least 1 minute at final temperature, up to 5 minutes (or monitor RH readings during heater test for when RH readings drop below 2%-3%RH).
3. Deactivate heater, allowing at least 1-5 minutes for cooldown (ensure temperature reading returns to prior ambient readings).
4. Remeasure RH and evaluate RH accuracy, repeat steps 1-4 as necessary.
5. Repeat steps 1-4 periodically to keep RH accuracy from deviating beyond spec limits. Heater loop frequency will depend on environmental conditions that are causing RH accuracy issues, heater efficiency, power levels, and will require user experimentation.

Heater performance should be characterized in a lab setup that closely replicates application conditions to determine the optimal settings. PCB design impacts heater efficiency. Soldering the thermal pad under the sensor may dissipate heat into the board, reducing heat available at the polymer surface. To improve heating, consider minimizing copper under the sensor, using thin PCBs (< 32 mils) or flex PCBs, introducing slot cutouts, and leaving the thermal pad unsoldered.

Using the heater does have tradeoffs. During and shortly after heater activation, RH readings will be inaccurate due to the rapidly rising temperature causing the RH reading to plummet towards 0%RH. Additionally, the heater draws significantly more current. For example, the HDC3020 can draw up to 112mA at 3.3V during full-power heating. In battery-powered systems, this could constrain usage. Designers must balance heater usage frequency with system power limitations, particularly in continuously humid environments. The heater will also not be able to assist in removing negative RH offsets, since these errors occur due to high temperature exposure.

4.8 RH Accuracy Debugging Flowchart

To help identify the source of RH accuracy issues, the flowchart shown in Figure 4-11 can be used. This image guides users through a structured evaluation based on the observed error type; positive offset, negative offset, or gain error.

Before using the flowchart, make sure the RH error is characterized by testing across a range of humidity levels. In cases where errors do not clearly fall into a single category, use this flowchart as a guide to explore potential causes and formulate corrective actions.

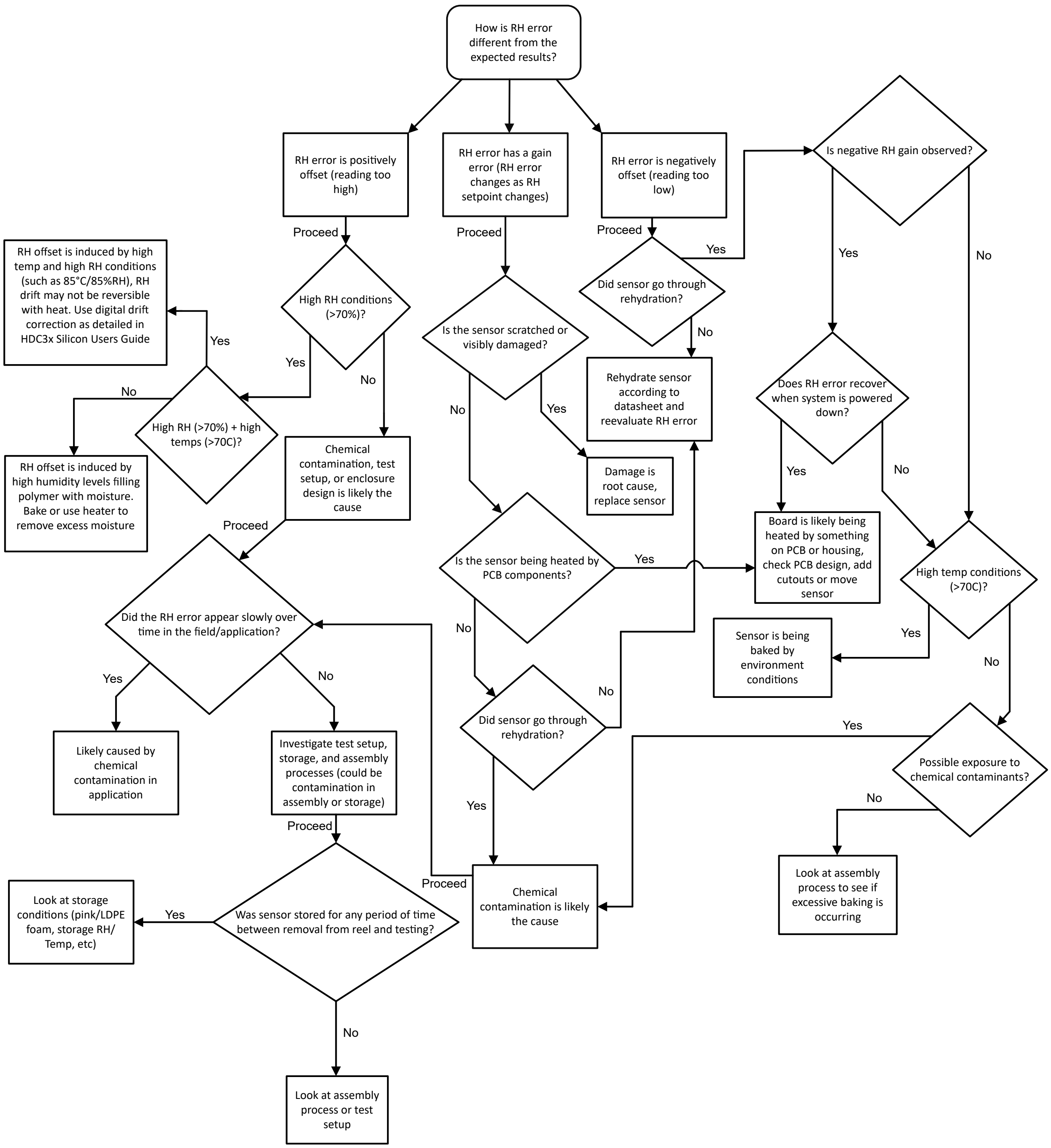

Figure 4-11. RH Accuracy Debugging Flowchart

5 Summary: Designing for and Debugging RH Accuracy

RH sensor accuracy can be affected by multiple contamination sources throughout the production and deployment process. This document outlines strategies to eliminate or mitigate error sources across assembly, handling, and system integration. Whether diagnosing an existing issue or designing a new application, following a systematic process improves reliability and accuracy in RH sensing.

Looking back at Figure 1-1 and #unique_14/unique_14_Connect_42_GUID-843E0264-5CDC-41F2-A8A4-5730FA2D0652, the design timeline illustrates how many potential vectors there are for RH accuracy errors to be introduced. Starting the design process with this in mind will allow users to eliminate risks in the areas they can control. RH accuracy matters because users need their RH sensors to last as long as possible in the field and deliver the right result to the end-user. That is why it is imperative for users making designs with RH sensors to understand the RH error sources and eliminate as many as possible before RH accuracy issues appear.

Table 5-1. Summary of RH Error Sources and How to Prevent/Mitigate Them

RH Accuracy Error Source	What is causing RH error?	How to mitigate & prevent RH errors
PCB & Enclosure Design	PCB and/or enclosure design that does not allow RH sensor to sense ambient temperature and humidity accurately.	Use PCB layout techniques that optimize ambient air sensing, and enclosures with unrestricted airflow.
Soldering & Assembly	Non-recommended reflow profiles and assembly materials that cause chemical contaminations or damage.	Follow recommended solder reflow profile and use assembly materials without VOCs and other potential contaminants.
Rehydration	Skipping or deviating from datasheet rehydration profiles.	Follow datasheet rehydration instructions.
Testing	Testing RH sensors without a calibrated reference, without sufficient temperature and humidity settling time, testing in an uncontrolled environment, and not taking into account test chamber errors like thermal gradients.	Test RH sensors with a calibrated reference inside a RH chamber, following manufacturer recommendations for settling time and temperature gradient compensation.
Storage and Handling	Damaging or contaminating RH sensors during handling, storing at extreme humidity conditions or in the presence of off-gassing chemical contaminants.	Handle RH sensors with vacuum pens and store RH sensors in metalized ESD bags in low temperature and low humidity conditions away from direct light exposure.
Chemical contaminations	RH sensors have their sensing polymer's dielectric properties altered by unwanted chemicals.	Identify potential sources of chemical contamination by examining production process and looking at the MSDS of different materials to look for potentially problematic chemicals. Mitigate existing chemical contamination with the integrated heater or an external oven for baking.
Operating conditions in application environment	Operating continuously in extreme humidity conditions.	Use the integrated heater periodically to bake out excess water vapor that accumulates over time in the sensing polymer to prevent RH errors from becoming too large.

6 References

- Texas Instruments, *HDC302x 0.5%RH Digital Relative Humidity Sensor, 0.19%RH/yr Long Term Drift, 4s Response, Low-Power, Offset Error Correction, 0.1°C Temperature Sensor*, datasheet.
- Texas Instruments, *HDC2080 Low-Power Humidity and Temperature Digital Sensor*, datasheet.
- Texas Instruments, *HDC2021 HIgh-Accuracy, Low-Power Humidity and Temperature Sensor With Assembly Protection Cover*, datasheet.
- Texas Instruments, *HDC2022 High-Accuracy, Low-Power Humidity and Temperature Sensor With IP67 Rated Water and Dust Protection Cover*, datasheet.
- Texas Instruments, *HDC2010 Low-Power Humidity and Temperature Digital Sensors*, datasheet.
- Texas Instruments, *HDC302x Silicon User's Guide*, user's guide.
- Texas Instruments, *HDC20XX Silicon User's Guide*, user's guide.
- Texas Instruments, *Humidity Sensor: Storage and Handling Guidelines*
- Texas Instruments, *85°C/85% RH Accelerated Life Test Impact on Humidity*, white paper.
- Texas Instruments, *Optimizing Placement and Routing for Humidity Sensors,* application note.
- Texas Instruments, TI Humidity Sensors: Programming & Integration Guide, application note.
- Texas Instruments, Humidity Sensor Comparison Guide, product overview.
- Texas Instruments, *Using Relative Humidity to Derive Vapor Pressure, Dew Point, Absolute Humidity, and Enthalpy*, application brief.
- Texas Instruments, *Guidelines for Returns*, specific guidelines.
- Texas Instruments, *MSL Ratings and Reflow Profiles*, application report.

7 Appendix

As mentioned in Section 1.3, this section contains a detailed overview of each case study. Each case study includes a description of the RH accuracy issue the customer was encountering (both written and graphically), the investigation steps taken by TI and the customer, and the final root cause and mitigation and prevention measures taken.

7.1 Case Study 1: Humidity-Induced Positive RH Offset

Problem Statement

The customer implemented the HDC3020 on a PCB and observed a positive RH offset on a subset of devices compared to a reference during their post-assembly evaluation. Two affected units were returned to TI for analysis after being desoldered from the board.

Investigation Phase

The initial step was to test the returned devices in a controlled RH chamber across a range of humidity levels. Compared to known-good control units, the returned devices showed a consistent RH offset, but no gain error. Since the error was limited to an offset, the investigation focused on temporary moisture absorption rather than chemical contamination. This RH offset is shown in Figure 7-1.

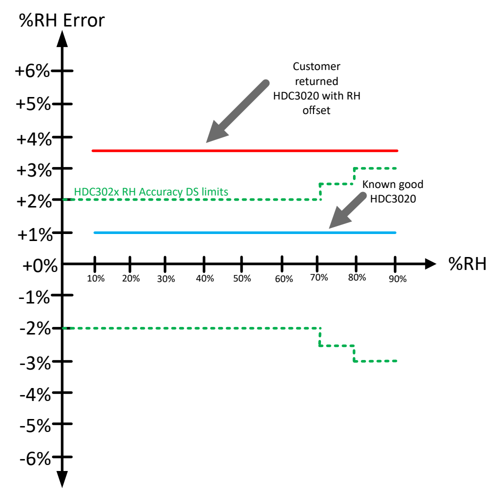

Figure 7-1. HDC3020 with RH Offset Vs Known Good HDC3020

Since this was only RH offset and not RH gain, the investigation focused on excess moisture absorption as the potential cause, instead of chemical contamination. To mitigate the suspected moisture-induced error, the sensors were baked at 100°C for 2 hours and retested. This baking successfully restored RH accuracy. If this had failed, a secondary bake at 100°C for 10 hours would have been considered. If the offset persisted, this suggests either permanent damage due to environmental stress or possible chemical contamination.

After baking the HDC3020, the sensor was able to have the RH offset removed. The customer's returned RH sensor had it's RH accuracy improve as seen in Figure 7-2.

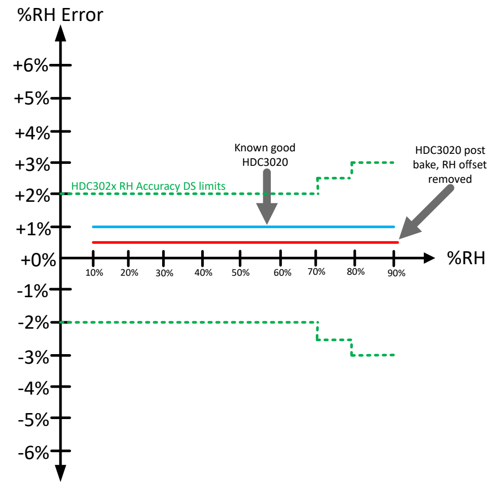

Figure 7-2. HDC3020 with RH Offset Post Bake

To find the root cause, the user needed to find differentiating information or steps taken between the HDC3020s showing this offset and those without offset. After ruling out lot differences or application differences, the user identified that all the sensors that were positively offset were being assembled at one particular manufacturer. That PCBA manufacturer may have been continually exposing the HDC3020 to high RH conditions (>70%) either during assembly or storage, leading to the positive RH offset.

Conclusions

- The RH error was most likely caused by temporary moisture absorption during high-humidity assembly conditions.
- Baking at 100°C for 2 hours effectively removed the offset.
- All affected devices were traced to a single manufacturer, highlighting the importance of controlling humidity during sensor assembly.
- Preventative action included implementing low-RH storage or avoiding high-humidity exposure during assembly.

7.2 Case Study 2: Gradual RH Accuracy Drift in 100%RH Environment

Problem Statement

The HDC3022 was deployed in three outdoor environments: urban, coastal, and mountainous. All devices initially met RH accuracy specifications. However, over a period of two to three months, devices showed RH accuracy degradation, failing to reach full 100% RH during high humidity conditions. For example, one sensor remained at 90% RH despite ambient humidity reaching 100% as seen in Figure 7-3.

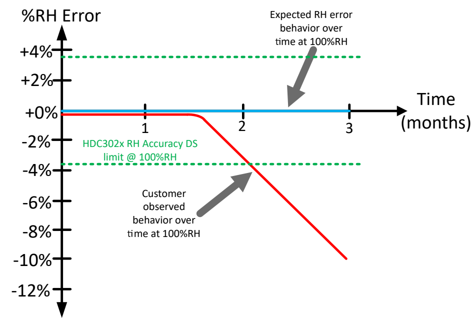

Figure 7-3. HDC3022 RH Error at 100% RH Dropping Over Time

Investigation Phase

As the devices operated within the specifications prior to deployment, early-stage causes such as PCB layout, assembly, or rehydration were ruled out. Although environmental exposures varied across the three locations, the symptoms were consistent, suggesting a shared root cause.

Despite prolonged exposure to 100% RH typically causing a positive RH offset, these sensors exhibited the opposite: reduced maximum RH readings. This pointed to an obstruction rather than polymer saturation. Baking the devices at 70°C and 10% RH for 6 hours restored RH accuracy, confirming a recoverable error.

The likely cause was determined to be dust accumulation on the PTFE filter, which inhibited moisture ingress. This hypothesis was formed by process of elimination, given that chemical contamination was unlikely due to the RH being accurate during initial deployment and the different application environments making it difficult to identify a common exposed chemical. The improvement after baking suggested that the accumulated dust was partially removed, allowing the sensing polymer to rehydrate.

Figure 7-4 is a representation of the root cause identification process, demonstrated on the RH Accuracy Debugging Flowchart:

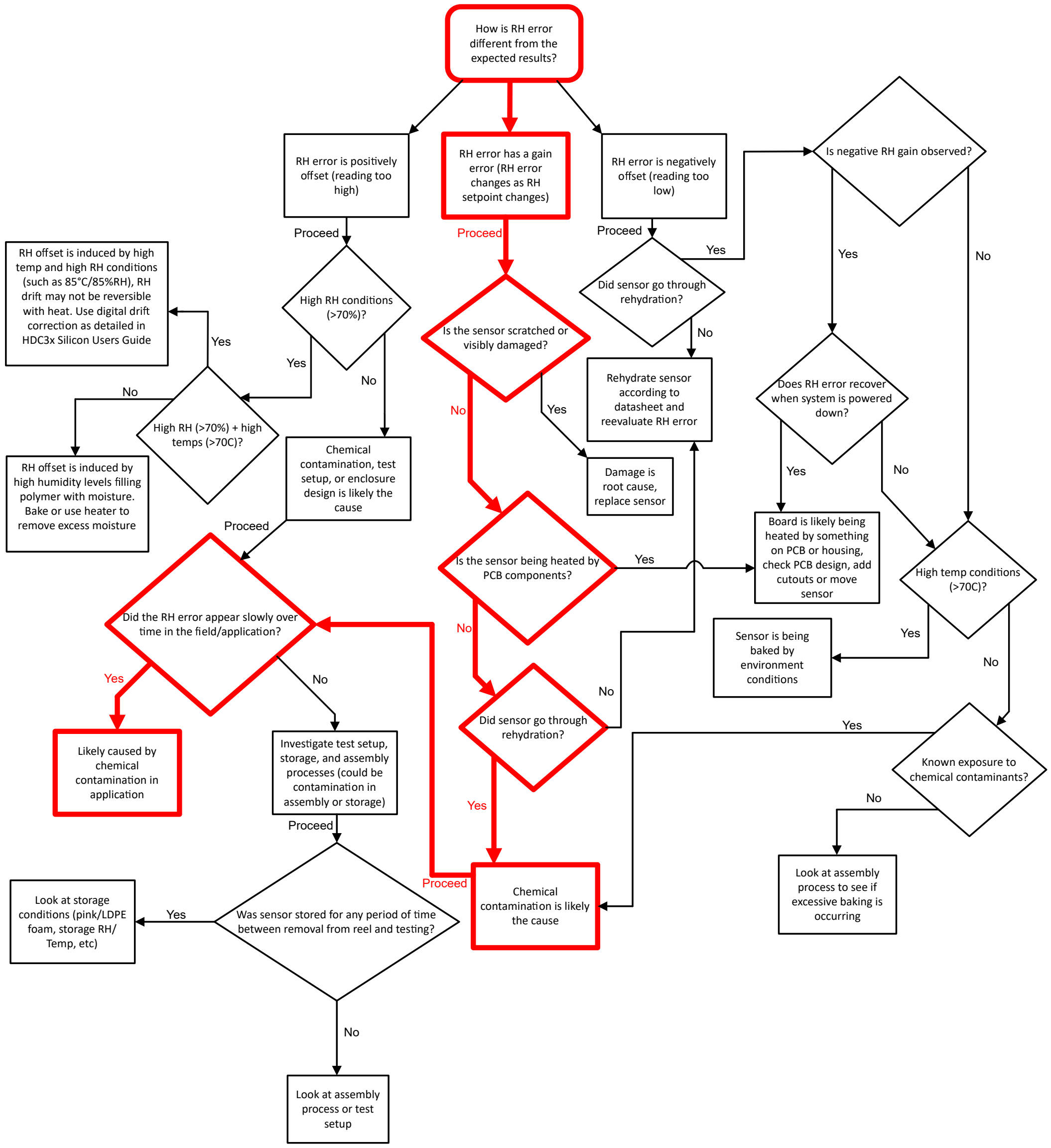

Figure 7-4. RH Accuracy Debugging Flowchart Case Study 2 Example

Conclusions

- A low-temperature baking step improved performance by clearing the obstruction.
- The issue was not tied to chemical contamination from VOCs or assembly quality.
- Enclosure design improvements can reduce future dust ingress by reorienting air intake so that dust cannot arrive to the HDC3022.
- Since oven access is impractical for fielded devices, the integrated heater is recommended for periodic use.

7.3 Case Study 3: Combined Factors from Assembly & Thermal Effects

This final case study involves multiple overlapping factors, each contributing differently to RH accuracy deviations. A systematic, multi-phase investigation was required to isolate and evaluate the impact of heating, contamination, and system design on the observed sensor behavior.

Problem Statement

The customer deployed both HDC2021 and HDC3021 devices in a gas sensing application, where RH sensors are used to compensate gas sensor measurements. The RH and gas sensors were mounted within an enclosure featuring a ventilation hole for ambient air exposure.

During testing, HDC2021 units appeared to operate within specification, while all HDC3021 devices consistently exhibited a negative RH error. The entire population of HDC3021s was affected. The customer returned sample modules to TI for failure analysis.

Investigation Phase 1: Test Replication & Initial Findings

At TI the customer modules were placed into a test chamber with still air and both temperature and RH were measured against a chilled mirror reference. As shown in Figure 7-5, the HDC2021 showed a flat RH error curve, while the HDC3021 exhibited a negative RH gain error. This confirmed the customer's observation.

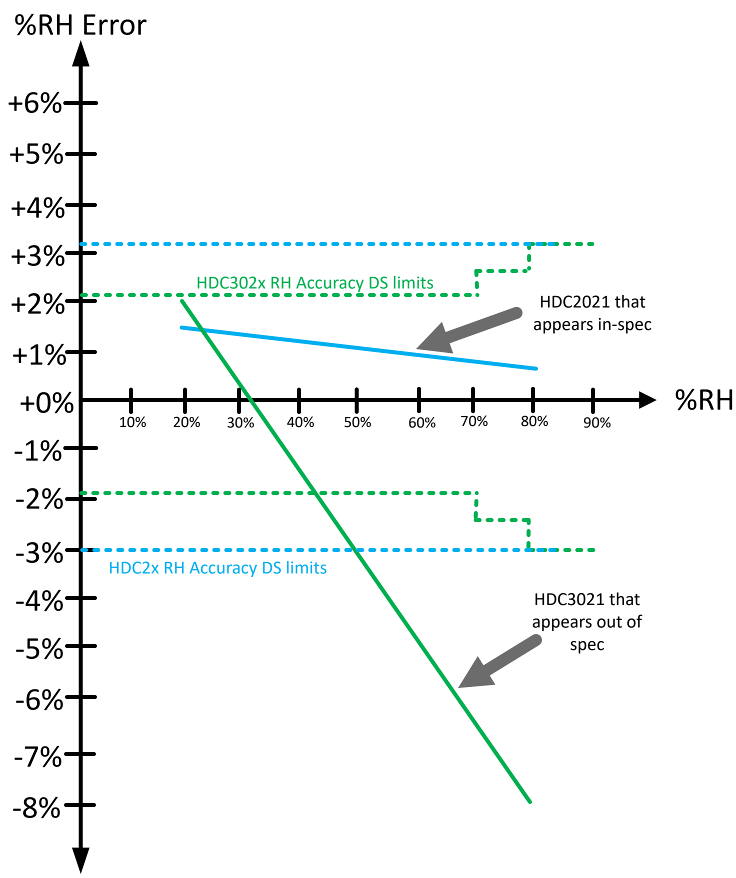

Figure 7-5. HDC2021 and HDC3021 on User's Boards & Enclosures Tested in Still Air

Further analysis of the test data revealed that both RH sensors reported internal temperatures approximately 2°C higher than the reference. This discrepancy indicated localized heating. Since RH is temperature-dependent, an increase in sensor temperature results in lower reported RH due to the dew point relationship. Table 7-1 summarizes the impact of heating, showing that a 2°C rise can introduce approximately:

- -2% RH error at 20% RH ambient
- -9% RH error at 80% RH ambient

Table 7-1. Calculated Dew Point at Varied Ambient Conditions

Ambient RH (%)	Ambient Temperature (°C)	Dew Point (°C)
20	25	0.48
80	25	21.31

Table 7-2. Resultant Delta RH Caused by 2°C Heating

Dew Point (°C)	Heated Temperature (°C)	Heated RH (%)	Delta RH (%)
0.48	27	17.77	-2.23
21.31	27	71.07	-8.93

This explained the HDC3021’s apparent negative RH offset and gain error. However, because both sensors experienced heating, the HDC2021’s “in-spec” result was misleading. Its true RH accuracy included a **positive RH offset** and gain error that was masked by the heating-induced negative shift.

Investigation Phase 2: Heating Isolation & Reassessment

To isolate heating effects, the RH sensors from the customer modules were removed at TI and mounted on TI test boards. In the controlled environmental chamber, fans were used to circulate humid air to ensure uniform temperature throughout the chamber. In this thermally optimized environment, both sensors showed a true positive RH offset and gain error. The HDC3021 exhibited a smaller error than the HDC2021 but was still out of spec as seen in Figure 7-6.

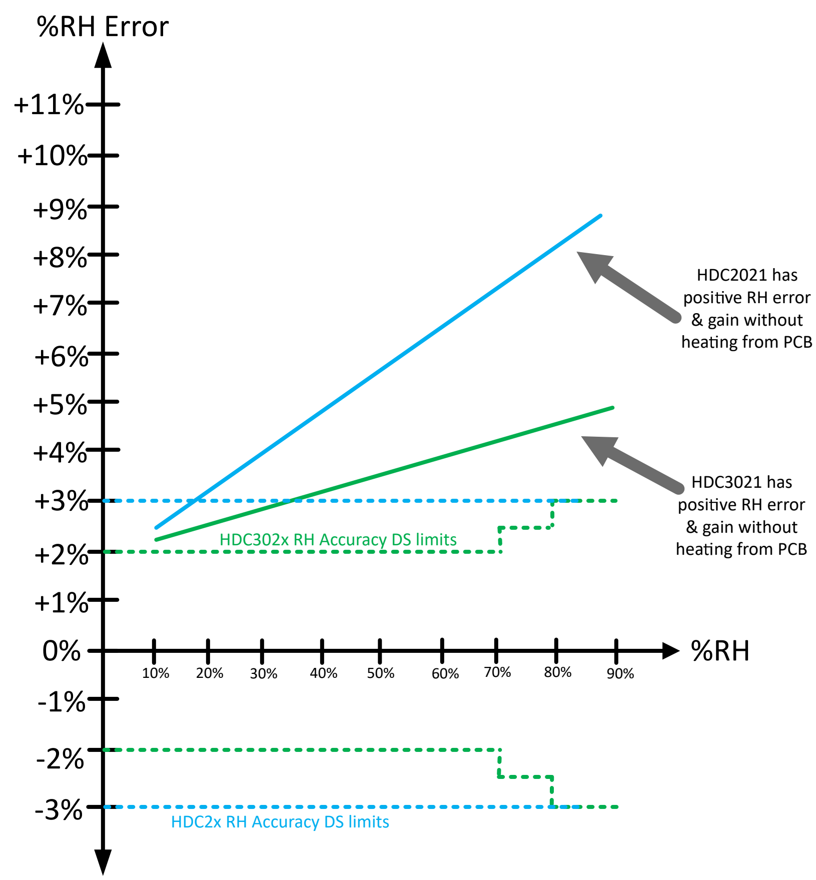

Figure 7-6. HDC2021 and HDC3021 Tested Off User's Boards, No PCB Heating, Moving Air

Investigation Phase 3: Failure Analysis and Contamination Detection

To determine any contamination or possible sensor damage, TI performed a failure analysis on the customer returned units. Failure analysis was performed on both sensor types:

- **HDC2021:** Optical and SEM inspection revealed visible contamination within the polymer cavity. EDX analysis detected abnormal levels of Cl, S, Sn, Ca, and Al—indicative of external chemical exposure.
- **HDC3021:** SEM imaging showed circular dot patterns across the surface, suggesting contamination beneath the tape cover. It is likely that the protective film lifted during assembly, allowing exposure.

An ABA swap was conducted by replacing the HDC3021 with known-good units. When tested under controlled airflow (still-air vs. fan-on), the new units returned to in-spec performance, confirming that prior measurements were affected by both internal heating and sensor damage as seen in Figure 7-7.

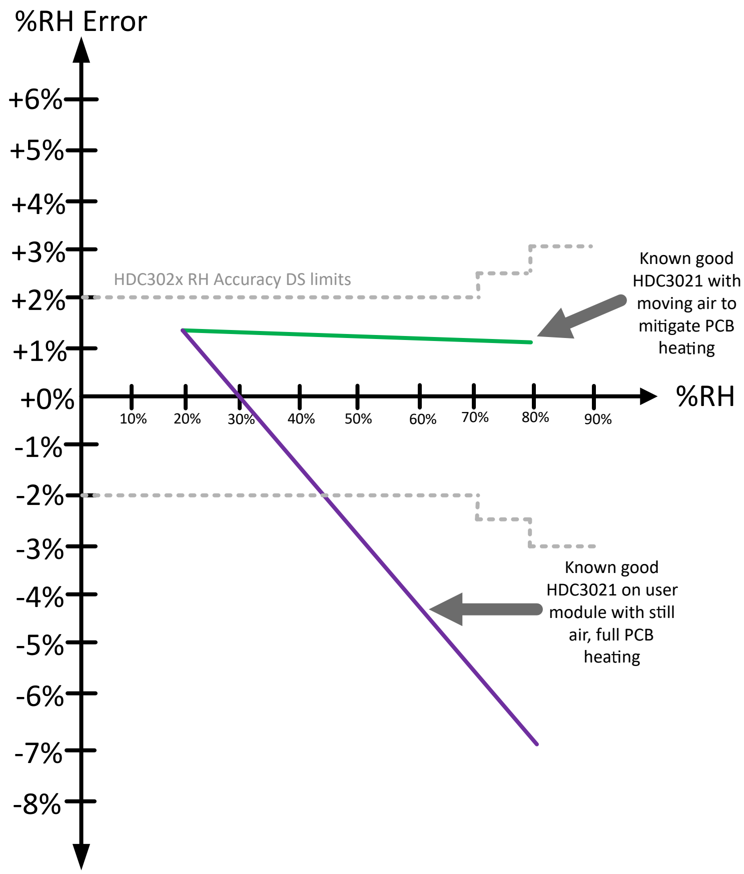

Figure 7-7. Known Good HDC3021 Tested On User's Boards, with Moving Air and Still Air

Investigation Phase 4: Root Cause Traceback and Material Audit

After isolating heating effects, both sensor types exhibited positive RH gain errors, consistent with chemical contamination. Given that the issue affected the entire sensor population, the source was traced to a systemic issue during manufacturing or storage.

The customer provided documentation and MSDS sheets for all materials used. TI identified the presence of polyglycol ether in a no-clean solder paste. This solvent, similar to ethylene glycol, is known to cause RH sensor offset and gain error. The HDC302x Silicon Users Guide explicitly advises avoiding exposure to glycol-based solvents. Glycol based solvents cause RH errors due the polarity of their molecules, which alters the relative permittivity of the sensing polymer as shown in Figure 7-8

A safer alternative is the recommended solder paste Kester R276, as it is free of known volatile contaminants.

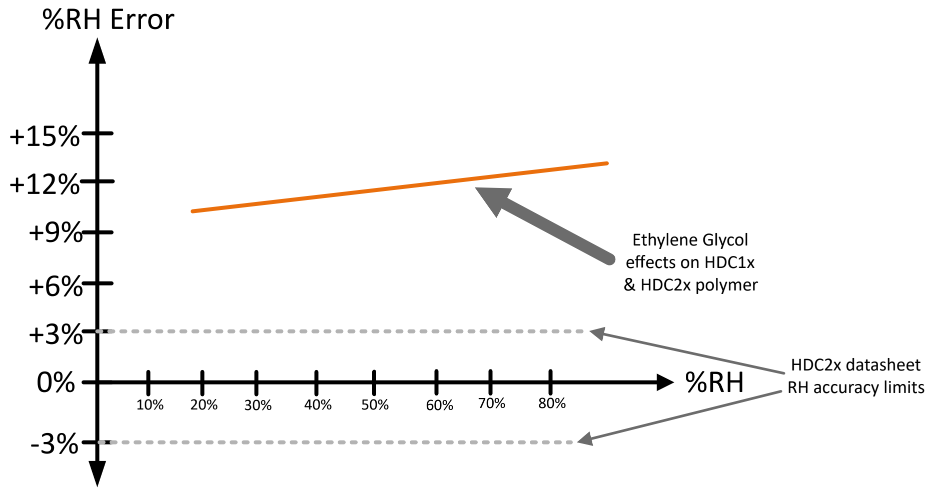

Figure 7-8. Effects of Ethylene Glycol on HDC10XX and HDC20XX Sensing Polymer

Conclusions

In this example three distinct error sources were identified:

1. PCB/enclosure heating -> negative RH error
2. Chemical contamination -> positive RH offset/gain
3. Test setup mismatch -> masked true performance

The root causes and mitigation efforts were:

- The HDC2021's apparent in-spec behavior was due to opposing error vectors (heating and contamination canceling each other).
- The user must ensure that PCB layout and enclosure design minimizes localized heating so that the RH sensor measures true ambient conditions.
- RH testing setup must use a reference probe placed near the sensor and inside the enclosure to reflect the same local environment. PCB heating changed the conditions around the sensor so testing with a probe outside of that local environment lead to misleading RH accuracy results.
- Contamination prevention is critical: avoid using solder pastes or materials containing volatile glycols or solvents. TI recommends no-clean solder paste and flux and do not clean PCBs after assembly. Always audit MSDS documentation for compatibility. Even no-clean solder paste can have volatile chemical contaminants.
- In thermally sensitive applications (for example, co-packaged with gas sensors), measurement compensation algorithms must account for local heating effects. Always design PCBs and enclosures to match the RH sensor's junction temperature with the ambient temperature for best accuracy.