MOLECULAR PROPERTY SPECTROMETER™ (MPS™)

FLAMMABLE GAS SENSOR

USER MANUAL

NNTS Proprietary Information

SM-UM-0002-09

Notices

SM-UM-0002-09

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Contents

Version	Issue Date (DD/MM/YYYY)	Change
SM-UM-0002-01	06/09/2019	First released version
SM-UM-0002-02	13/09/2019	Corrections to status field table and 0x09 command description
SM-UM-0002-03	20/09/2019	Updated status field table (new status 0x37), updated 0x04 command output table (new IDs 253, 254)
SM-UM-0002-04	07/10/2019	Updated status field table and Section 4. Note: this version of the manual pertains to firmware versions 3.0.0.0 and forward.
SM-UM-0002-05	14/10/2019	New command to query 'sensor info' (0x43)
SM-UM-0002-06	02/12/2019	Updated status table and Section 4.1. Note: this version of the manual pertains to firmware versions 3.0.2.0 and later. Added Section 2.2, Analog output mode
SM-UM-0002-07	10/12/2019	Added Section 4.2 and Section 5
SM-UM-0002-08	03/01/2020	Added Section 6
SM-UM-0002-09	15/01/2020	Updated Sections 4.1 and 6.2

1. How the MPS Flammable Gas Sensor Works

The MPS Flammable Gas Sensor is a smart sensor with built-in environmental compensation that detects and accurately quantifies a dozen gases as well as gas mixtures. It is intrinsically safe, robust, extremely poison-resistant, and calibrated for all gases by performing only a single calibration with methane. Sensor readings are output on a standard digital bus or industry-standard analog output.

The MPS transducer is a micro-machined membrane with an embedded Joule heater and resistance thermometer. The MEMS transducer is mounted on a PCB and packaged inside a filtered enclosure that is permeable to ambient air. Presence of a flammable gas causes changes in the thermodynamic properties of the air/gas mixture; these properties are measured by the transducer and processed by patent-pending algorithms to report an accurate concentration and to classify the flammable gas.

Other sensing technologies (e.g. catalytic bead, NDIR) require a "k-factor" multiplier to convert raw sensor signals to gas concentrations in %LEL. These "k-factors" are based on known relative sensitivities of these sensors to different gases. A single "k-factor", corresponding to a particular gas, must be selected manually during system setup; if the sensor is then exposed to a gas other than the one selected, significant errors in reported concentration occur.

In contrast, the MPS Flammable Gas Sensor applies a real-time conversion factor automatically, using the latest measured thermal properties of the ambient air/gas and the environmental conditions (Figure 1). The %LEL values reported for the bulk, which may contain a mixture of gases, achieves the same high levels of accuracy achieved with single gases. Additional smart algorithms enable determination of the class of gas present, according to the categories in Figure 2.

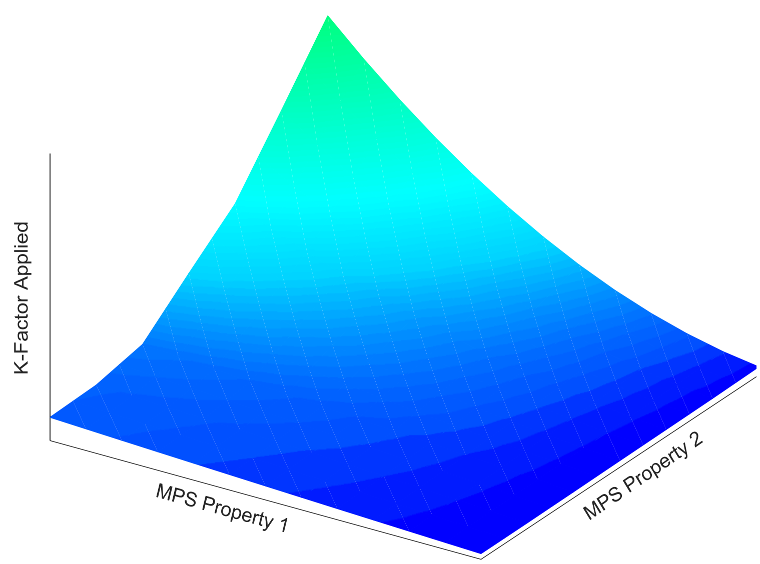


Figure 1: The MPS uses multiple measured properties of the air/gas mixture to automatically apply a real-time conversion factor—enabling high accuracy for 12 different gases at all times.

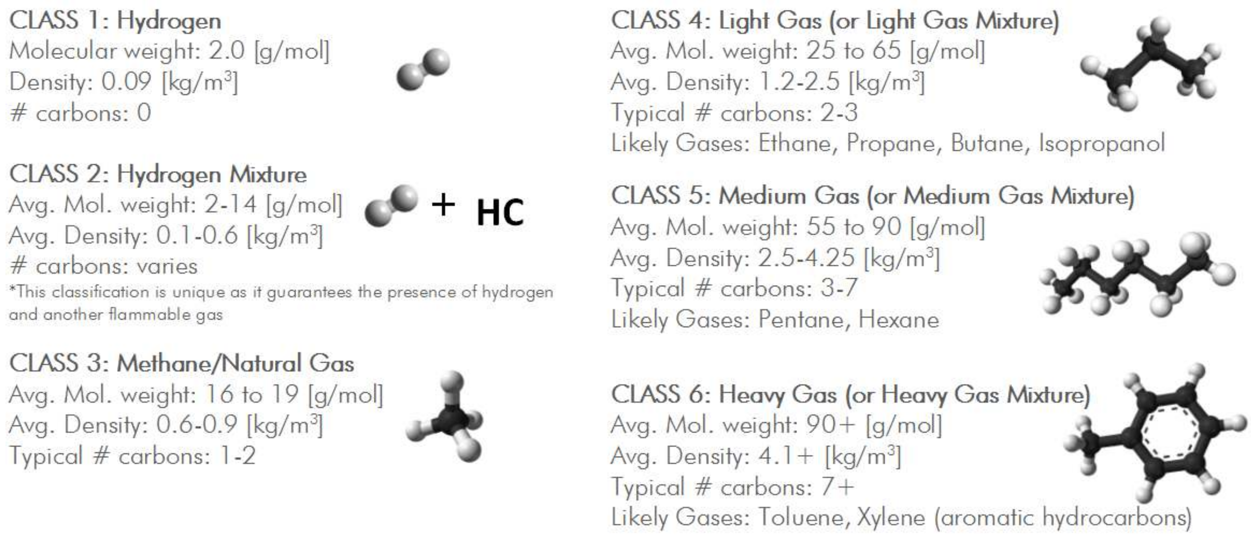


Figure 2: The MPS Flammable Gas Sensor outputs the class of gas present. This capability to discriminate amongst gases is what enables the sensor to provide accurate %LEL readings for 12 different flammable gases. The MPS is the only technology on the market with this capability.

2. Communicating with the MPS Flammable Gas Sensor

This section describes the software interface requirements for the MPS Flammable Gas Sensor and will be useful to system integrators when designing the sensor assembly into a final product.

The preferred method of communicating with the sensor is over the serial interface using the UART (Universal Asynchronous Receiver/Transmitter) protocol. Section 2.1 provides the necessary information for communicating using UART.

Communication over I^2C (Inter-integrated Circuit) protocol is also supported, and has been verified to work with the following host systems: Beaglebone Black and Expressif ESP32. Contact NevadaNano for further information about communicating using I^2C.

2.1. Serial (UART) Communication

Communication with the system over the serial interface (UART) will allow an external user or system to execute the commands provided in the Command Table in Section 2.1.5. Users may also refer to the Command Descriptions in Section 2.1.6 for usage descriptions.

Serial connection parameters:

Parameter	Size
Baud Rate	38400
Data Size	8 bits
Parity	None
Stop Bit	1 bit

2.1.1. Data Representation

All integer values (16 bits or 32 bits) are represented in Little Endian format (LSB first). This means when an integer is transmitted on the serial interface, the least significant byte (LSB) is transmitted first and the most significant byte (MSB) is transmitted last.

Floating point numbers are represented in IEEE 754 format.

2.1.2. Protocol Specification

Communication to and from the MPS Flammable Gas Sensor is made up of "packets." The communication paradigm is that of "request" and "reply." An external host sends a "request" packet to the sensor. The sensor returns a "reply" packet to the external host. A packet consists of a fixed size "header" and a variable length "payload." It is possible for a packet to have no payload (length of zero) where a packet contains only a header. The payload, if any, typically consists of "parameters" for a request or "result" for a reply. Even when a reply does not contain any result, a reply is still sent with the header as an acknowledgement of the request.

Command Request

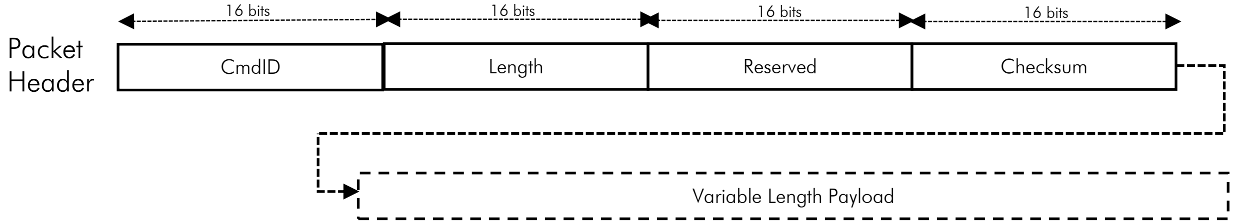


Figure 3: Request Packet Structure

The Request Packet (Figure 3) consists of the following fields:

Field	Size	Description
CmdID	2 Bytes	Command ID of this request (see Command Table in section 2.1.5). Although CmdID uses only 1 byte, it is extended to 2 bytes in the Request Header for alignment purposes.
Length	2 Bytes	Length of the Payload (0 if no payload)
Reserved	2 Bytes	Reserved for future use (zero filled)
Checksum	2 Bytes	Checksum of the entire packet
Variable Length Payload	variable	Command parameters for this request

Command Reply

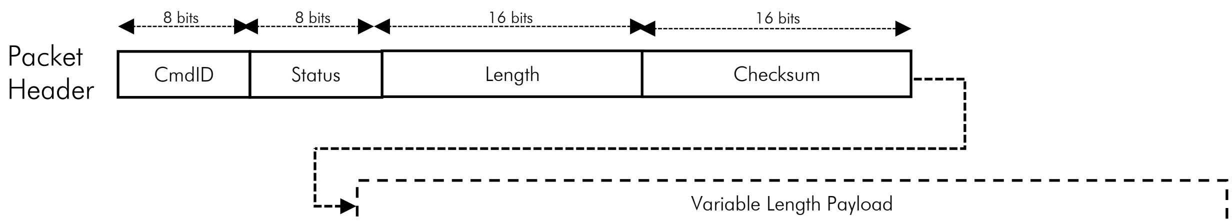


Figure 4: Reply Packet Structure

The Reply Packet (Figure 4) consists of the following fields:

Field	Size	Description
CmdID	1 Byte	Command ID (should match the original request)
Status	1 Byte	Return status of the request
Length	2 Bytes	Length of the Payload (0 if no payload)
Checksum	2 Bytes	Checksum of the entire packet
Variable Length Payload	variable	Command parameters for this request

The Status field consists of the following possible return values:

Fault	Fault Message	Explanation	%LEL Output	User action
0x00	OK	MPS is operating normally and has no errors	Normal	None
0x01	CRC_FAILED	Transmitted data failed checksum	N/A	Verify checksum calculation is correct. See Section 2.1.3.
0x02	BAD_PARAM	Illegal or bad parameters specified	N/A	Verify parameter given in command is correct.
0x03	EXE_FAILED	Execution of command failed	N/A	Contact support.
0x04	NO_MEM	Insufficient memory for operation	N/A	Contact support.
0x05	UNKNOWN_CMD	Unknown Command ID specified	N/A	Verify Command ID is correct. See Section 2.1.5.
0x07	INCOMPLETE_COMMAND	Incomplete or truncated command	N/A	Verify entire packet header and payload (if any) is fully sent.
0x20	HW_ERR_AO	Analog out malfunction (only if AO functionality enabled)	-100 %LEL	Contact support.
0x21	HW_ERR_VDD	Internal voltage out of range	-100 %LEL	Contact support
0x22	HW_ERR_VREF	Voltage out of range	-100 %LEL	Supply 3.3-5.0 ±5% VDC. If this error persists for more than 5 cycles, this error will latch until the sensor is power cycled and supplied correct voltage
0x23	HW_ENV _XCD_RANGE	Environmental (Temp., Press., Humid.) out of range	Normal	Return sensor to specified operating range. See Section 4.1.
0x24	HW_ENV_SNSR_MALFUNCTION	Environmental sensor malfunction	-100 %LEL	Occurrence of this error will latch the sensor in this condition and no longer allow normal operation. Contact support.
0x25	HW_ERR_MCU_FLASH	Microcontroller error	-100 %LEL	Contact support.
0x26	HW_SENSOR_INITIALIZATION	Sensor in initialization mode (10 cycles)	-100 %LEL	Wait 10 cycles (~20 sec) for sensor to initialize.
0x30	HW_SENSOR_NEGATIVE	Sensor output <-15%LEL; accuracy affected if flammable gas initially detected while in this condition	Normal	Wait for sensor to return to zero. If message persists >10 minutes, contact support.
0x31	HW_CONDENSE_COND	Condensation condition exists at sensor (out of specification)	Normal	Raise temperature and/or lower humidity. See Section 4.1.
0x32	HW_SENSOR_MALFUNCTION	Gas sensing element malfunction	-100 %LEL	Contact support.

2.1.3. Checksum Calculation

The algorithm for checksum calculation is that of 16-bit CRC CCITT with start byte 0xFFFF. Checksum is computed over the entire packet (header and payload). The checksum field in the header is initialized with zeros before computing checksum. If there is no payload, checksum is computed against the header only. The following sample C code can be used to calculate the checksum for a buffer of a given size:

```
#include <stdlib.h>
#include <stdint.h>

static uint16_t crc_table[256] = {
  0x0000, 0x1021, 0x2042, 0x3063, 0x4084, 0x50a5, 0x60c6, 0x70e7,
  0x8108, 0x9129, 0xa14a, 0xb16b, 0xc18c, 0xd1ad, 0xe1ce, 0xf1ef,
  0x1231, 0x0210, 0x3273, 0x2252, 0x52b5, 0x4294, 0x72f7, 0x62d6,
  0x9339, 0x8318, 0xb37b, 0xa35a, 0xd3bd, 0xc39c, 0xf3ff, 0xe3de,
  0x2462, 0x3443, 0x0420, 0x1401, 0x64e6, 0x74c7, 0x44a4, 0x5485,
  0xa56a, 0xb54b, 0x8528, 0x9509, 0xe5ee, 0xf5cf, 0xc5ac, 0xd58d,
  0x3653, 0x2672, 0x1611, 0x0630, 0x76d7, 0x66f6, 0x5695, 0x46b4,
  0xb75b, 0xa77a, 0x9719, 0x8738, 0xf7df, 0xe7fe, 0xd79d, 0xc7bc,
  0x48c4, 0x58e5, 0x6886, 0x78a7, 0x0840, 0x1861, 0x2802, 0x3823,
  0xc9cc, 0xd9ed, 0xe98e, 0xf9af, 0x8948, 0x9969, 0xa90a, 0xb92b,
  0x5af5, 0x4ad4, 0x7ab7, 0x6a96, 0x1a71, 0x0a50, 0x3a33, 0x2a12,
  0xdbfd, 0xcbdc, 0xfbbf, 0xeb9e, 0x9b79, 0x8b58, 0xbb3b, 0xab1a,
  0x6ca6, 0x7c87, 0x4ce4, 0x5cc5, 0x2c22, 0x3c03, 0x0c60, 0x1c41,
  0xedae, 0xfd8f, 0xcdec, 0xddcd, 0xad2a, 0xbd0b, 0x8d68, 0x9d49,
  0x7e97, 0x6eb6, 0x5ed5, 0x4ef4, 0x3e13, 0x2e32, 0x1e51, 0x0e70,
  0xff9f, 0xefbe, 0xdfdd, 0xcffc, 0xbf1b, 0xaf3a, 0x9f59, 0x8f78,
  0x9188, 0x81a9, 0xb1ca, 0xa1eb, 0xd10c, 0xc12d, 0xf14e, 0xe16f,
  0x1080, 0x00a1, 0x30c2, 0x20e3, 0x5004, 0x4025, 0x7046, 0x6067,
  0x83b9, 0x9398, 0xa3fb, 0xb3da, 0xc33d, 0xd31c, 0xe37f, 0xf35e,
  0x02b1, 0x1290, 0x22f3, 0x32d2, 0x4235, 0x5214, 0x6277, 0x7256,
  0xb5ea, 0xa5cb, 0x95a8, 0x8589, 0xf56e, 0xe54f, 0xd52c, 0xc50d,
  0x34e2, 0x24c3, 0x14a0, 0x0481, 0x7466, 0x6447, 0x5424, 0x4405,
  0xa7db, 0xb7fa, 0x8799, 0x97b8, 0xe75f, 0xf77e, 0xc71d, 0xd73c,
  0x26d3, 0x36f2, 0x0691, 0x16b0, 0x6657, 0x7676, 0x4615, 0x5634,
  0xd94c, 0xc96d, 0xf90e, 0xe92f, 0x99c8, 0x89e9, 0xb98a, 0xa9ab,
  0x5844, 0x4865, 0x7806, 0x6827, 0x18c0, 0x08e1, 0x3882, 0x28a3,
  0xcb7d, 0xdb5c, 0xeb3f, 0xfb1e, 0x8bf9, 0x9bd8, 0xabbb, 0xbb9a,
  0x4a75, 0x5a54, 0x6a37, 0x7a16, 0x0af1, 0x1ad0, 0x2ab3, 0x3a92,
  0xfd2e, 0xed0f, 0xdd6c, 0xcd4d, 0xbdaa, 0xad8b, 0x9de8, 0x8dc9,
  0x7c26, 0x6c07, 0x5c64, 0x4c45, 0x3ca2, 0x2c83, 0x1ce0, 0x0cc1,
  0xef1f, 0xff3e, 0xcf5d, 0xdf7c, 0xaf9b, 0xbfba, 0x8fd9, 0x9ff8,
  0x6e17, 0x7e36, 0x4e55, 0x5e74, 0x2e93, 0x3eb2, 0x0ed1, 0x1ef0,
};

uint16_t crc_generate(uint8_t *buffer, size_t length, uint16_t startValue)
{
  uint16_t crc;
  uint8_t *p;
  int ii;

  crc = startValue;

  for(p = buffer, ii = 0; ii < length; ii++) {
```

```
    crc = (crc << 8) ^ crc_table[(crc >> 8) ^ *p];
    p++;
  }

  return crc;

}
```

For more information on how to use the above function, please look at the sample test program "Sample Code" located here: https://nevadanano.com/downloads

2.1.4. Startup and Measurement Sequence

Figure 5 describes the recommended steps after powering on the sensor plus the measurement sequence for getting answer data. The major steps consist of the following:

- After powering on the sensor, wait for the sensor to boot up completely (~3 seconds).
- Verify communication channel by asking the sensor for version information.
    - Firmware version information can be used to determine if a new firmware is available for upgrade.
    - Protocol version can be used to determine available commands, answers or new data.
- Start measurement in "continuous" mode.
- Wait 2 seconds for the first measurement to complete.
- Get Answer.
- Repeat process to get answer at desired frequency.

The sensor initializes for the first 10 cycles after powering up. During this period, the sensor output is set to "-100 %LEL", the sensor status is set to HW_SENSOR_INITIALIZATION, and the sensor is not capable of reporting gas concentrations. Once initialization is complete, the sensor is ready to report gas concentrations, and the status is set to 0x00.

Note: It takes approximately 2 seconds to calculate and complete a measurement. If multiple requests to read the Answer register (0x01) were made within a two-second window, one might get the same answer. This depends on whether a new measurement is calculated between multiple Answer requests. The MPS Cycle Count ("COUNT") in the Answer Response is incremented after each measurement is calculated. Therefore, when processing an "answer," one should compare the COUNT value in the answer against the COUNT value from the previous answer. If the COUNT value did not increment, this a repeated answer. If the COUNT value incremented, this is a new answer from the latest measurement cycle. When continuous measurement is stopped and restarted, the COUNT value resets to 1 with the first measurement.

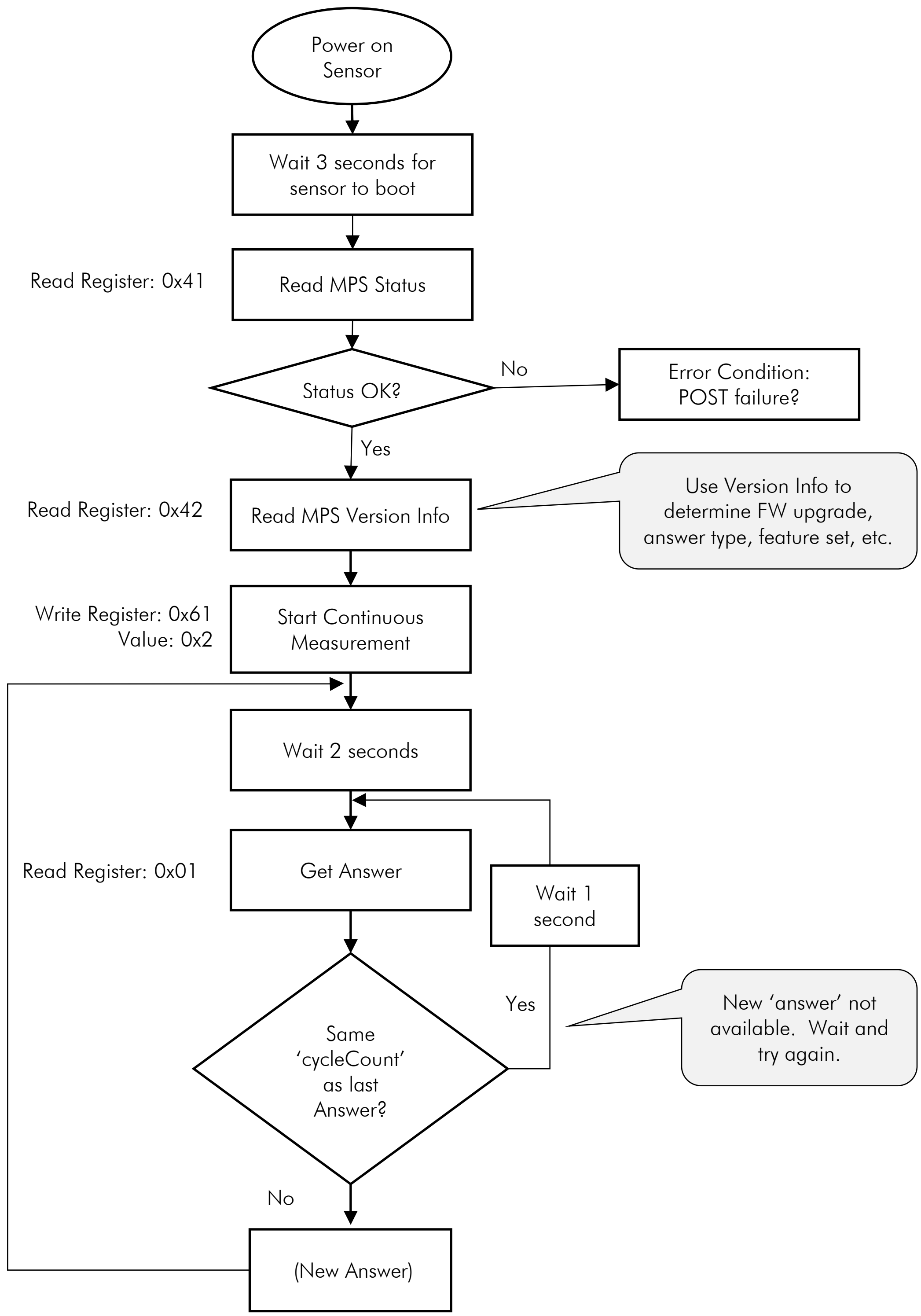
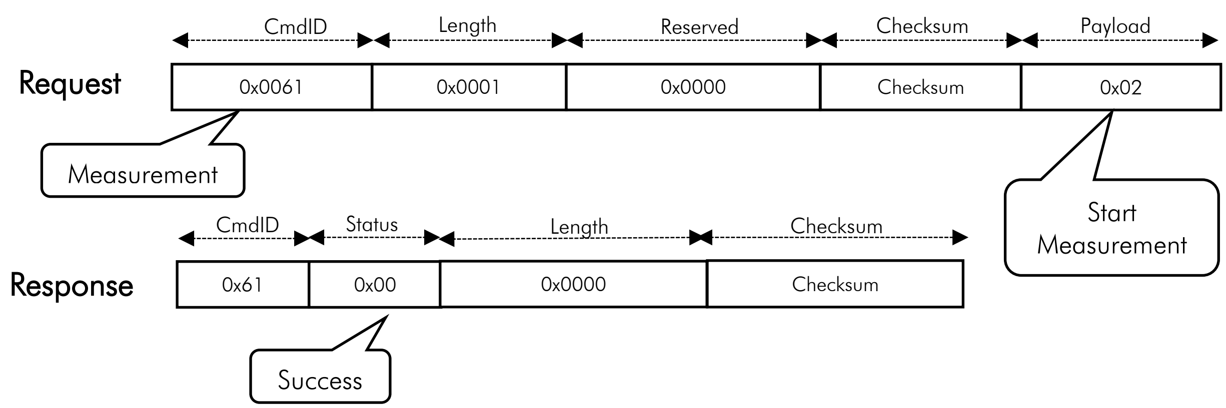


Figure 5: Startup and Measurement Sequence

Figure 6 describes sample Request and Response packets for the Perform Measurement and Get-Answer Vector sequences.

Perform Measurement



Get Answer Vector

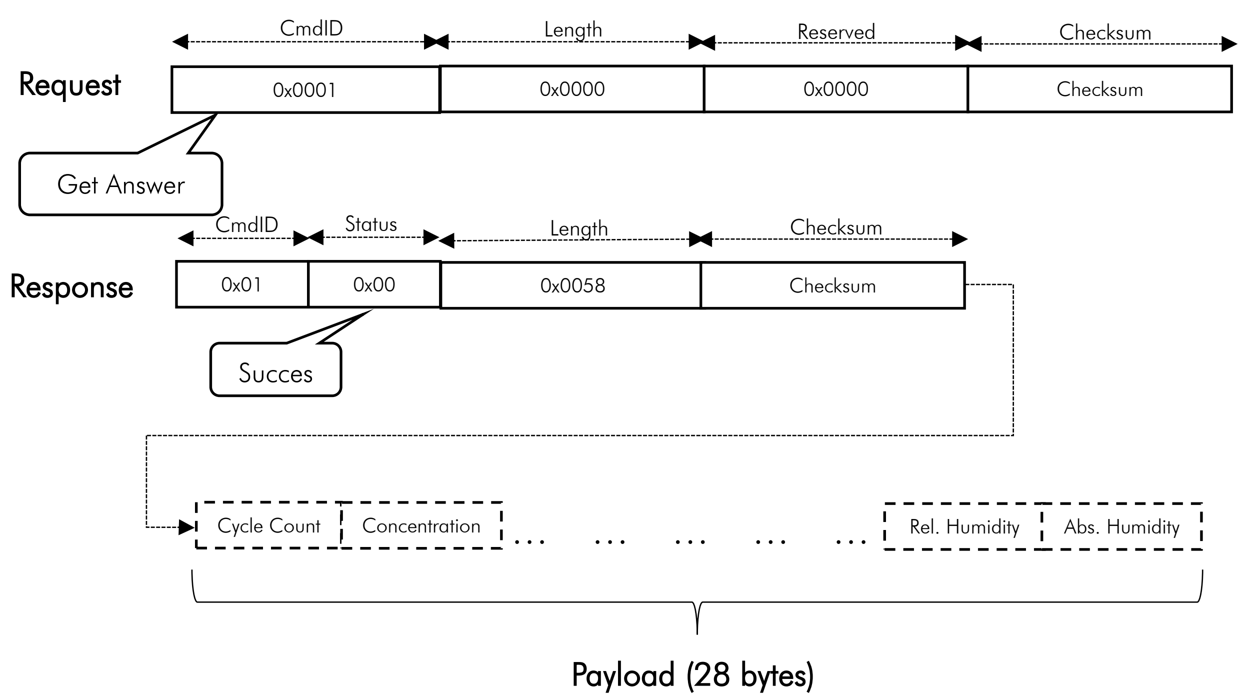


Figure 6: Sample Request and Response Packets for Performing Measurement and Get Answer Vector

2.1.5. Command Table

Hex Code	Command ID	Payload Length [bytes]	
		Request	Response
0x01	ANSWER	0	28
0x03	CONC	0	4
0x04	ID	0	4
0x09	ENG_DATA	0	84-128
0x21	TEMP	0	4
0x22	PRES	0	4
0x23	REL_HUM	0	4
0x24	ABS_HUM	0	4
0x41	STATUS	0	1
0x42	VERSION	0	8
0x43	SENSOR_INFO	0	68
0x61	MEAS	1	0
0x62	SHUT_DOWN	0	0

2.1.6. Command Descriptions

1. Command 0x01 – ANSWER – Read Complete Answer

Description: Returns a complete answer in one read operation.
Parameters: N/A
Response:

CYCLE_COUNT	32-bit unsigned value. Cycle Number of this measurement (incremented after each measurement)
CONC	32-bit floating point value. Flammable gas concentration [%LEL or %VOL]
ID	32-bit unsigned value. Flammable gas ID. See “Command 0x04 – ID” for descriptions of gas ID values.
TEMP	32-bit floating point value. Ambient temperature [°C]
PRESSURE	32-bit floating point value. Ambient pressure [kPa]
REL_HUM	32-bit floating point value. Ambient relative humidity [%RH]
ABS_HUM	32-bit floating point value. Ambient absolute humidity $[\frac{g}{m^3}]$

2. Command 0x03 – CONC – Read Flammable Gas Concentration

Description: Returns flammable gas concentration (%LEL or %VOL) as measured by the MPS.
Parameters: N/A
Response: CONC 32-bit floating point value. Flammable gas concentration (%LEL or %VOL)

3. Command 0x04 – ID – Read Flammable Gas ID

Description: Returns flammable gas ID as determined by the MPS.
Parameters: N/A
Response: ID 32-bit unsigned value. Flammable gas ID.

ID	Description
0	No Gas
1	Hydrogen
2	Hydrogen Mixture
3	Methane
4	Light Gas
5	Medium Gas
6	Heavy Gas
253	Unknown Gas
254	Under Range – Concentration less than -5 %LEL
255	Over Range – Concentration greater than 100 %LEL

4. Command 0x09 – ENG_DATA – Read Engineering Data

Description: Returns raw engineering (binary) data for analysis and debugging.
Parameters: N/A
Response: LENGTH 32-bit unsigned value. Length of engineering data.
DATA Engineering data (80 to 124 bytes). Actual size of data is specified in the LENGTH field.

5. Command 0x21 – TEMP – Read Temperature

Description: Returns the ambient temperature (°C) as reported by the integrated environmental sensor.
Parameters: N/A
Response: TEMP 32-bit floating point value. Ambient temperature (°C).

6. Command 0x22 – PRES – Read Pressure

Description: Returns the ambient pressure (kPa) as reported by the integrated environmental sensor.
Parameters: N/A
Response: PRESSURE 32-bit floating point value. Ambient pressure (kPa).

7. Command 0x23 – REL_HUM – Read Relative Humidity

Description: Returns the ambient relative humidity (%RH) as reported by the integrated environmental sensor.
Parameters: N/A
Response: REL_HUM 32-bit floating point value. Ambient relative humidity (%RH).

8. Command 0x24 – ABS_HUM – Read Absolute Humidity

Description: Returns the ambient absolute humidity ($\frac{g}{m^3}$) as calculated by the MPS.

Parameters: N/A

Response: ABS_HUM 32-bit floating point value. Ambient absolute humidity ($\frac{g}{m^3}$).

9. Command 0x41 – STATUS – Read MPS Status

Description: Returns the status of the MPS; refer to Sec. 2.1.2 for status descriptions.

Parameters: N/A

Response: STATUS 8-bit unsigned value. Status of MPS

10. Command 0x42 – VERSION – Read MPS Version Info

Description: Returns the software, hardware and protocol versions of the MPS.

Parameters: N/A

Response:

SW_VERSION	8-bit unsigned values. Version is W.X.Y.Z
HW_VERSION	8-bit unsigned values. Version is W.X
PROTOCOL_VERSION	8-bit unsigned values. Version is W.X

MPS Version Info

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
SW Version W [7:0]								SW Version X [7:0]								SW Version Y [7:0]								SW Version Z [7:0]							

33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64
HW Version W [7:0]								HW Version X [7:0]								Protocol Version W [7:0]								Protocol Version X [7:0]							

11. Command 0x43 – SENSOR_INFO – Read MPS Sensor Info

Description: Returns information about the sensor.

Parameters: N/A

Response:

SERIAL_NUM	Sensor serial number. 32 bytes, zero-padded ASCII string.
SENSOR_TYPE	Sensor type. 32-bit unsigned integer. (Note: "MPS Flammable Gas Sensor" sensor type = 0x03)
CAL_DATE	Date of last calibration. 16 bytes, zero-padded ASCII string. Format is MM/DD/YYYY.
MFG_DATE	Date of manufacture. 16 bytes, zero-padded ASCII string. Format is MM/DD/YYYY.

12. Command 0x61 – MEAS – Perform Measurement

Description: Sets the sensing mode (idle, single, or continuous) and "concentration unit" in the measurement.

Parameters: The parameter to the Measurement command is 1 byte in length but consists of two, 4-bit values: Concentration Unit (bits 7:4) and Mode (bits 3:0).

Measurement Value (Byte)		
	Conc. Unit [7:4]	Mode [3:0]

The "concentration unit" (bits 7:4 of the measurement byte) can be either %LEL or %VOL. By specifying the desired unit, the response for commands 0x01 and 0x03 will be either %LEL or %VOL.

Unit	Name	Description
0x0	PERCENT_LEL	Concentration reported as %LEL.
0x1	PERCENT_VOL	Concentration reported as %VOL.

The measurement mode (bits 3:0 of the measurement byte) consists of the following possible values:

MODE	Name	Description
0x2	MPS_CONT	MPS operates in an autonomous, continuous mode
0x3	MPS_STOP	Stop measurement – no measurements are being taken

Response: N/A

13. Command 0x62 – SHUT_DOWN – Shut down MPS

Description: Prepares the MPS for a shutdown by saving necessary data and states.

Parameters: N/A

Response: N/A

2.2. Sensor Analog Output Mode

The MPS Flammable Gas Sensor is factory-configurable to report gas concentrations via an analog signal that mimics the output of conventional catalytic bead flammable gas sensors. By default, this feature is disabled. The analog output signal from the MPS Flammable Gas Sensor is generated with a digital-to-analog converter. The standard analog output range, shown in Fig. 7, is 0.4 V (0 %LEL) to 2.0 V (100 %LEL), linearly increasing at 0.016 $\frac{V}{\%LEL}$. As with the digital communication mode, the MPS output concentration resolution is 0.1 %LEL for analog outputs. Upon startup, the analog output pin may report between 0.75-1.75 V momentarily (<100 ms) during initialization.

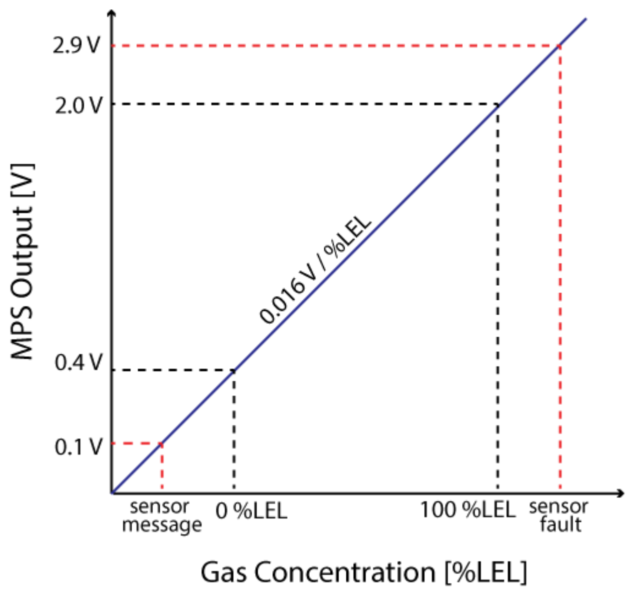


Figure 7: MPS Flammable Gas Sensor output when configured in analog mode.

When there is an error condition or special status, as reported by the sensor status field (outlined in Section 2.1.2.), the voltage level does not indicate gas concentration. Instead, the voltage is set to report an error or special status (see table below). Only critical statuses, messages that indicate the sensor's initialization sequence, or the indication that the sensor output is negative are conveyed to the user. Non-critical status messages (e.g.: HW_ENV _XCD_RANGE, HW_CONDENSE_COND) are not reported in analog output mode. The following table indicates the output voltage corresponding to each sensor message and critical status.

Status	Voltage [V]
HW_ERR_VDD	2.9
HW_ERR_AO	2.9
HW_ERR_VREF	2.9
HW_ENV_SNSR_MALFUNCTION	2.9
HW_ERR_MCU_FLASH	2.9
HW_SENSOR_INITIALIZATION	0.1
HW_SENSOR_NEGATIVE	0.1
HW_SENSOR_MALFUNCTION	2.9

3. Testing the MPS Flammable Gas Sensor

The MPS measures molecular properties to determine the quantity of flammable gas present in a sample. The system is optimized for "real-world" operation. As such, the effects of humidity, temperature and pressure are automatically compensated out. However, sudden, wholesale changes to the molecular properties of the sample (i.e. artificial changes which can only be generated in a lab test rig) can lead to inaccurate MPS outputs. This of course excludes changes due to the presence of flammable gas.

An example of an inadvisable change (shown in Fig. 8c, 8d) would be alternating between ambient air (which contains argon, carbon dioxide and other trace gases) and flammable gas + synthetic "zero air" balance (which contains none of the trace constituent gases in ambient air). To properly simulate the real-world application (Fig. 8a) in artificial laboratory testing, the same type of "air" must be used for the background and the carrier of the flammable gas for the duration of the test. An example of a proper protocol is shown in Fig. 8b. Using a variation of the "incorrect" procedure will invalidate the accuracy of MPS measurements.

A "best practice" for performance testing in a laboratory is to use a humidified zero-air background, followed by a switch to a humidified analyte stream with the same zero-air composition as balance gas, then a switch back to humidified zero-air to clear the test chamber. This mimics real-world MPS performance, where flammable gas is introduced into relatively invariant ambient air (Fig. 8a).

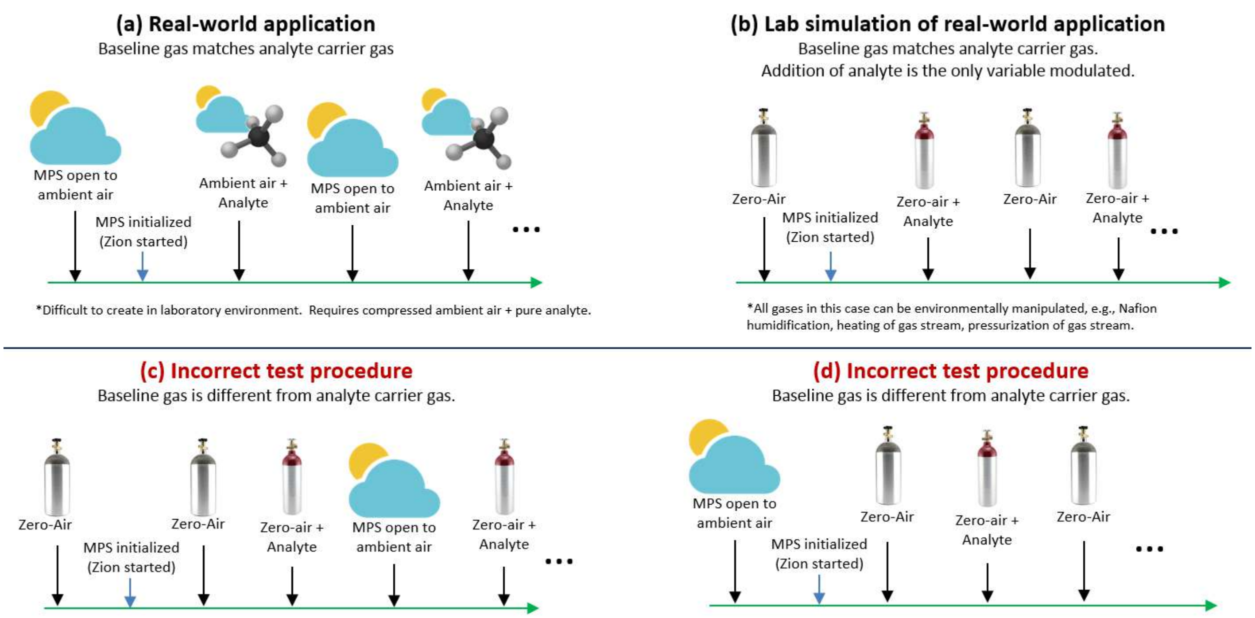


Figure 8: (a) The real-world flammable gas leak scenario. (b) The method for simulating the real-world scenario in a laboratory. Incorrect test procedures are shown in (c) and (d); in these cases, the carrier-only condition does not use the same "air" as the carrier + flammable gas condition, causing inaccurate results.

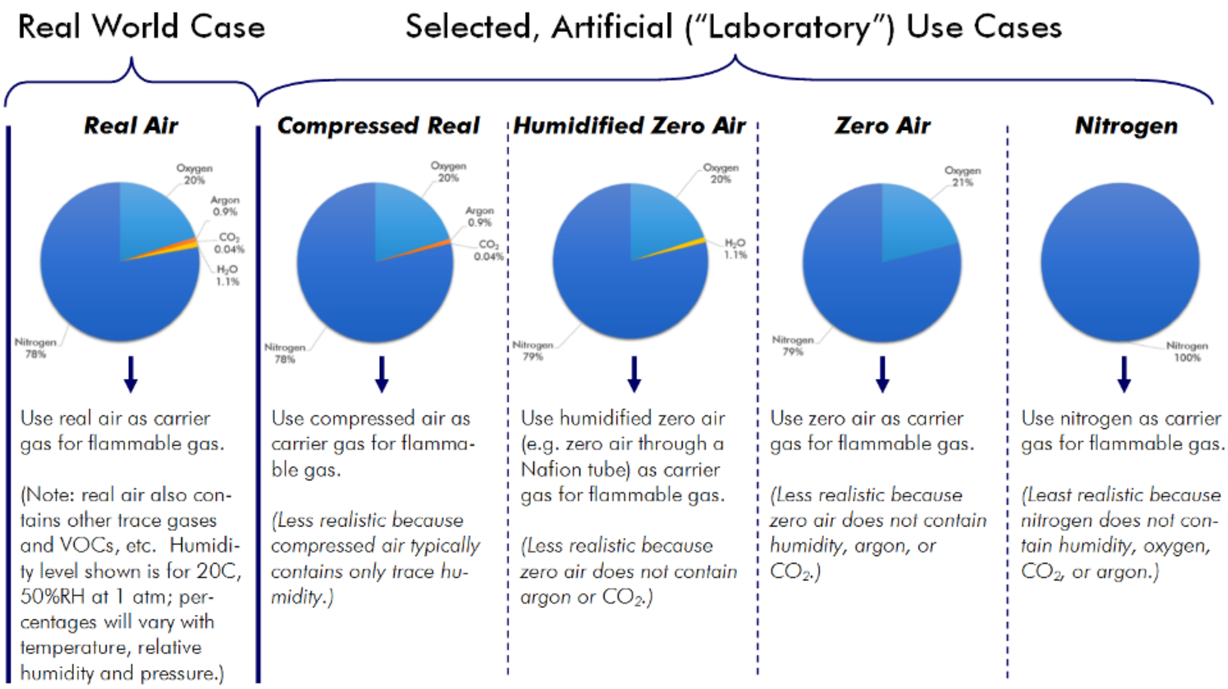


Figure 9: Various "air" options for use as the carrier, or background, gas during flammable gas testing. The best practice is to use one of the options toward the left side of the figure. In addition, do not switch between two different types of "air" during an experiment, as this can produce unwanted (and unrealistic) testing artifacts.

3.1. Typical Test Setups

Various test setups can be used to perform tests with the MPS Flammable Gas Sensor. One common test setup uses two regulated gas cylinders: zero air (20.9 %volume oxygen in nitrogen), and 50 %LEL methane in a balance of zero air.

3.1.1. Setup #1: Gas Testing in Various Environmental Conditions

Regulated gas cylinders are connected to a gas mixing system (e.g. Environics 4040) to control gas flow rates and concentrations. The gas travels through a heat exchanger and humidity-permeable tubing (e.g. Nafion™ TT-110[1]), allowing the gas to reach the chamber temperature and relative humidity. Gas then flows serially through each of the MPS sensors and out a vent exhaust-tube. The environmental chamber is programmed with the required temperature/humidity profiles for each test. Gas profiles are created in the gas mixing system software to deliver the analyte at the correct time. Flow rate is constant at 300 mL/min for both analyte and zero air throughout the tests.

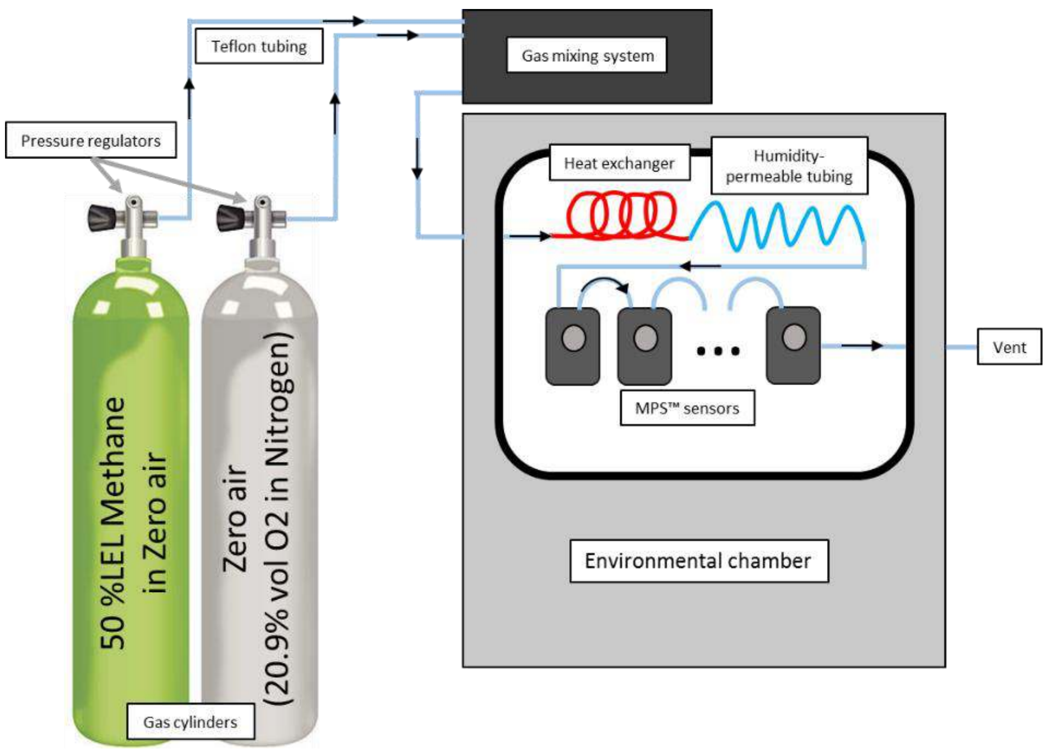


Figure 10: Setup #1: Gas Testing in Various Environmental Conditions

[1] https://www.permapure.com/products/nafion-tubing/nafion-dryer-performance-and-selectivity/

3.1.2. Setup #2: General Benchtop Testing

Regulated gas cylinders are connected together via a 3-way valve, a rotameter, and humidity-permeable tubing to the sensors. The sensors are encased in a plastic box with a removable lid that seals against the face of the sensor. The lid contains an inlet and an outlet that allows for multiple sensors to be connected in series. The 3-way valve allows gas switching, the rotameter enables flow control, and the Nafion™ tubing humidifies the gas stream. The flow is regulated at 300 mL/min throughout the test to maintain near-constant gas concentration throughout all sensors.

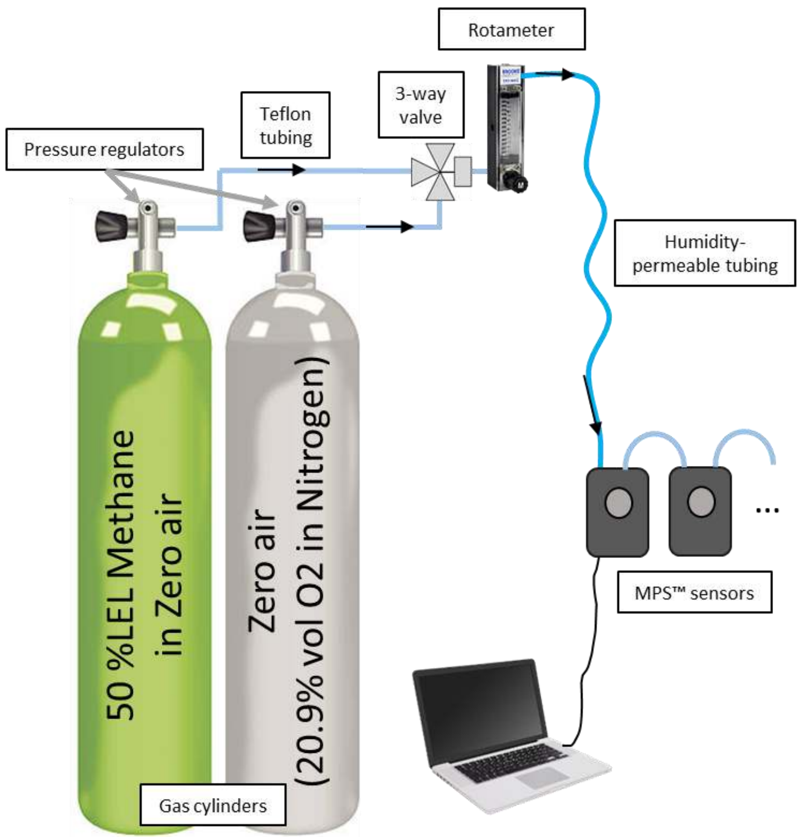


Figure 11: Setup #2: General benchtop testing.

4. Operating Conditions for the MPS Flammable Gas Sensor

The table below provides a summary of standardized tests and test conditions to which the MPS Flammable Gas Sensor has been subjected. The sensor has passed all of these tests by demonstrating performance within the MPS Flammable Gas Sensor specification both before and after each test.

Test	Specification	Summary of Test Conditions
High Temperature Operating	IEC 60068-2-2	1000 Hours @ 85°C
Low Temperature Operating	IEC 60068-2-1	1000 Hours @ -50°C
Drop	IEC 60068-2-31	1-meter drop onto concrete
Shock	IEC 60068-2-27	50G peak/11ms half sine pulse, 3-axes (positive and negative pulses)
Vibration	IEC 60068-2-6	31Hz – 150 Hz (2G acceleration), 1 hour per axis, 3-axes
Sand/Dust	MIL-STD-810G Method 510.5	Sand: 150-600 μm SiO_2 particle size, 23 m/s nom. velocity, 5 hours @ 70°C per axis, 3-axes Dust: Red China Clay, 1.5 m/s nom. velocity, 6 hours @ 70°C per axis, 3-axes
Poisoning	NevadaNano	1000 ppm-hours H_2S (50 ppm for 20 hours) 100 ppm-hours HMDSO (10 ppm for 10 hours)
EMC: Radiated Immunity	IEC/EN 61000-4-3	80 MHz – 2.7 GHz up to 10 V/m
EMC: Magnetic Immunity	IEC/EN 61000-4-8	30 A/m, 3-axes
EMC: Electrostatic Discharge	IEC/EN 61000-4-2	Up to 4kV on ground plane; up to 8kV corona discharge

4.1. Extreme Environmental Conditions Affecting Accuracy

The MPS Flammable Gas Sensor is specified to operate in the following conditions: -40 to 75 °C, 0 to 100 %RH; and 80 to 120 kPa. The sensor has built-in self-test capabilities to detect and report excursions outside these regimes:

- Fault 0x23, HW_ENV _XCD_RANGE -- Environmental (Temp., Press., Humid.) out of range
- Fault 0x31, HW_CONDENSE_COND -- Condensation condition exists at sensor

The sensor is capable of operating outside of these regimes, as well as during abnormally rapid environmental fluctuations. The impact on sensor performance and output in such conditions is summarized in the following table:

Condition	Fault reported	Impact on sensor performance and output
Sensor environment out of range	Fault 0x23 HW_ENV_XCD_RANGE	The sensor will still detect and report flammable gas, though output accuracy can be diminished while the condition persists.
Condensation condition at sensor	Fault 0x31 HW_CONDENSE_COND	The sensor will still detect and report flammable gas, though output accuracy can be diminished while the condition persists and for one minute afterward.
Rapid humidity changes	None	If the sensor is already reporting flammable gas, no adjustments are made to sensor output. If gas is not being detected, the sensor output may be automatically adjusted to 0 %LEL for a maximum of 10 cycles (20 seconds) in a row during a rapid humidity increase. This adjustment has been programmed such that the largest possible concentration change to go unreported is 15 %LEL (methane). During rapid humidity decreases, the sensor output may be automatically adjusted to 0 %LEL for a maximum of 2 cycles (4 seconds) in a row. This adjustment has been programmed such that the largest possible concentration change to go unreported is 6 %LEL (methane). In both cases, the sensor will still detect and report flammable gas, though accuracy can be diminished for up to 80 seconds.
Rapid temperature change	None	The sensor will still detect and report flammable gas, though output accuracy can be diminished while the condition persists. For an MPS sensor exposed on all sides to ambient air, it is possible for this condition to occur when moving from conditioned, indoor air to cold or hot outdoor conditions, or vice versa. For MPS sensors integrated in portable or fixed detector units, the added thermal mass and insulation provided by the unit serves to slow the thermal transients acting on the MPS, making this condition less likely.

4.2. Hazardous Locations and System Integration

Integrating the MPS into intrinsically safe systems requires additional design consideration. Refer to the MPS Hazardous Locations User Guide (https://nevadanano.com/downloads/) for information regarding certifications, protection concepts, entity parameters, etc.

5. Certificates of Compliance

The following certificates of compliance are available at https://nevadanano.com/downloads/

Certificates of Compliance	Certification Body	Certificate Number
Certificate of Conformity (USA)	FM Approvals LLC	FM19US0145U
Certificate of Conformity (Canada)	FM Approvals LLC	FM19CA0077U
ATEX Certificate	FM Approvals LLC	FM19ATEX0184U
IECEx Test Report	FM Approvals LLC	IECEx FMG 19.0028U
IECEx Quality Assessment Report	FM Approvals LLC	GB/FME/QAR19.0020/00
ATEX Quality Assurance Notification	FM Approvals LLC	FM19ATEXQ0200
Certificate of Registration of Quality Management System (ISO 9001:2015)	National Standards Authority of Ireland (NSAI)	19.8213

6. Flammable Gas Detection Capability and Accuracy

The MPS™ Flammable Gas Sensor detects a wide spectrum of flammable gases and gas types. NevadaNano has done extensive testing and characterization of 12 of the most common gases. The table below compares the %LEL accuracy one can expect when detecting these representative gases using the MPS as compared to pellistor (a.k.a. catalytic, or "cat," bead) sensors and nondispersive infrared (NDIR) sensors.

This table shows the representative detection capability and accuracy for 12 common flammable gases, based on calibration using a single gas (methane). The %LEL error levels correspond to a delivered concentration of 50 %LEL.

GAS	MPS™	Pellistor (Cat Bead)	NDIR
methane	±3		
propane	±5		
butane	±5		
isopropanol	±5		unknown
pentane	±5		
hexane	±8		
hydrogen	±5		NOT DETECTED
toluene	±5		unknown
xylene	±10		unknown
ethylene	±15		
ethane	±5		
propylene	±10		unknown

KEY
±0-15 %LEL error
±16-30 %LEL error
>30 %LEL error

NevadaNano has further verified the MPS' capability to detect other flammable gases. These include: isobutylene, isobutane, acetylene, ammonia, methanol, ethanol, and acetone. The approximate %LEL errors to be expected when detecting these gases are: 5 %LEL for isobutylene and isobutene; 35 %LEL for acetylene (sensor under-reports); 30 %LEL for methanol, ethanol, and acetone (sensor under-reports); and 50 %LEL (sensor over-reports) for ammonia.

For additional information about a flammable gas not mentioned here, please contact NevadaNano at www.nevadanano.com.

6.1. Flammable Gases Not Detected

The MPS Flammable Gas Sensor as currently configured does not detect:

- **Carbon Monoxide (CO):** CO is a toxic gas, immediately dangerous to life and health (IDLH) at 1,200 ppm; the lower explosive limit is 109,000 ppm. The sensor is immune to poisoning by CO.
- **Hydrogen Sulfide (H_2S):** H_2S is a toxic gas, immediately dangerous to life and health (IDLH) at 100 ppm; the lower explosive limit is 40,000 ppm. The sensor is immune to poisoning by H_2S.

There may be other gases the sensor does not detect that have not yet been assessed or tested. For additional information about a particular flammable gas, please contact NevadaNano at www.nevadanano.com.

6.2. Response to Non-Flammable Gases

Because the MPS performs an analysis of the molecular properties of a given "air" sample, large-scale fluctuations in the relative components of the air can lead to sensor responses. Here are the sensor's responses to some of the most common non-flammable gases:

- **Oxygen (O_2):** Normal air has an O_2 concentration of 20.95% by volume. Higher ambient O_2 concentrations up to ~21.8% v/v have little to no effect on the sensor. Concentrations exceeding this can be reported as a flammable gas at %LEL levels, and possibly identified as Class 2—Hydrogen Mixture. The sensor is immune to poisoning by O_2.
  - Note: if O_2 concentrations *decrease*, the sensor response will depend on what gas is displacing the oxygen. Flammable gases displace oxygen. Methane at 100%LEL (5% v/v methane) will reduce oxygen's relative concentration by 1.05% in ambient air, meaning the O_2 concentration decreases from 20.95% to 19.85%. Such flammable-gas-caused O_2 depletions are already taken into account by the sensor calibration and therefore cause no unwanted effects on sensor output.
- **Carbon Dioxide (CO_2):** CO_2 is a component of normal air at concentrations near 400 ppm. This ambient amount of CO_2 is already taken into account by sensor calibrations. The sensor is unaffected by elevated CO_2 concentrations up to approximately 1% by volume (10,000 ppm); concentrations above this can be misinterpreted by the sensor as flammable gas. The sensor is immune to poisoning by CO_2.

- Note: Exhaled human breath contains CO_2 at concentrations of approximately 4-5% by volume (40,000-50,000 ppm). (During respiration, the CO_2 replaces oxygen, reducing its concentration from 20.95% by volume in normal air to 13.6-16% in exhaled air.) **As such, breathing directly onto the sensor can cause it to falsely report flammable gas for a brief period.**

- **Nitrogen (N_2):** Normal air has an N_2 concentration of 78.1% by volume. This ambient amount of N_2 is already taken into account by sensor calibrations. The sensor is unaffected by elevated N_2 concentrations up to approximately 85% by volume. Above such concentration levels, the sensor can enter a fault condition: "HW_SENSOR_NEGATIVE". The sensor is immune to poisoning by N_2.

Digital Scent for the Internet of Things

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SM-UM-0002-09