DIAGNOSTIC TESTS FOR THE INTELLIGENT GAS SENSORS, iSERIES

Technical Note

Honeywell introduces the Next-Generation intelligent (iseries) gas sensors. These sensors have a digital interface, longer life and numerous built-in diagnostics features.

The iseries' intelligent diagnostic features help enhance the overall instrument performance, making them smarter and safer by indicating faults and monitoring health, thereby decreasing downtime and cost of ownership.

The purpose of this document is to describe the Predictive Calibration and End-of-life functions, and outline the principles of the diagnostic tests.

BACKGROUND

All gas sensors drift over time and eventually need recalibrating, and the amount of drift is strongly dependent on the environment that the sensor is used in. Traditionally, instrument developers, fleet managers or end users would work out for themselves by experience how often they need to recalibrate sensors, or would use recommendations from the sensor or instrument manufacturer as it is not known what conditions the sensors are being used in. This often results in unnecessarily frequent recalibrations which is costly and time consuming.

Intelligent Features

The iseries platform uses internal tests to monitor the condition of the sensor and apply algorithms both to compensate for drift and to predict when the sensor accuracy exceeds a predefined limit and needs recalibrating.

It can also predict when it is wearing out and can give warning in advance that the sensor needs replacing. As both the Predictive Calibration and End-of-life indication use predictions based on the environment that the sensor is being used.

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Definition of Diagnostic Tests

Predictive Calibration: The calibration process can be very tedious, costly and a time-consuming process. With this function, sensors can predict in advance when its accuracy is becoming too poor to give a reliable reading. This function helps to identify exactly when a recalibration is required.

The sensor can estimate the time to recalibration up to six months in advance. Recalibration intervals will be typically at least twice as long as for conventional sensors and will adapt depending on the environment – with sensors used in more benign environments needing less frequent calibrations than those in aggressive ones.

The user can configure the accuracy limit of the sensor, and this will determine the interval at which the calibration is needed. In other words, the tighter the accuracy value, the more frequent calibration needed.

The user can therefore trade off accuracy against recalibration interval. There is also a configurable built in fixed interval recalibration countdown timer for applications where legislation requires calibration at certain intervals.

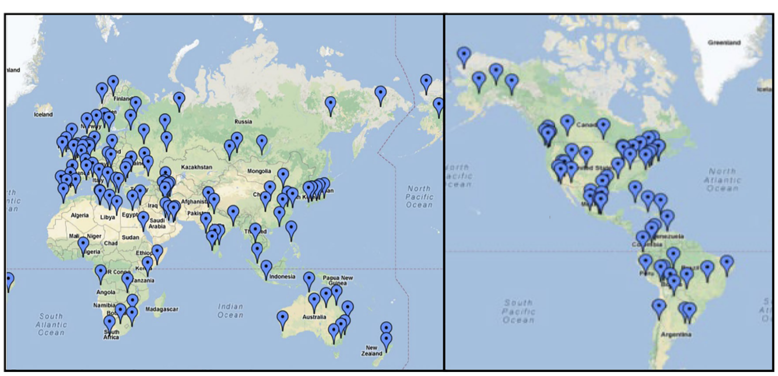
End-of-Life: The lifespan of a sensor depends mostly on the environmental conditions at which the sensor is exposed. With this function, the sensor can predict in advance when its sensitivity is falling too low to give a reliable and accurate reading.

When the End-of-life function is triggered, the sensor automatically warns the instrument via a set of fault flags sent together with the gas reading. If the fault is detected the instrument can warn the user to stop using the sensor.

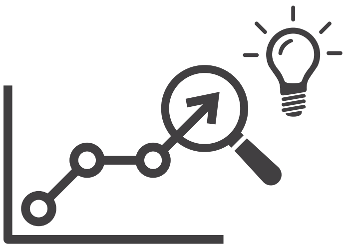
How was the design of the sensor optimised?

Honeywell engineers performed finite element analysis of the water management and electrolyte distribution within sensors and gained an extensive understanding of the optimum designs for retaining the electrolyte in the right place at the right concentration.

Subsequently, safety operating area charts were developed based on a combination of fundamental physical theory, modelling and experimental verification to show how sensors will perform and withstand over the full temperature, humidity and time.



To validate that the sensor will last in real-world applications, an environmental database was obtained. The database contains hundreds of locations around the world, with temperature and humidity data for **10 years with two hourly resolution**. The knowledge of use cases for sensors was combined, for example time spent indoors and outdoors, charging to provide input data on the actual conditions sensors are exposed to in the real world. This information was fed into the models to predict how long sensors will last and how their performance will change in real world conditions, and to assist us in optimising the sensor design for maximum performance and life.



How do the End-of-life and Predictive Calibration work, and how were they generated?

To be able to predict the behaviour of a sensor, a predictive model was developed that uses historical data such as time, temperature and electrolyte concentration as inputs.

The environmental performance data was generated by storing sensors in a range of environmental conditions over a two-year period. There were more than 8000 individual gas responses recorded for each gas type

During this period, the sensors were tested to generate different databases corresponding to the performance of the sensor at particular environments.

The resulting predictive algorithm keeps track of the electrolyte concentration and environmental conditions over time and extrapolates this data with a linear regression in order to accurately predict when does the sensor need to be calibrated or when does the sensor is about to reach its lifespan.

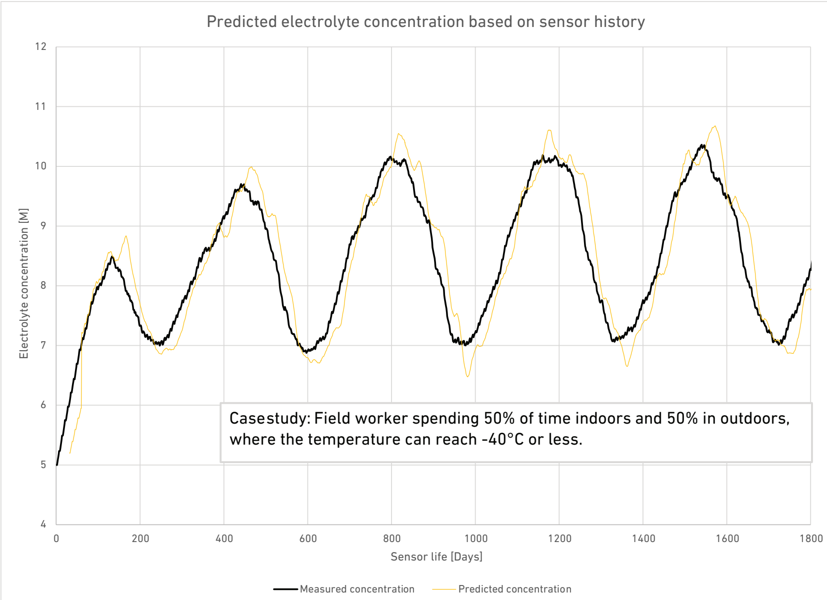
How does the predictive model for EoL and Predictive Calibration works?

To estimate the EoL and Predictive Calibration, a 30-day time period is defined. During this period, the sensor will keep track of the environmental changes. The model works under the assumption that the sensor will be exposed to similar conditions.

For instance, if the sensor has been in an extremely hot and dry environment, the predicted model will calculate the corresponding water loss as if the conditions remained the same; giving warning to the user in order to prevent further dry out.

Figure 1 shows how the electrolyte concentration and predicted electrolyte concentration vary for a sensor in an extreme environment. The environment chosen corresponds to a challenging environment for the sensor to survive: during winter, outdoor temperatures can be -40°C or less, and in a heated unhumidified building or car, the relative humidity can be extremely low due to the very low water content of the cold outside air. Therefore, a sensor which spends part of the day indoors and part outdoors (a typical 'field worker' use case) not only gets very dry in winter but is also expected to function at very low temperatures.

Figure 1. Predicted time to recalibration generated by future prediction algorithm.



A perfect prediction (theoretical) would follow the dashed black line. In other words, the predicted days to recalibration would be exactly equal to the actual days to recalibration.

The solid black line shows the true electrolyte concentration, which gets dry (high concentration) each winter but recovers to some extent each summer. The yellow line shows how the concentration has been predicted. The historical relative humidity is calculated from the average of another 30 days prior to that. As the prediction is made over a longer time, it becomes less accurate, mainly because the historical environmental conditions become less representative of the future conditions.

How often does the sensor updates the EoL and Predictive Calibration?

The diagnostic test runs automatically every 24 hours. However, the test is only performed when the sensor is in sleep mode, so it is highly recommended to change the sensor to sleep mode whenever it is not in use (otherwise the End of Life and Predictive Calibration estimations will not be updated/recalculated, leading to non-accurate results).

The sensor needs to be in sleep mode at least two minutes per day, so it can update the EoL and Predictive Calibration values.

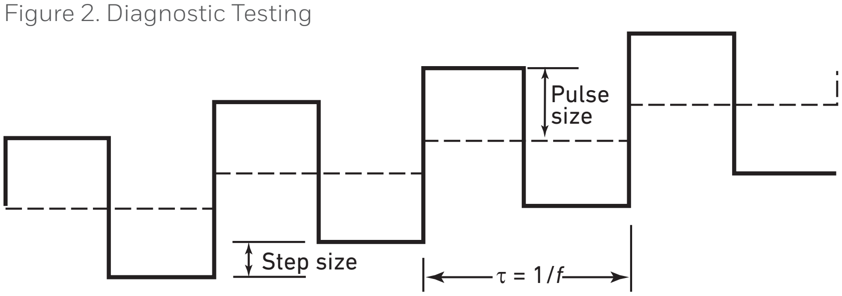
What technique is used for the diagnostic tests?

For this test, a smart indicative gadget is used as a diagnostic electrode. Then an electrochemical technique called square wave voltammetry is applied to the electrode.

The technique is a linear potential sweep voltammetry that uses a combined staircase potential and a square wave, which has the advantage of having better peak definition and location than conventional cyclic voltammetry or staircase voltammetry.

The diagnostic test is performed to determine the electrolyte concentration of the sensor.

Figure 2. Diagnostic Testing



How and when the End-of-Life and Predictive Calibration are flagged?

The error and faults can be transmitted to the instrument every time it requests a gas reading from the sensor. For additional information about the gas reading format consult get data pack command (0x30) in the User's Manual.

- The **Predictive Calibration** alarm consists of two different parameters, and the alarm will be triggered when either the countdown or the accuracy threshold are reached (whichever is triggered first):
  - The Predictive Calibration estimation will depend on the requested accuracy of the sensor. This parameter can be configured by the user: the tighter the accuracy value, the more frequently the calibration.
  - Additionally, a countdown timer can be set by the user. This period can reflect the time required to calibrate the sensor, which may vary depending on the specified standard or applications.

- Likewise, the **End-of-life** is flagged when either the countdown or the future prediction algorithm conditions are met (whichever is triggered first):
  - The predicted End-of-Life algorithm is flagged when the sensor detects less than 50% of its initial sensitivity or when the electrolyte concentration is above or below its limit. The sensitivity estimation is constantly updated and its calculation is based on the measure at the minimum temperatures at which the sensor has been exposed to.
  - Along with this, there is a five-year countdown timer. The alarm is flagged after the sensor has reached its expected lifespan.

How accurate are the End-of-life and Predictive Calibration functions?

The predictive model for End-of-life and time to calibration is highly accurate if the environmental conditions remain adequately constant.

An analogy to this is the ETA (estimated time to arrival) in a car's GPS system, which is based on previous average speed. If you travel at a constant speed, the ETA will count down linearly and be quite accurate over long distances. However, if you speed up or slow down the ETA could increase of decrease significantly throughout the journey.

Similarly, if a sensor is kept in constant conditions, the future prediction based on historical conditions should predict a long way into the future quite accurately, and as a result the time to end of life or recalibration would decrease linearly over time. If the sensor is put into a more aggressive environment, then its predicted time to EOL/recalibration will start to drop rapidly, whereas if a sensor that has been running in aggressive (e.g. dry) conditions is transferred to more benign conditions, the time to end of life or recalibration prediction may even increase over time.

Other diagnostic tests:

Just like the End-of-life and Predictive Calibration flags, the sensor can warn the instrument about other possible errors and failures that may appear on a sensor whenever a gas reading command is requested. These flags could also be used to indicate to the end user what type of maintenance is required, for example if the sensor warns that its electrolyte is getting too dry or wet the instrument could advise the user to store it in a suitable humidity environment to recover it.

The following table shows the possible failures that the sensor may encounter along with their corresponding automatic detection methods:

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ERROR DESCRIPTION	DETECTION METHOD	DESCRIPTION
Diagnostic electrode failure	Diagnostic electrode	Internal diagnostic electrode has failed or is unable to take a reading. This does not necessarily mean the sensor itself is not working, but diagnostics capability is compromised
Sensing electrode impedance too high	Reflex test	A small electrical pulse (reflex test) is used to check if the impedance of the sensing electrode circuit is outside the expected range. May be due to mechanical loss of contact or electrode damage/degradation
Reference electrode failure	Diagnostic electrode	The electrochemical voltage of the reference electrode is compared with an internally generated standard. If the reference voltage has drifted out of range, the sensor performance may be compromised (slow response, low sensitivity, baseline offset, etc.)
Electrolyte too dry	Diagnostic electrode	Sensor has lost too much water from its electrolyte by evaporation due to operation for too long in dry conditions. Sensor performance is likely to be degraded
End of life	Diagnostic electrode	The sensitivity has decayed below its acceptable lower limit and the sensor is no longer usable, or it has exceeded its five-year life. Replace sensor
Counter electrode failure	Counter polarisation measurement	Counter electrode in sensor is overloaded or not working correctly. This may result in the sensor being unable to maintain correct operating conditions, causing performance degradation
Span calibration is due	Prediction algorithm and countdown timer	Calibration is due, based on either fixed countdown timer or predicted accuracy out of range, whichever occurs first
Bump test is due	Countdown timer	Predefined time since last bump test has been exceeded. A bump test is a brief exposure of the instrument to the target gas in order to verify that the sensor responds and the alarms function accordingly
User factor not valid		User factor has not been set or instrument has selected a user factor that is not defined. This is likely to be caused by using a sensor that has not been characterised for use with this instrument. The user factor is used to correct the sensor reading for effects of the instrument on the gas concentration
Temperature out of range	Temperature out of range (-40 °C, 60°C)	Sensor has been exposed to temperatures outside of the rated operating range, which may have damaged it
Electrolyte too wet	Diagnostic electrode	The sensor electroyte has absorbed too much water. Due to operation in high humidity for too long. Performance may be degraded, and there is risk of the sensor bursting or leaking due to the volume increase of the electrolyte
ROM check failed	Non-volatile memory check	The program memory stores the firmware code. After system start-up, the LRC is calculated (32 bytes per second) for the whole app firmware code, then the result is compared with the initial value stored in the ROM memory. If these parameters do not match, an error is flagged.
RAM check failed	Volatile memory check	Volatile memory is the microcontroller internal RAM used as the runtime data memory. In the firmware, the RAM is tested with checkboard algorithms: during the test, a 4 bytes words are written and the readback is checked.

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