CBRN Sensor Evaluation for Improved Situational Awareness

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ABSTRACT

Proper decisions are the right decisions made at the proper time. Accurate situational awareness is required to make those decisions. Situational awareness is among others based upon intelligence, threat analysis, sensor information and professional experience. Intelligence and threat analysis are in general less affecting situational awareness in real-time. Sensor information however is affecting situational awareness real-time or nearly real-time. In this paper the quality of sensor information ('detection') is addressed. The quality of detection is often influenced by the operational environment. Current sensor testing and evaluation (T&E), however, does not properly quantify the impact of the environment on the actual sensor response. Alternative routes are required which visualise the detection reliability for the user, in order to evaluate the influence of the environment on detection characteristics. For this purpose T&E based upon on a new approach, the so-called Receiver Operator Characteristic (ROC) curves, can offer an important improvement.

1.0 INTRODUCTION

Defence organisations may encounter incidents, which are caused by the intentional or accidental release of Chemical, Biological, Radiological or Nuclear (CBRN) agents. To accommodate operational decision making under these circumstances accurate situational awareness is required. To achieve situational awareness, detection architectures are developed, which combine information from e.g. intelligence, subsequent threat analysis and detection. Based upon all available information a proper decision should be made in due time.

Based on the consequence of a decision regarding a CBRN attack or incident, various levels of reliability of the information upon which a decision is made can be set. (Figure 1) In case a release is detected, one of the first actions to take is to don personal protective equipment (PPE). Since PPE usually has less favourable ergonomic characteristics than the standard battle dress uniform, resulting in significant degradation of performance, a certain reliability of detection is required to take this decision.

After donning PPE headquarters and neighbouring units have to be informed about the decision taken. The information about a CBRN release can be spread by a so-called ATP-45 message, in order to enable neighbouring units to take adequate countermeasures. Before such a message will be spread (and mitigating measures can be taken) an improved detection confidence is required To achieve this increased reliability some time is needed, however not an infinite period. Otherwise neighbouring troops might be affected by the exposure to the release and performance degradation will impact combat operations significantly, for example.

In general, each decision after donning PPE will have an increasing effect on combat operations, until the hazard has been adequately dealt with. To deal with this expanding impact an increased level of confidence in sensors is required. This confidence should be reached within a certain (and limited) reaction time. However, increase in confidence is not a linear function of time, but is increasing with certain steps. If the confidence is not increasing to an adequate level, decisions cannot be made based upon required reliability, resulting in a negative impact on operations.

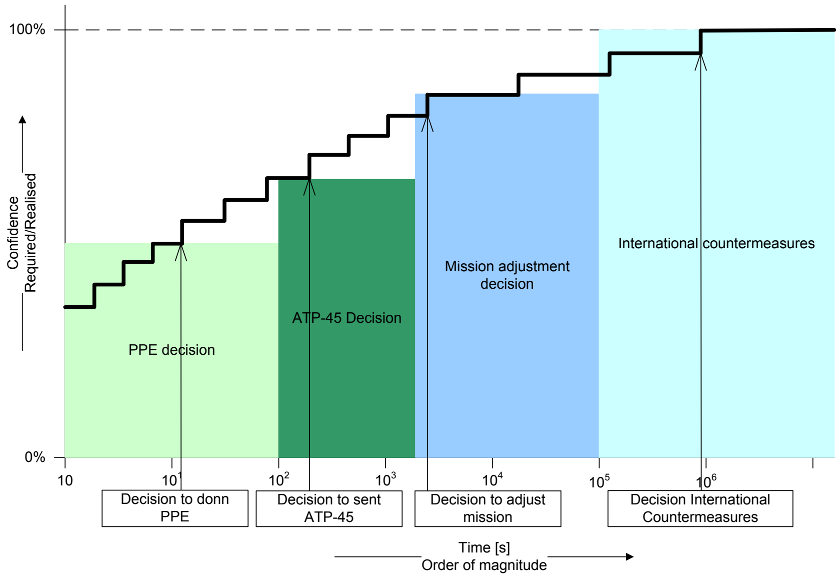

Figure 1 Example of required/desired Detection Identification Monitoring (DIM) confidence to take increasing regret/impact actions as function of available time.

In case of an incident with chemical warfare agents, an incident with a low probability of occurrence but high impact consequences, the current doctrine usually allows each soldier in the field to detect a chemical incident by shouting “gas-gas-gas” (the so-called immediate action drill). After this (or other) initial notification of a chemical release, enhanced, more reliable situational awareness is needed in order to take optimal decisions, given the circumstances. The impact of these decisions may vary between a delay in completing a mission or failure to accomplish the mission within the set time constraints. (Figure 2) In case a mission is undertaken without an incident as described, it is assumed that the mission can be accomplished without any delays and within the proper operation time. However in case of a ‘supposed’ incident several consequences are possible. A release of a chemical warfare agent can be missed or can be detected. In case a release is detected time is required to evaluate the detection characteristics. During the evaluation of the situation the mission is retarded. After evaluation one has the option to reject the detection event justly or wrongly, to continue the mission with decreased operational effect due to the use of PPE, or to abandon the original mission targets. In a number of the previous options the mission is not completed within the proper time period. In some of these cases the number of potential casualties is minimised, however not in all. To reduce the chance to take the wrong decisions improved situational awareness is required, which can be acquired by improved detection. However, the confidence in a detection signal varies with the environment. The characteristics related to confidence in a detection signal are currently not adequately assessed in material procurement requirements and acceptance tests. As a consequence, CBRN specialists have to evaluate information regarding these low probability yet high impact events, the reliability of which can usually only be judged by experience, due to lack of insight in the quality of the information provided by the detection architecture. However, decisions based on this information can have a significant and increasing impact on operations. This is an undesired situation.

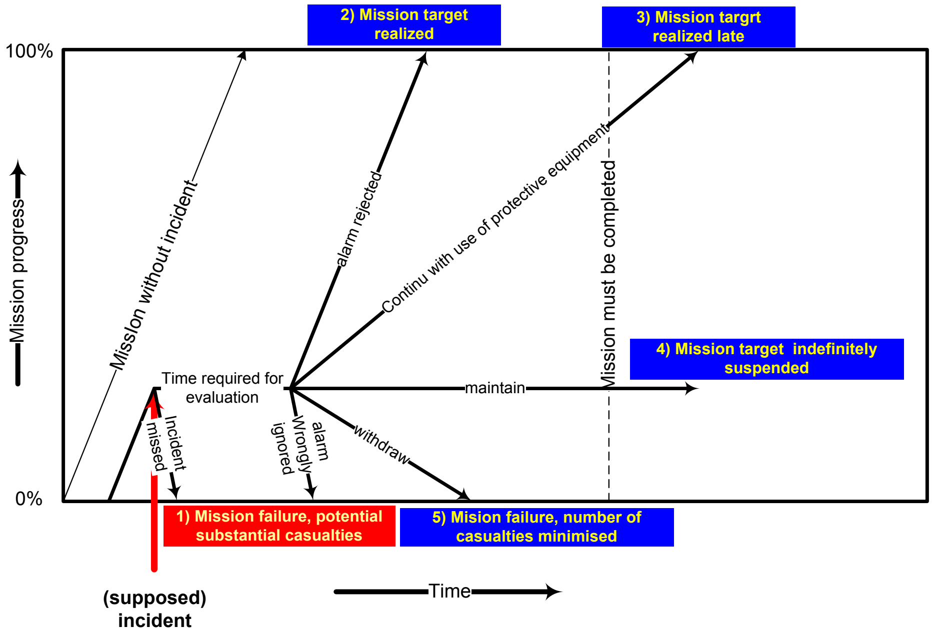

Figure 2 Overview of possible consequences of a detection event on the progress of a mission.

Instead of providing a detection signal only, or a detection signal and concentration indication, information related to the detection confidence should also be provided by the detection architecture. To assess detection characteristics properly, CBRN sensors should be evaluated on four interrelated key metrics: response time, false alarm rate, detection confidence and sensitivity. This can be accomplished through the determination of so-called Receiver Operator Characteristic curves rather than by solely measuring the limit of detection.

2.0 REQUIRED SITUATIONAL AWARENESS

Adequate situational awareness enables the commander to take optimal decisions. Not all decisions have similar impact on a mission. For instance the decision to start wearing PPE will slow down the execution of a mission, but still makes fulfilment of a mission possible. However, a decision to halt will result in failure to perform a military task within the proper time window.

The available time window to make decisions with more impact is in general increasing with increasing impact. To take such a decision with increased impact improved situational awareness is required. Situational awareness is achieved by several components:

- Intelligence. In preparation and during execution of a mission it is important to gather sufficient information regarding the threats that might be encountered.
- Detection, Identification and Monitoring (DIM) sensor data. Sensors generate data, which should be processed to information upon which decisions can be made.
- Threat analysis. Data gathered by intelligence and the DIM architecture needs to be analysed to estimate the abilities of the opponent.
- Professional experience. An important factor in the current decision making process is professional experience. The reliability of sensor signals is influenced by the environment. Therefore knowledge regarding the abilities of actors, processes and capabilities involved in the detection architecture is an important factor in making the proper decision. Since processes and capabilities cannot be

processed purely mathematically professional experience is an important factor in the final decision to follow up on a detection signal or supposed release.

Intelligence will help to prepare for a situation that might be encountered during a mission. However it will not provide timely awareness. Professional experience will help to interpret the information acquired by intelligence and a DIM architecture in a proper way. This approach is however peculiar. CBRN incidents show a low probability yet high impact. So experience, which will need to be relied upon, will usually be relatively limited, especially taking into consideration that military jobs tend to rotate quite frequently.

The only way to achieve improved, timely situational awareness is by relying less on professional experience and improving the detection. Not only in quality, but also in the type of information presented. Detection should not only provide the presence or non-presence of a threat agent. It should also provide the reliability of a detection signal.

To understand the viability of such an approach, the way sensors behave and how the signal should be analysed is addressed.

3.0 DETECTION EVENTS

In case of low probability yet high impact events an operator of a detection system expects the system to function reliably. The system should (ideally) only warn when a detection is justified. In general, detection events can be classified in several types:

- True positive. A threat agent is present and detected. The true positive detection can in principle be subdivided in two classes; the necessary and the unnecessary detections. Especially in case of chemical events one has to be exposed to a certain concentration before relevant negative effects are experienced. Below this concentration action is not required. To detect only those cases suitable detection thresholds should be set.
- False positive. Detection takes place, although no threat agent is present.
- True negative. No threat agent is detected or present.
- False negative. Although a threat agent is present at a concentration above the detection threshold no agent is detected.

A too high false positive rate will not only effect the faith of the operator in the reliability of the sensor. False positives will also have a low or high regret level, depending on the follow up of the detection event. Usually, a false positive leads to waste of resources. This includes time, manpower and costs and as a result operational degradation. In the worst case the time aspect results in such a delay the mission cannot be fulfilled within set time constraints.

The acceptance level of false positive is dependent on the threat situation. In case of a high threat level, a higher number of false alarms, however not too many, is accepted in contrast to a low threat level perspective. In the event of a high threat level, a false positive might be regarded as an opportunity to practice the drill, where at a low threat level the false positive is regarded as a waste of resources.

To understand the occurrence of false positives, and to investigate the possibility to assess the reliability of a sensor signal it is important to describe a sensor with the proper characteristics

4.0 SENSOR CHARACTERISTICS

A sensor is described adequately by four key metrics;

- Response time. The response time is the amount of time a sensor needs to analyse a possible threat agent, determine if an alarm needs to be given and provide feedback of its detection results. In general the response time is of importance since a higher response time will lead to an increased exposed dose.
- Sensitivity. The sensitivity can be described as the minimal concentration (threshold value) at which a sensor will give an alarm when facing threat agents. The sensitivity influences the true positive rate. If the sensitivity is increased the threshold value will be decreased which will result in more alarms.
- Probability of detection. The probability of detection corresponds with the fraction of true threat events that are detected at a certain sensor setting. The probability of detection is affected by interference of the operational environment (background).
- Specificity or false positive rate. The false positive rate is the number of occasions a threat is detected, while no threat agent is present. Increase in sensitivity will generally increase the false positive rate: more detection events will be generated, but not all events will be correct.

To understand how those characteristics can be determined from a sensor response it is important to understand out of which contributions a sensor response is constructed. Three components can be discriminated in a sensor response;

- Noise. A sensor is built of components, which all contribute to the final sensor response. The part of the response, which is not correlated with the measurement environment is called noise.
- Clutter. The sensor response to all factors associated with the measurement environment other than the agent and noise.
- Signal. The sensor response to exposure to an agent.

The response of a sensor to an agent can be described by a sigmoid function, which incorporates the limit of detection, the lower limit of quantification, the upper limit of quantification, the sensitivity and the saturation of the sensor. (Figure 4) The slope of the curve between the lower limit and upper limit of quantification

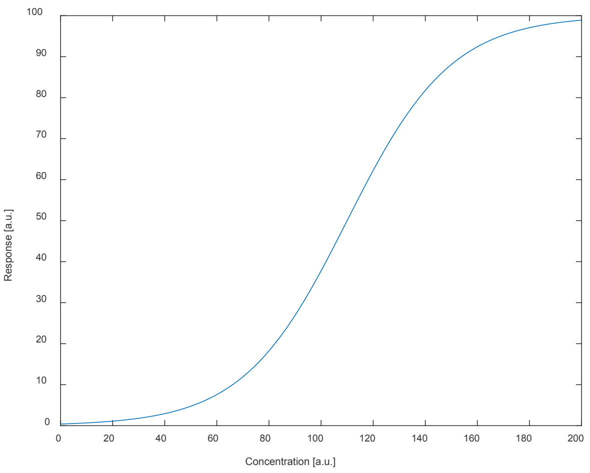

Figure 3 Example of a dose-response curve of a detector as can be found by practical

evaluation.

discriminates whether the sensor is a quantitative or qualitative. In case of a steep slope almost no concentration dependent signal can be determined. In this case this sensor is called a qualitative sensor.

Background is in general far too complex to measure or model. A viable approach for Test and Evaluation of a sensor is proposed by Carrano [1]. The response of a sensor to the environment is determined by derivation of a sensor response distribution

4.1 Sensor response distribution

Since the response of a sensor to an agent also includes the contribution of that sensor to the measurement environment, the sensor response distribution should also be taken into account. In case one performs a frequency analysis upon a sensor response, a distribution pattern is generated. (Figure 4)

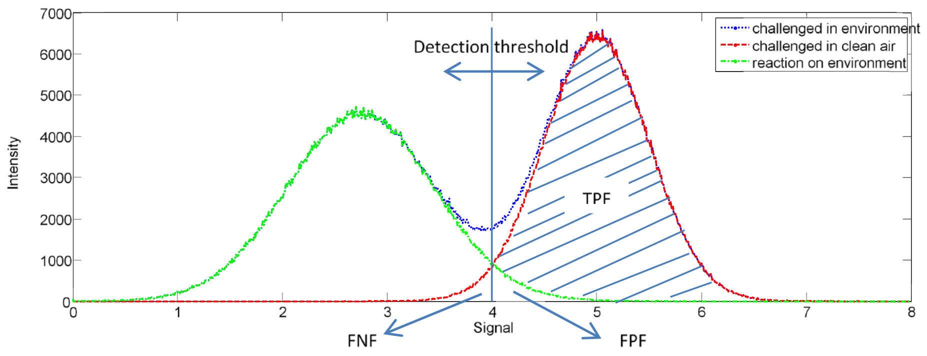

Figure 4 Frequency analysed sensor response. The red curve corresponds with the threat agent. The green curve corresponds with the signal originating from electronics (Noise) and the operational environment (Clutter) .

Figure 4 shows the over-all response of a sensor after multiple exposures. On the horizontal axis the signal magnitude is given, while on the vertical axis the number of times this magnitude occurred is given. In case of the presented distribution a clear bi-modal distribution is presented. The left (green) distribution is the contribution of the clutter and noise, while the right (red) distribution is related to the agent. In case a detection threshold is set in between the two peaks one can determine which fraction is correctly awarded. Adjustment of the sensitivity influences the false negative fraction (FNF) as well as the false positive fraction (FPF) and hereby as well the true positive fraction (TPF) a.k.a. the probability of detection.

In case a sensor faces a more interfering environment the distance between the clutter and related distribution and the agent related distribution may decrease as well as the absolute position of the valley between the two distributions. In case the detection threshold is not adjusted for that specific environment this may result in an increased false alarm rate and deteriorated probability of detection.

The trade-off to be made in sensor performance can be visualized by construction of a Receiver Operator Characteristic-curve. In this curve two of the sensor key metrics are depicted, while the others are kept constant. The correct positive fraction is placed on one axis, the false positive fraction is placed on the other axis.

5.0 SENSOR EVALUATION EMPLOYING ROC

In procurement programs the anticipated usage of sensors is often hardly taken into account. More specifically, earlier mentioned trade-off between the key-metrics is hardly taken into account. Additionally, in many cases the operator cannot even make an optimization in the trade-off between the four interrelated key-metrics for his application. To evaluate a sensor in such a way that insight is generated in the key metrics under operational circumstances an alternative way of testing is required.

Based upon insight in the anticipated use of the sensor in combination with generic threat analysis requirements on the key metrics can be set. These requirements are used to design the actual test approach.

5.1 Data collection

In the traditional way a sensor is evaluated by determination of the limit of detection. In case of determination of a ROC-curve for a sensor the response of the system to both the environment and the threat agent is statistically evaluated.

To illustrate the feasibility of ROC-based approach exposure results a flame photometric sensor are shown below. (Figure 5) The sensor is exposed to a step-wise exposure of an agent.

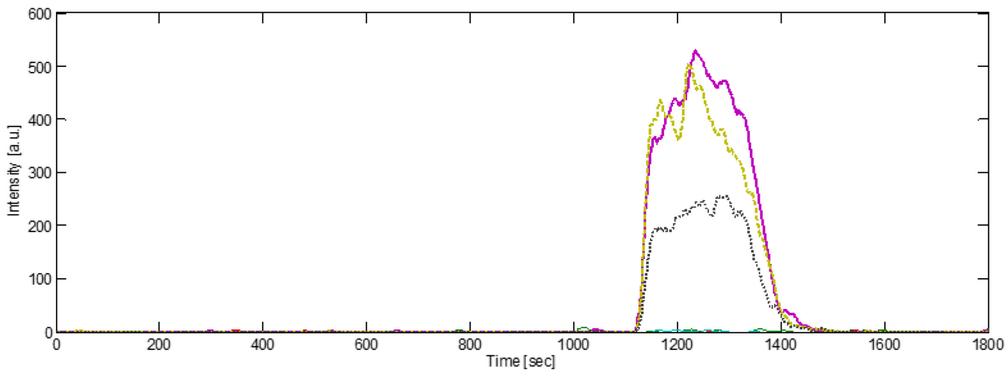

Figure 5: Sensor response to a step-wise exposure to an agent.

Input is generated to construct ROC-curves by performing a frequency analysis of the response. In case of a more interfering environment the distance between the background related distribution and the agent related distribution may change, dependant on the position of the background and the agent related contribution on the concentration response curve (see 4.1). If such a change occurs the distance between the agent related distribution and the environment related distribution decreases resulting in an increased false alarm rate for a similar exposure to a threat agent.

Some resulting ROC-curves can be depicted. (Figure 6) In the figure the correct positive fraction is displayed on the y-axis, while the false positive fraction is set on the x-axis for three different response times. As a function of increasing response time the ROC-function becomes more steep. This means the detector becomes more accurate with increasing response times, i.e. when the sensor becomes slower.

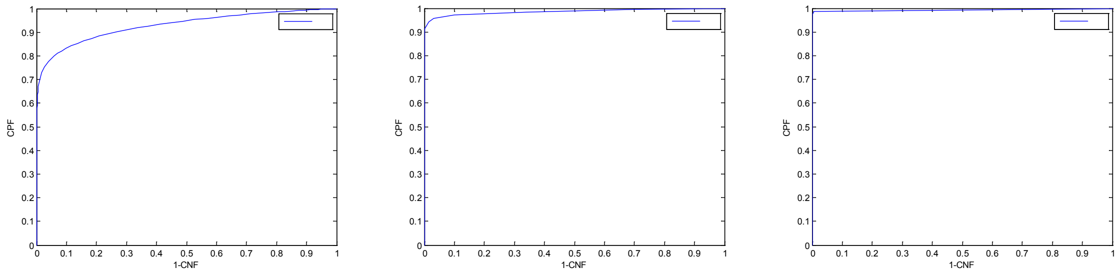

Figure 6 Specificity vs Selectivity of a FPD detector for respectively instantaneous response, 30 and 60 seconds delay time.

5.2 Environment

As mentioned earlier the environment, to be more specific the interferents present in the environment, is affecting the discriminative power of a sensor. The complex environment is difficult to generate during sensor evaluation and the variation in the environment is huge, causing evaluation for all environments to become impossible from both a practical as well an economical point of view. Nobody will be able to determine the response of a sensor in all operational relevant environments, e.g. because it is not allowed to determine the response to a threat agent in a heavily populated area or for the simple reason that nobody is able to mimic the background sufficiently due to the complexity of the background. However this does not mean that evaluation of sensors by ROC-methodology is not able to provide insight in e.g. the probability of detection for the proper environment.

For this purpose sensor evaluation as well as the operational doctrine should be adjusted. Time should be reserved to determine the response of the sensor to the environment. During test and evaluation in a test facility a dose response curve of a sensor can be derived. (Figure 3) In case the sensor is exposed to an interfering environment, sampling during a sufficiently long period enables to generate a distribution frequency plot for that specific environment. (Figure 7) The length of this time period cannot be given specifically since this will be dependent on the length of the analysis steps of the

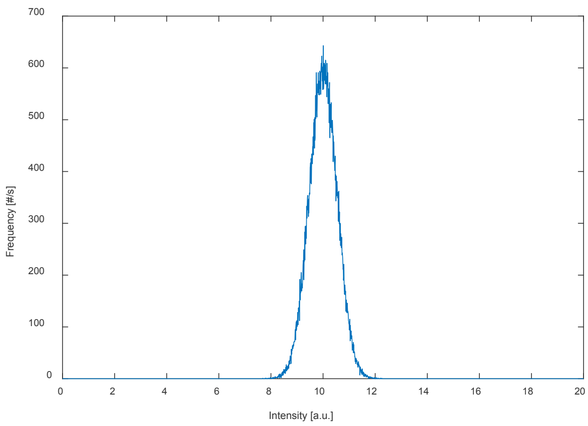

Figure 7: Example of experimental determined frequency response in case of exposure of a detector to a certain environment.

Combining the laboratory determined dose response curve of the sensor with the measured real back-ground response offers the possibility to predict the concentration-dependent sensor response in that specific environment. (Figure 8)

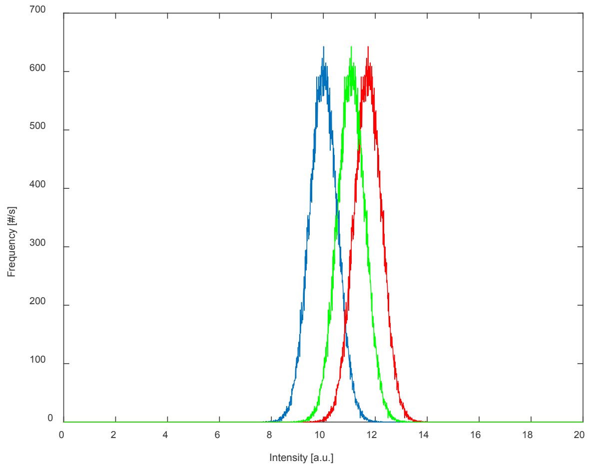

Figure 8 Frequency plot of a detector response, consisting of the response to a background and two concentrations in the same background. The over-all response has been deconvoluted in the attribution of the background (blue) and the contribution of two different concentrations (green and red).

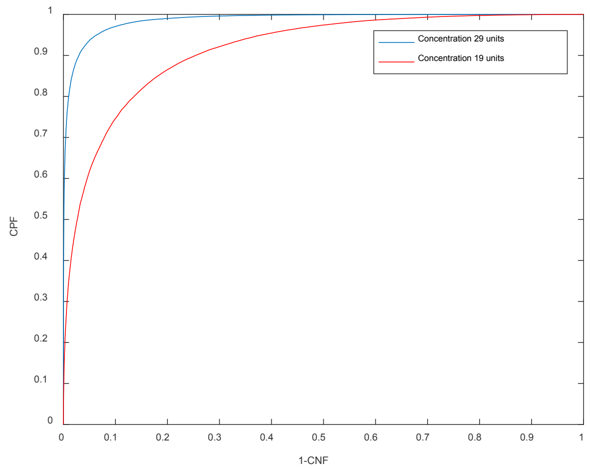

Figure 9 Two ROC-curves for challenging the sensor under evaluation with two different challenge concentrations. The correct positive fraction is given as function of 1-correct negative fraction.

As soon as both the sensor response to the target chemical agent and to the environment are derived a ROC-curve can be derived, which supports the optimization of sensor detection settings and provides direct insight in the detection reliability by providing insight in the probability of detection for a certain detection threshold and its associated false positive fractions. In Figure 9 the corresponding ROC-curve for two different challenge concentrations in the same environment is given in which the correct positive fraction is given as function of the false positive fraction. As expected the graph indicates that a higher detection threshold less false positive reactions are generated at the expense of a lower number of correct positive reactions.

6.0 CONCLUSION

Current sensor evaluation does not adequately assess the sensor from an operational point of view. The assessment focusses on determination of the response of a sensor under a well determined environment and not a possible operational environment, thereby not supporting, the operational required, insight in detection quality.

Improving sensor evaluation from the classical determination of limit of detection to an ROC-based approach offers the possibility to determine not only the limit of detection for a certain environment, but also provides a tool, which enables the determination of the detection quality. Subsequently, the operator will be provided not only with a detection event, but also a probability of detection and a false positive rate for the specific operational environment.

The improved quality of the acquired information will improve the situational awareness, since the quality of information is quantified. As a consequence increased regret decisions can be taken after certain levels of confidence are reached.

7.0 ACKNOWLEDGEMENT

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8.0 REFERENCES

[1] Chemical and Biological Sensor Standards Study, DARPA, 2005