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Conceptual Design and Functional Assessment of a Modular Multi-Sensor CBRN Architecture for Fire and Rescue Operations

Daniela Marasová, Michal Cehlár, Ivanna Betušová, Bibiána Blaškovanová and Miroslav Betuš *

Faculty of Mining, Ecology, Process Control and Geotechnologies, Technical University of Košice, 040 22 Košice, Slovakia; daniela.marasova@tuke.sk (D.M.); michal.cehlar@tuke.sk (M.C.); ivanna.betusova@tuke.sk (I.B.); bibiana.blaskovanava@student.tuke.sk (B.B.)
* Correspondence: miroslav.betus@tuke.sk; Tel.: +421-917-433-352

Abstract

This study presents the conceptual design and functional assessment of COMBI-CBRN, a modular architecture for initial chemical, biological, radiological and nuclear reconnaissance by fire and rescue services. The architecture combines atmospheric monitoring, chemical screening, targeted Raman analysis, radiological assessment and biological sample collection. The biological component provides no on-site biological identification. Exploratory observations from separate reference instruments illustrate interpretation limitations relevant to the design but do not establish integrated-system performance. A standalone Python implementation of the proposed interpretation rules was evaluated using 29 synthetic cases, 87 supplementary checks and eight additional boundary test functions. The audited implementation matched the predefined expected decision signatures in all 29 primary cases. Disabling individual safeguards changed selected outputs, illustrating their functional role within the constructed test suite. These results support agreement between the implementation and the specified policy under prescribed metadata assumptions; they do not establish analytical accuracy, operational reliability or the correctness of the policy for field use. The contribution is an application-specific architecture specification accompanied by executable interpretation rules and documented verification results. No integrated hardware prototype was evaluated, and system-level detection performance, response time and usability advantages remain unverified.

Keywords: CBRN detection; multi-sensor integration; sensor systems; hazardous materials; fire and rescue operations; Raman spectroscopy; ion mobility spectrometry; radiological detection

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1. Introduction

Incidents involving chemical, biological, radiological, and nuclear (CBRN) hazards represent a distinct category of emergency response in which the quality of the initial reconnaissance is directly linked to responder safety and subsequent incident management. Unlike conventional technical emergencies or fire incidents, the nature of the hazard at a CBRN scene may not be immediately apparent during the initial phase of the response. Hazardous substances may occur in gaseous, vapor, aerosol, liquid, or solid form, while radiological incidents may involve sources of ionizing radiation; consequently, different hazard types require different principles of detection and identification. The incident commander's decision-making therefore depends not only on how rapid information can be obtained, but also on its reliability, mutual interpretability, and ability to provide a sufficiently comprehensive understanding of the hazard [1–3].

In fire and rescue operations, the initial assessment of the environment is generally performed using several stand-alone instruments. These include multi-gas detectors, devices based on electrochemical, catalytic, or photoionization sensors, spectrometric systems, chemical warfare agent detectors, radiological instruments, and, depending on the nature of the incident, specialized systems for the identification of unknown substances [4]. The diversity of sensing and identification technologies reflects the fundamentally different detection principles required for individual groups of CBRN hazards [4]. Although this approach enables the use of technologically advanced and highly specialized instruments, it also results in a fragmented flow of information. Individual devices provide different types of outputs and differ in response characteristics, sensitivity, selectivity, and operating conditions, while their deployment may require several consecutive measurement procedures [4,5].

The practical significance of this issue increases under operational conditions in which responders work while wearing protective clothing and self-contained breathing apparatus. The use of such personal protective equipment can impose additional operational constraints during CBRN response activities [6]. Handling several detection devices may further increase the time and physical demands associated with reconnaissance and can reduce operational efficiency within a contaminated area. An analysis of the operational environment of the Fire and Rescue Corps identified the lack of uniformity among detection devices, differences in their measurement ranges, and the need to operate several instruments during a single incident as important practical limitations. During a dynamically evolving CBRN incident, delays in substance identification may affect the selection of protective equipment, delineation of the hazardous zone, decontamination procedures, evacuation measures, and the tactical deployment of responding units [7].

Advances in portable electronics, miniaturized sensors, spectroscopic methods, and digital data processing are creating the conditions for a transition from stand-alone detection devices to integrated multi-sensor systems [8,9]. The principal advantage of such an approach lies not merely in combining several instruments within a single transportable unit. From a technical perspective, a more important aspect is the ability to combine measurement methods based on different physical principles and exhibiting different levels of selectivity so that their capabilities complement one another [8]. Electrochemical and photoionization sensors can provide rapid information on the presence of gaseous contaminants, while ion mobility spectrometry (IMS) enables the preliminary identification of selected toxic industrial chemicals and chemical warfare agents. Raman spectroscopy enables the identification of solid and liquid substances based on their molecular spectra [10,11], whereas radiation detectors provide information on the presence and characteristics of ionizing radiation.

However, these detection principles are not interchangeable. Each type of technology covers a different part of the potential hazard spectrum and is associated with specific limitations. Gas sensors may be affected by cross-sensitivity and interfering compounds [12–14], while IMS systems can be influenced by environmental conditions and the characteristics of the analyzed sample. Raman spectroscopy may be affected by surface properties, fluorescence, or the type of packaging, whereas radiation measurements depend on factors such as distance, shielding, and radiation energy. Consequently, the versatility of a CBRN system cannot be assessed solely based on the number of integrated sensors. Of greater importance is the complementarity of the measurement principles, their appropriate operational arrangement, and their ability to provide information that can support decision-making during the initial phase of an incident response.

On this basis, the COMBI-CBRN concept was developed as a proposed arrangement of complementary detection, identification, and sampling functions. It comprises atmospheric gas monitoring, IMS chemical screening, Raman analysis of solid and liquid materials,

radiological measurement with proposed radionuclide identification, and biological sample collection. The biological module is limited to sample collection and transport for subsequent laboratory analysis; it does not provide field identification of biological agents [15]. Physical integration of the proposed modules has not been demonstrated.

For initial fire and rescue reconnaissance, selecting complementary instruments does not by itself define how their outputs should be interpreted together. A gas-channel alarm, a chemical classification, a Raman library match, a radiation reading, and a collected biological sample represent different analytical claims. An architecture assessment must therefore specify the conditions under which these outputs can be associated, the evidence required for corroboration, and the treatment of faults or conflicting results. This study addresses that design problem through an explicit assessment framework and proposed interpretation rules, with operational evaluation remaining a subsequent validation task [16].

The objective of this study is to specify a modular CBRN reconnaissance architecture and make its interpretation requirements explicit and executable. The architecture combines atmospheric monitoring, chemical screening, targeted substance identification, radiological assessment and biological sample collection. Its physical integration and operational advantages remain to be demonstrated.

The application-specific contribution comprises an assessment framework, an interpretation specification linking sample association, evidence acceptance and conflict handling, and a standalone reference implementation accompanied by traceable synthetic verification cases. The contribution concerns the explicit specification and examination of these relationships rather than the introduction of a new sensing principle or a generally superior fusion algorithm.

This study combines architecture specification, exploratory observations from separate reference instruments, and software verification of the interpretation rules. The observations illustrate measurement and interpretation limitations relevant to the design. Software verification examines agreement with predefined expected outputs under prescribed metadata assumptions; it does not establish integrated analytical performance or independently validate the interpretation policy.

Reduced measurement fragmentation, shorter task-completion time and improved operational efficiency remain hypotheses for subsequent comparative testing. The present study provides design requirements, executable interpretation rules and documented verification results to support that further evaluation.

2. Materials and Methods

2.1. Research Design

This study combines three components: conceptual architecture design, exploratory observations obtained using stand-alone reference instruments, and synthetic verification of a standalone interpretation-rule implementation. The observations document selected instrument responses under indoor conditions. The design component specifies module functions, assessment criteria and integration requirements. The software component evaluates agreement between implemented rules and predefined expected outputs. None of these components constitutes validation of an integrated COMBI-CBRN prototype.

The assessment framework was applied retrospectively to the available instrument observations. Requirements needing additional measurements are specified prospectively and are not presented as completed experiments.

Information was classified by provenance: E—experimental observations from the reference instruments; M—manufacturer-reported characteristics; P—proposed design features or validation requirements; and S—synthetic software-verification results. These categories identify the source of a statement rather than a numerical level of reliability.

Synthetic software results do not establish experimentally demonstrated performance of the proposed hardware.

Figure 1 summarises the architecture and reference-observation components. The software-verification procedure is described separately in Section 2.9, with rule traceability in Table S1.

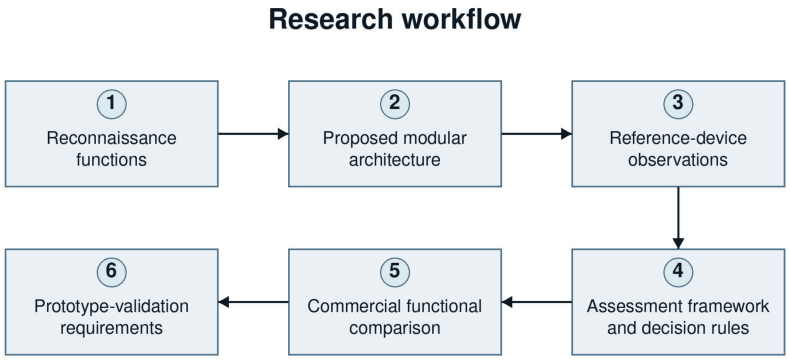


Figure 1. Analytical structure of the conceptual design and functional assessment. Reference-device observations are distinguished from proposed system requirements (prepared by the authors).

2.2. Operational and Experimental Framework

The experimental measurements were conducted at facilities in Zemianske Kostoľany used for professional training and exercises in CBRN response. All measurements were performed in enclosed indoor spaces under relatively stable environmental conditions. During testing, the temperature ranged from approximately 18 to 19 °C, relative humidity was approximately 60%, and atmospheric pressure ranged from 1000 to 1003 hPa. No forced airflow was generated, and natural air velocity was estimated to remain below 0.2 $m \cdot s^{-1}$. Strong airflow, turbulence, rapid concentration changes, and extreme environmental conditions were not simulated.

The reference instruments were operated in accordance with the manufacturers' operating instructions and procedures used during operational deployment. The measurements were not designed as certification or type-approval tests. Each experimental procedure was repeated a minimum of three times under comparable conditions. Between repetitions, the test area was ventilated, and sufficient time was allowed for the measured environment and instrument indication to return toward baseline conditions.

The original experimental records were compiled primarily as operational comparison data. Individual numerical values from each repetition were not reported separately in the original dataset; consequently, the results presented in this study are expressed as observed ranges, maximum values, or representative values, depending on the respective experiment. Although each procedure was repeated under comparable conditions, the retained records support descriptive reporting rather than a statistical estimate of repeatability or measurement uncertainty. Reported ranges describe the recorded observations and are not confidence intervals.

2.3. Reference Detection Equipment

The experimental part of this study employed selected devices available in the operational practice of the Fire and Rescue Corps (HaZZ), representing four distinct principles of information acquisition: multi-gas sensor detection, ion mobility spectrometry (IMS), Raman spectroscopy, and radiological measurement.

2.3.1. MultiRAE Lite

A portable MultiRAE Lite analyzer (Honeywell Analytics /RAE Systems, Charlotte, NC, USA) was used for multi-gas detection. This modular multi-gas monitor can accommodate, depending on its configuration, multiple electrochemical, photoionization, and other sensor types [17–19]. Two units with different operational configurations were used: the first incorporated Cl_2, NO_2, NH_3, HCN, and PID-based VOC sensors, whereas the second incorporated CO, O_2, LEL, H_2S, and CO_2 sensors. The applicability of the MultiRAE Lite for portable monitoring of volatile organic compounds has also been demonstrated in previous experimental studies [17,18]. According to the manufacturer's documentation, the MultiRAE platform is intended for monitoring toxic gases, oxygen, combustible atmospheres, and volatile organic compounds (VOCs) [19].

For the experiment, VOC, CO, and O_2 concentrations and the time required for signal stabilization were recorded. VOC values obtained from the PID channel were expressed as isobutylene equivalent.

2.3.2. IMS LCD 3.3

An LCD 3.3 detector (Smiths Detection, London, UK), based on ion mobility spectrometry (IMS), was used for the preliminary detection of chemical warfare agents [20]. In IMS, molecules of the analyzed substance are ionized, and the resulting ions are subsequently separated according to their mobility in an electric field [21,22]. The drift time constitutes a characteristic parameter that can be used for the differentiation and classification of ion species [21]. The LCD 3.3 is specifically designed for field detection of chemical warfare agents and selected toxic industrial chemicals [20,22].

The device used was intended for the detection of gaseous and aerosolized chemical hazards. The technical documentation reports an operating temperature range of −30 to +55 °C and data output capability via USB or a serial interface [20]. In the experiment, particular attention was paid to the response of the IMS system to organic vapors and to the occurrence of incorrect classification, which may directly affect tactical decision-making during an incident response.

2.3.3. Rigaku Progeny ResQ

Identification of solid and liquid chemical substances was evaluated using a handheld Progeny ResQ Raman spectrometer (Rigaku Analytical Devices, Wilmington, MA, USA). The instrument employs Raman spectroscopy with an excitation wavelength of 1064 nm, and the acquired spectrum is compared with an internal reference library [23,24]. The device is designed for field use and incorporates a touchscreen interface, an integrated digital camera, and USB/WLAN connectivity [23]. During testing, the assessment focused on identification success, the time required to obtain a result, the need for repeated measurements, and the influence of fluorescence background, which is a recognized limitation in Raman measurements [24].

2.3.4. Polimaster PM-1401K-3

The radiological part of the experiment employed a handheld PM-1401K-3 radiation monitor (Polimaster Inc., Sterling, VA, USA). This series of instruments is designed for the detection of ionizing radiation, dose-rate measurement, and, depending on the specific configuration, acquisition of spectrometric data [25]. The main characteristics of the reference detection devices used in the experimental part are summarized in Table 1.

The experiment focused primarily on the relationship between the distance from a low-activity ^{137}Cs control source and the measured dose rate. Reference measurements were performed at distances of 30 cm and 5 cm.

Table 1. Reference devices used in the experimental assessment (prepared by the authors).

Device	Manufacturer	Detection Principle	Primary Function in the Study
MultiRAE Lite	Honeywell Analytics/RAE Systems, USA	EC/PID/other sensors depending on configuration	Multi-gas measurement and VOC detection
LCD 3.3	Smith's Detection, London, UK	Ion mobility spectrometry (IMS)	CWA/TIC screening
Progeny ResQ	Rigaku Analytical Devices, Wilmington, USA	Raman spectroscopy, 1064 nm	Identification of solid and liquid chemical substances
PM-1401K-3	Polimaster Inc., Sterling, VA, USA	Radiation detection/spectrometry depending on configuration	Dose-rate measurement

2.4. Proposed Multi-Sensor CBRN Architecture

The proposed COMBI-CBRN architecture was developed as a modular system intended for the initial assessment of an unknown CBRN environment. The design was not intended to replace laboratory analysis, but rather to provide, within a short period of time, the broadest possible set of operationally relevant information while maintaining system mobility.

The functional architecture was divided into five main modules:

1. Gas sensor module;
2. IMS chemical screening module;
3. Raman identification module;
4. Radiological identification module;
5. Biological sampling module.

The proposed gas-sensor core comprises twelve measurement channels supplied through an actively sampled inlet assembly. A total pump flow of 1–1.5 L·min^{-1} is an initial design assumption rather than a validated specification. It denotes the total flow through the sensor-core sampling assembly, not the flow available to each channel. The final manifold arrangement and branch flows must satisfy the operating requirements of the selected sensors. Pressure losses, analyte transmission, transport delay, and simultaneous channel operation remain to be characterised. The proposed 12 V DC supply and approximate −20 to +50 °C operating range are also design targets; they do not establish the operating envelope or analytical performance of an integrated system.

The proposed twelve-channel configuration comprises electrochemical channels for CO, O_2, NH_3, H_2S, Cl_2, NO_2, SO_2, and HCN; infrared channels for CO_2 and CH_4; a catalytic LEL channel; and a photoionization (PID) channel for VOCs. The use of separate sensor positions does not eliminate chemical cross-sensitivity; cross-response and interference between sensing principles therefore remain subject to experimental characterization during prototype validation.

Chemical indicator tubes are proposed as a task-dependent verification method. Their use must follow the target-specific sampling volume, flow or pump-stroke requirements, and interference limitations stated by the manufacturer. The envisaged flow of 0.5 L·min^{-1} ± 5% is a candidate engineering specification and cannot be assumed suitable for all tube types. The final design requires a tube-specific operating procedure and an independently regulated or separately pumped sampling path. Activation of this branch must not move the sensor-core flows outside their validated limits. A tube result can support a candidate identity only when its analytical scope and interference characteristics are appropriate to that claim.

A Pendar X10 handheld standoff Raman spectrometer (Pendar Technologies, Cambridge, MA, USA) is proposed as a task-dependent module for the identification of solid and

liquid substances, with a documented working distance of approximately 0.3–2 m [26]. The proposed architecture thereby separates continuous gas detection from targeted molecular identification of a suspected solid or liquid substance.

The radiological branch is represented by the RIIDEye X (Thermo Fisher Scientific Inc., Waltham, MA, USA), a handheld radioisotope identification device (RIID) [27–29]. The instrument employs scintillation detection and gamma-ray spectrometric analysis over an energy range of approximately 20 keV–3 MeV and enables the identification and classification of radionuclides [27–29]. The working distance and energy range describe the selected commercial instruments. They do not establish the corresponding performance of a combined COMBI-CBRN configuration.

The biological branch does not perform automated identification of a biological agent. It represents a separate sampling and transport module designed for the safe collection of a sample and its subsequent laboratory processing.

In the proposed physical arrangement, the twelve-channel gas-sensor unit and the indicator-tube branch form the common sampled sensor core. The Pendar X10, RIIDEye X, and biological sampling kit remain separate modules that are removed from the transport unit when required. The IMS branch is included at the functional-architecture level, while its final hardware implementation within the portable system has not yet been experimentally established. Integration within a common operational workflow does not imply that all modules share a sampling inlet, enclosure, or implemented electronic interface. These interfaces remain design requirements unless explicitly identified as realised hardware.

A common information record requires a documented interface for each selected instrument. The implementation must establish which outputs can be exported, their units and coding, timestamp resolution, quality and fault flags, and the association between each record and its sampling location or physical sample. If an instrument cannot provide an automated output, any manual transfer must retain its origin and be identified as operator-entered information. No common communication protocol or automated data interface has yet been implemented for the proposed arrangement.

The functional architecture of the proposed COMBI-CBRN system, including the information flow between the individual detection, identification, and sampling modules, is shown in Figure 2.

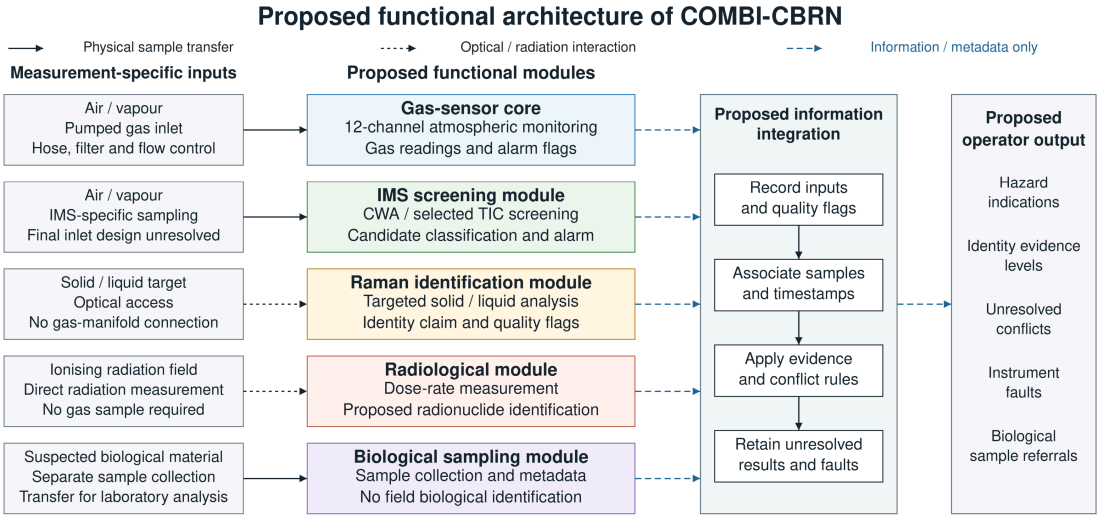


Figure 2. Proposed functional architecture of COMBI-CBRN. Solid arrows indicate physical sample transfer, dotted arrows indicate optical or radiation interaction, and blue dashed arrows indicate information or metadata flow. Module-specific inputs do not imply a shared gas-sampling manifold. Information integration and operator outputs remain proposed functions (prepared by the authors).

2.5. Experimental Procedures

The experimental assessment was designed to characterize the behavior of selected detection technologies used in operational practice and to provide a reference basis for evaluating the proposed integrated architecture. A physical COMBI-CBRN prototype was not constructed at this stage of the research. The experimental part therefore assessed stand-alone reference devices, whereas the characteristics of the proposed architecture were evaluated based on the defined configuration, the technical parameters of the individual components, and the functional organization of the system.

The chemical samples used in the experimental procedures originated from routine CBRN training stocks. Manufacturer or supplier information is provided at the first occurrence of each material for which such information was available. The remaining unidentified training samples were not independently characterised and were not treated as certified analytical reference standards.

All measurements were conducted in a controlled indoor environment at a temperature of approximately 18–19 °C, a relative humidity of about 60%, and an atmospheric pressure of 1000–1003 hPa. No forced airflow was generated, and the natural air velocity was estimated to be below 0.2 $m \cdot s^{-1}$. Each measurement was performed at least three times under comparable conditions. Between repetitions, the test area was ventilated and the instruments were allowed to return towards their pre-exposure indications. Separate numerical baseline records were not retained for all procedures.

2.5.1. Experimental Procedure for Multi-Gas Detection of Volatile Organic Compounds

The first experiment focused on the response of multi-gas detectors in the presence of volatile organic compounds. In an enclosed space with low air circulation, a 30 L container labelled as acetone (PENTA s.r.o., Prague, Czech Republic) was opened. The source was used to create a locally elevated concentration of organic vapors in the immediate vicinity of the container opening.

Measurements were performed using the two MultiRAE Lite units described in Section 2.3.1, as neither available configuration alone covered all parameters required for the experiment.

Both instruments were positioned directly at the container opening to record the locally elevated vapor concentrations. VOC, CO, and O_2 values and the time required for signal stabilization were recorded. **PID-based VOC readings ranged approximately from 180 to 230 ppm, expressed as isobutylene equivalent;** the short-term CO concentration reached approximately 15 ppm, and the oxygen concentration decreased by approximately 0.3 percentage points. Signal stabilization required approximately 15 s.

The results of this experiment were used as a reference observation for defining the requirements of the proposed multi-sensor architecture.

2.5.2. Experimental Procedure for IMS Detector Response to Organic Vapors

The second experiment documented the LCD 3.3 response in a technical-gasoline (PENTA s.r.o., Prague, Czech Republic) exposure scenario, with emphasis on the displayed classification, alarm timing, and output stability. The procedure provided a case observation relevant to interpretation rules rather than a systematic assessment of selectivity across target agents and interfering substances.

A container with technical gasoline was opened in a controlled environment. A solid white substance placed on a support was simultaneously located nearby, representing a second unknown material in the modelled incident scenario. The LCD 3.3 IMS detector was sequentially exposed to the vapor source and subsequently brought closer to the second

solid sample. The displayed classification, response time, and stability of the alarm output were recorded.

Upon exposure to vapors from the organic liquid, the device activated an alarm and displayed the classification "GB". The time to alarm ranged approximately from 8 to 12 s, and an unstable alarm–reset–re-alarm cycle was observed following alarm activation.

Because the tested vapor source was technical gasoline and therefore did not correspond to GB, the displayed classification was considered inconsistent with the known test source under the specific experimental conditions. No independent compositional analysis of the technical gasoline sample or dedicated clean-air control dataset was available; therefore, the cause of the displayed classification and the false-positive rate of the instrument cannot be determined from this experiment.

The experiment was therefore interpreted as a case observation illustrating the need for independent verification of an unexpected IMS classification. The nearby white solid was not independently characterised and was therefore not treated as a defined additional interferent.

2.5.3. Experimental Procedure for Raman Identification of Liquid Samples

The third experiment documented Raman outputs for five liquid samples measured through glass vials (DWK Life Sciences, Mainz, Germany) under the indoor conditions described in Section 2.2. The procedure examined acquisition duration, spectral interference, and the handling of an inconclusive identification output.

The experimental set consisted of five samples: isopropyl alcohol (PENTA s.r.o., Prague, Czech Republic), acetone, Shell Helix HX7 motor oil (Shell plc, London, UK), citric acid solution prepared from citric acid (CENTRALCHEM s.r.o., Bratislava, Slovakia), and an unknown solvent originating from material used during training.

Sample names indicate nominal identities. Independent reference characterisation was not available for every sample, and the sample set was not designed to estimate identification accuracy across a representative population of materials.

The samples were placed in standard glass vials and analyzed using the Progeny ResQ spectrometer. The laser beam was directed through the vial wall onto the sample. A single acquisition required approximately 10–15 s, including for spectral stabilization.

For some samples, particularly the motor oil and the unknown liquid, pronounced fluorescence background was observed, which reduced spectral quality and required repeated measurement. The unknown sample was not unambiguously identified during the first measurement, and the system returned a result characterized as a "low-confidence match".

The experiment was used to document the time required to obtain an instrument response, the occurrence of fluorescence-related limitations, and the need for repeated measurement when the initial spectral result was inconclusive.

2.5.4. Radiological Measurement of a ^{137}Cs Source

The fourth experiment examined the indication of a handheld radiation monitor at two defined distances from a low-activity gamma-radiation source.

A control ampoule containing ^{137}Cs with an activity of approximately 3.5 kBq was used as the reference source. The manufacturer and supplier of the control source could not be reliably identified from the retained experimental records.

The measurement was performed in a simulated laboratory environment. The dose rate was recorded first at 30 cm and subsequently at 5 cm from the source.

At 30 cm, the measured values ranged approximately from 0.32 to 0.35 $\mu Sv \cdot h^{-1}$. After reducing the distance to 5 cm, the values increased to approximately 1.8–1.9 $\mu Sv \cdot h^{-1}$.

The two measurement positions produced clearly different dose-rate indications. Because independent background measurement, integration time, and measurement uncertainty were not recorded in the original experimental dataset, the reported values are presented as total instrument readings rather than background-corrected source contributions. The experiment therefore only demonstrates the difference in instrument indication between the two tested distances and does not constitute a detailed characterization of distance dependence.

2.5.5. Data Treatment and Uncertainty Considerations

The available records were reviewed to determine which quantitative assessments could be supported. Complete replicate-level results and the associated calibration, reference, and timing information were not available for reconstruction of statistical estimates or measurement uncertainty budgets. The analysis therefore retains the recorded intervals and individual descriptive endpoints without assigning standard deviations, confidence intervals, or expanded uncertainties.

For the multi-gas procedure, the PID interval, maximum CO indication, and oxygen change represent different quantities and were evaluated separately. For IMS and Raman, assessment concerns the recorded classifications, timing, and inconclusive outputs; identification error rates require independently characterised samples and complete trial-level outcomes. For the radiological procedure, uncertainty assessment additionally requires documented background, integration time, measurement geometry, and calibration information. Manufacturer specifications alone cannot establish uncertainty for these particular measurements.

These requirements define the additional records needed for quantitative validation while preserving the present observations as evidence relevant to architecture development.

2.6. Assessment Criteria and Rating Rules

Six dimensions were considered: detection capability, response time, identification capability, stability, operational usability, and functional complementarity. Table 2 defines the ordinal rules used to classify the available evidence and specify requirements for future validation.

A rating applies only to a stated task, target or sample, instrument configuration, and set of conditions. It is not a general ranking of an instrument. For detection capability and stability, the higher categories additionally require evidence from more demanding validation conditions; they should therefore be interpreted as evidence-qualified assessment categories rather than equally spaced performance scores.

Unavailable evidence is recorded as not evaluable (NE). A function outside the intended scope of a module is recorded as not applicable (NA). Neither designation is assigned a zero score. Each assessment retains its E, M, or P provenance. In particular, an M specification or P requirement cannot establish an experimental system-level rating.

The dimensions are reported separately. Their ordinal values are not averaged or combined into a weighted total because the data do not justify numerical distances between categories or compensation between safety-relevant functions.

Detection capability is evaluated for a defined target, concentration or source strength, exposure duration, and sample phase. Future validation should report detection probability, false-negative and false-positive proportions, and, for continuous monitoring, false alarms per hour. Trial counts and confidence intervals are required. The present observations do not establish detection limits or detection probabilities.

Response time requires a defined starting event and output. Timing begins when the challenge reaches the external inlet for pumped measurements, or when acquisition starts

after safe positioning for Raman analysis. Alarm onset, signal stabilisation, and accepted identification are distinct endpoints. The task-specific budget B must be established before validation; no value is assigned retrospectively here. Observed durations remain reported in seconds.

Table 2. Ordinal assessment rules and evidence requirements (prepared by the authors).

Criterion	Rating Definitions	Required Evidence
Detection capability	0: No valid response. 1: Response observed. 2: Controlled-test requirements met. 3: Requirements also met under interference challenges.	Defined targets, blanks, concentrations, and test conditions.
Response time	0: No usable result by 2B. 1: $B < t \leq 2B$. 2: $B/2 < t \leq B$. 3: $t \leq B/2$.	Defined timing endpoint and task-specific budget B.
Identification capability	0: No interpretable identity, or identity disproven by an independent reference. 1: Tentative classification. 2: Accepted result reproduced. 3: Independently corroborated identity.	Acceptance rules, repeat acquisitions, and linked samples.
Stability	0: Alarm cycling or failed limits. 1: Quantitatively uncharacterised. 2: Controlled-test limits met. 3: Limits also met under interference challenges.	Time-series data, repeatability, and predefined limits.
Operational usability	0: Task failure or critical error. 1: Assistance required or $t > 2T$. 2: Unassisted, $T < t \leq 2T$. 3: Unassisted, $t \leq T$.	Standardised task, reference time T, and error records.
Functional complementarity	0: No added information. 1: Alternative principle duplicates coverage. 2: Uncovered function added. 3: Uncovered function and independent verification added.	Defined decision variables and applicable verification methods.

B denotes the predefined task-specific response-time budget; T denotes the reference task-completion time; t denotes the measured duration. Identification rating 2 requires two separately initiated accepted acquisitions. Operational-usability ratings 2 and 3 require completion without critical errors.

Identification acceptance follows the documented instrument-specific threshold or categorical rule and requires satisfactory quality flags. Numerical library-match scores are not probabilities of correct identification. Without a documented acceptance rule, an output remains tentative. Repeated acquisition demonstrates consistency, whereas independent corroboration requires another applicable analytical principle and a demonstrably linked sample.

Stability assessment requires a constant, independently monitored challenge and channel-specific acceptance limits defined before testing. Endpoints include within-run variation, baseline drift, recovery, between-run repeatability, and alarm–reset transitions. A coefficient of variation is appropriate only for positive signals sufficiently above zero; near-zero measurements require absolute variation.

For future validation, operational usability should be assessed through matched tasks performed in the intended protective equipment. Completion time, assistance, handling actions, instrument changes, and predefined critical errors should be recorded against the stand-alone workflow. Testing order should be counterbalanced to limit learning effect.

Functional complementarity is assessed against required atmospheric, chemical-identification, radiological, and biological-sampling functions. Broader coverage does not establish improved accuracy, and verification requires analytical applicability to the same

claim. Criteria unsupported by the available records remain NE; prospective requirements are not interpreted as demonstrated performance.

The assessment categories in Table 2 and the evidence levels in Section 2.8 serve different purposes. The former classify evidence supporting instrument or system assessment, whereas the latter describe support for an analytical claim. Synthetic software verification is reported separately. Passing an interpretation test does not justify replacing an NE classification for detection capability, response time, stability or operational usability.

2.7. Separation of Experimental and Design Data

Experimental observations concern only the reference instruments and procedures described in Sections 2.3 and 2.5. Manufacturer information describes the stated capabilities of particular products or configurations. Proposed functions, decision rules, sampling arrangements, and validation criteria belong to the design component.

The reference instruments are not identical to all modules selected for the proposed architecture. Results obtained with Progeny ResQ, LCD 3.3, PM-1401K-3, or the tested MultiRAE configurations are therefore not transferred as performance specifications of Pendar X10, a future IMS implementation, RIIDEye X, or the proposed twelve-channel core.

No system-level sensitivity, specificity, identification accuracy, response time, or usability advantage is inferred from the separate observations. The assessment identifies functional requirements and unresolved integration tasks.

Synthetic software records constitute a separate evidence category. Their validity, acceptance, applicability, sample association and dependency information are prescribed inputs rather than attributes established through additional measurements. Software-verification results are therefore not transferred to the analytical performance of the reference instruments or proposed hardware modules.

2.8. Proposed Decision Rules and Evidence Levels

A rule-based decision layer separates hazard indication from evidence supporting an analytical claim. A standalone reference implementation was developed and evaluated using synthetic records, as described in Section 2.9. It was not connected to an integrated COMBI-CBRN prototype and did not establish instrument validity, analytical acceptance or physical sample association from raw measurements.

Each measurement record must contain the instrument identifier, timestamp, sampling location or sample identifier, measurement mode, reported output, and available quality information. Applicable validity checks include calibration status, sampling-flow status, over-range indication, and instrument operating limits. A failed check prevents the record from supporting a negative finding or increasing identification confidence. The original output and fault indication remain visible.

Measurements are combined only when they address the same analytical claim and their sampling relationship is documented. Gas measurements require allowance for channel-specific transport delays. Raman analysis of a nearby material is contextual information unless its relationship to the sampled atmosphere is established. Radiation outputs and biological sample collection do not corroborate a chemical identity.

An accepted identification contribution must satisfy the instrument-specific acceptance rule and be reproduced in two separately initiated acquisitions. Repeated measurements from one instrument count as a single analytical contribution. A second contribution must use a different applicable analytical principle. Distinct principles are not assumed to be

statistically independent, and a known shared interference or sampling failure prevents their use as independent corroboration.

$$L(h) = \min\left[2, N_{eligible}(h)\right] \quad (1)$$

where h is a candidate identity and $N_{eligible}(h)$ is the number of eligible analytical principles supporting that identity for a demonstrably linked sample.

The resulting levels are:

$L = 0$: no accepted identification contribution; tentative outputs remain visible.

$L = 1$: repeatable accepted identification from one analytical principle.

$L = 2$: corroboration of the stated analytical claim by two eligible analytical principles, conditional on the validity of the acceptance, sample-association and dependency information.

The equation defines an ordinal evidence classification rather than a probability of correct identification or an optimised fusion estimator. The implementation also evaluates class-level claims. Support for a class cannot by itself increase the evidence level of a more specific identity.

These levels describe the status of the available evidence, not the probability that an identity is correct. A hazard alarm may be present at any level, including L = 0. Laboratory confirmation remains a separate outcome. A conflict flag is reported independently of L, and an unresolved conflict prevents the system from issuing an unqualified consolidated identity.

In the reference implementation, known shared-failure restrictions are encoded using supplied dependency labels. Contributions sharing the same declared label cannot provide the pair required for L = 2, although an otherwise eligible single contribution may retain L = 1. Missing dependency information is represented by shared = None and does not itself block a computed L = 2. Such an output does not demonstrate analytical independence or corroborated field identification. Internally inconsistent dependency declarations exclude the affected grouped contribution and are reported separately as metadata conflicts. These implementation conventions are documented in Table S1. The proposed rules for hazard indication, evidence integration, and conflict handling are summarised in Table 3.

Conflict resolution does not use majority voting or cancellation of positive outputs by unrelated negative channels. An invalidated record remains in the event history with its exclusion reason. Subsequent measurements can resolve a conflict only when they address the disputed claim and satisfy the applicable acceptance rules. The operator must be able to inspect the original outputs, evidence level, validity flags, and rule that produced the system message.

For a given set of measurement records, rule application follows a defined order. Instrument validity is checked first, followed by analytical applicability and sample association. Only eligible records contribute to the evidence level in Equation (1), with repeated acquisitions from the same analytical principle counted once. Compatible contributions are evaluated at the level of identity supported by all contributing methods; an agent-class result cannot by itself corroborate a more specific molecular identity.

Conflicts are evaluated separately from the evidence level. Valid outputs that cannot be reconciled for the same analytical claim remain visible as an unresolved conflict, and no unqualified consolidated identity is issued. A numerical reading is not converted into identity evidence unless its analytical scope supports that identity claim. The processing sequence is implemented for synthetic metadata records and evaluated in Sections 2.9 and 3.7. Its analytical effectiveness and suitability for operational use remain unverified.

Three illustrative cases show the intended behaviour. First, an IMS agent-class alarm accompanied by an elevated PID response remains an uncorroborated chemical alarm

because PID does not establish agent identity. Second, a low-confidence Raman output remains at L = 0 even if the same tentative match is repeated. Third, two accepted classifications obtained by different applicable principles for a linked sample support L = 2, provided no unresolved conflict or known common failure invalidates corroboration. These examples explain the intended interpretation policy. Executed synthetic verification cases and their actual outputs are reported separately in Table S2.

Table 3. Proposed rules for hazard indication, evidence integration, and conflict handling (prepared by the authors).

Input Condition	Interpretation	Required Handling
A valid channel exceeds its configured alarm threshold	Hazard indicated; identity may be unresolved	Preserve the alarm and identify the contributing channel
IMS reports an agent class without eligible corroboration	Chemical alarm with uncorroborated identity	Retain the alarm and request an applicable verification method
IMS alarm accompanies an elevated PID response	Chemical alarm with additional nonspecific vapour information	Do not treat PID as confirmation or rejection of the IMS identity
Another method is negative but lacks relevant sensitivity or sample-phase coverage	Non-informative negative result	Do not cancel the alarm or reduce the evidence level
Valid methods report incompatible identities for a linked sample	Unresolved identification conflict	Display both outputs and investigate quality, sample association, mixtures, and carry-over
Two eligible principles support the same identity	Corroboration conditional on acceptance, sample association and dependency requirements	Assign L = 2 only within the stated policy; retain supporting records and report unresolved limitations
Flow failure, over-range indication, or an applicable quality failure occurs	Affected measurement is compromised	Display the fault and exclude the record from absence claims
No channel alarms	No hazard detected within the monitored scope and conditions	Do not infer that the environment is safe or that unmeasured hazards are absent

In the reported technical-gasoline scenario, the GB output would be retained as an IMS alarm with unresolved identity. Recurrent alarm cycling would additionally produce a stability warning. The observations do not establish a concurrent PID measurement for that event, and none is assumed in applying this example.

2.9. Synthetic Verification of the Interpretation Rules

A standalone implementation developed in Python 3.11 was used to evaluate the interpretation rules specified in Section 2.8. It processes synthetic records containing instrument and analytical-principle identifiers, acquisition identifiers, analytical claims, sample identifiers, and prescribed acceptance, validity, applicability and dependency information. These metadata are test inputs rather than independently established analytical facts. The implementation was evaluated using the synthetic verification cases documented in the Supplementary Materials.

Twenty-nine primary cases were linked to nine requirement groups: alarm preservation, repeated acquisitions, distinct analytical principles, sample association, validity exclusion, analytical applicability, known shared-failure restrictions, class-versus-identity specificity and conflict handling. Table S1 documents this traceability and distinguishes manuscript requirements from implementation conventions. Fixed time-window behaviour

and mixture resolution are excluded from the primary suite because they are not sufficiently specified in Section 2.8. Historical case identifiers are retained.

Each case contains synthetic inputs and an authored expected decision signature. The compared signature comprises per-claim evidence levels, a conflict flag, permission to consolidate a specific identity, a raw-alarm flag, a warning flag and a validity-related fault flag. Expected outputs were derived from the interpretation policy and have not received independent CBRN domain-expert validation. Expected and actual decision signatures are presented in Table S2. Figure 3 summarises the implemented processing sequence.

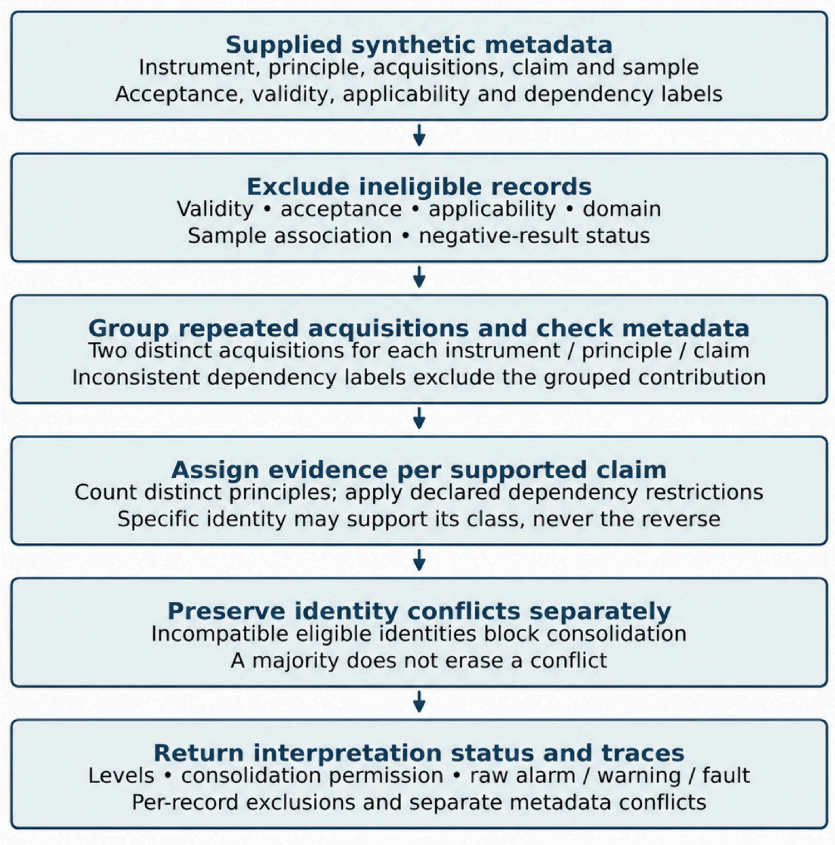


Figure 3. Processing sequence of the standalone interpretation-rule implementation.

Three supplementary checks were performed for each primary case: reversal of record order, duplication of transmitted records, and a trace-structure check, yielding 87 checks in total (Table S3). The trace check verifies correspondence between input and trace counts and the presence of exclusion fields; it does not establish complete preservation or integrity of every original data field.

Five safeguard-removal variants were executed on the same 29 cases. Validity, sample association, analytical applicability, repeated-acquisition requirements and the known common-failure restriction were disabled individually. Resulting signatures were compared with those of the complete implementation.The 145 variant executions are detailed in Table S4; they are not independent experimental observations.

Eight additional boundary test functions examined selected aggregation, dependency, specificity, conflict and ordering behaviours (Table S5). One function evaluated 60 deterministic shuffled orders of one six-record dataset, rather than independent operational scenarios. The tested boundary conditions, asserted behaviours and outcomes are summarised in Table S5. These procedures evaluate implementation behaviour under prescribed assumptions, not sensor accuracy or integrated-system reliability.

3. Results

Sections 3.1–3.6 report exploratory observations from separate reference instruments and their implications for the proposed architecture. Section 3.7 reports synthetic software-verification results. Neither evidence category establishes the analytical performance of an integrated COMBI-CBRN prototype.

3.1. Multi-Gas Detection of Volatile Organic Compounds

During measurements directly above the open container labelled as acetone, PID-based VOC readings ranged from approximately 180 to 230 ppm, expressed as isobutylene equivalent. A short-term CO indication of up to approximately 15 ppm and a decrease in O_2 concentration of approximately 0.3 percentage points were observed concurrently. Because separate numerical baseline and control measurements were not retained in the original experimental dataset, the origin of the CO and O_2 changes cannot be conclusively attributed to the acetone source. These observations may reflect local environmental variation and/or sensor response under specific test conditions and are therefore reported without causal interpretation. Signal stabilization required approximately 15 s.

Under the tested operational configuration, two separate MultiRAE Lite units were required to obtain the complete set of monitored parameters. One unit provided PID-based VOC measurements, while the second provided CO and O_2 information. Thus, the tested scenario required simultaneous handling of two instruments with complementary sensor configurations.

The measurements show that the available sensor configurations provided complementary information, and that simultaneous monitoring of the selected parameters required two separate units. The observed VOC range, maximum CO indication, and change in O_2 concentration are illustrated in Figure 4.

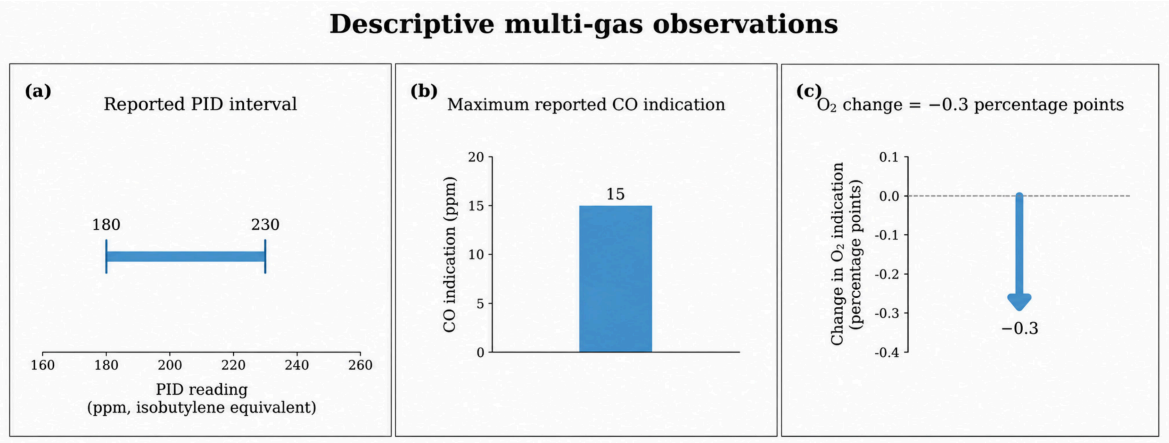


Figure 4. Observed parameters of the multi-gas measurement: isobutylene-equivalent PID readings, maximum CO indication, and change in O_2 indication. The panels show a reported interval, a maximum, and a change, respectively; they do not represent mean values or uncertainty estimates (prepared by the authors).

3.2. IMS Detector Response to Organic Vapors

Upon exposure of the LCD 3.3 IMS detector to technical gasoline vapors, the alarm mode was activated. The device displayed the classification "GB", corresponding to the nerve agent sarin, although the known test source was technical gasoline. The alarm was activated after approximately 8–12 s. This was followed by an unstable cycle of alarm activation, reset, and subsequent reactivation. Bringing the device closer to the second white solid sample did not alter this behavior.

Because the known test source was technical gasoline and did not correspond to GB, the displayed classification was inconsistent with the known source in this specific test scenario. The experiment does not establish the cause of this response, and a general false-positive rate for the device cannot be inferred from this single test scenario.

The result highlights the importance of complementary verification when using a selective chemical detector. In operational decision-making, a critical classification of an unknown substance should therefore not be based solely on a single sensing principle when operational conditions allow confirmation by an alternative method.

The proposed verification workflow for resolving an ambiguous IMS result using complementary detection methods is illustrated in Figure 5.

Decision workflow for verification of an ambiguous IMS result

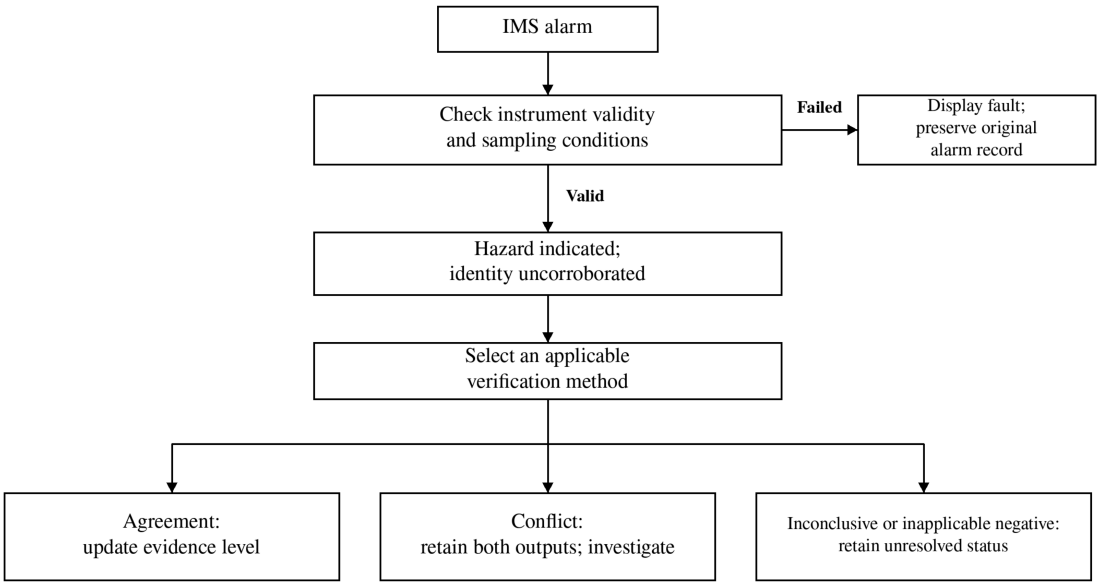


Figure 5. Proposed handling of an IMS alarm. Hazard indication is retained while validity, analytical applicability, and evidence supporting the reported identity are assessed (prepared by the authors).

3.3. Raman Identification of Liquid Samples

Raman spectroscopy was used to evaluate five samples: isopropyl alcohol, acetone, motor oil, citric acid solution, and an unknown liquid originating from training material. A single acquisition using the Progeny ResQ required approximately 10–15 s, including for spectral stabilization.

For the unknown liquid, pronounced fluorescence background was observed, and the instrument returned a "low-confidence match". Because the identity of this sample was not independently confirmed, the response cannot be evaluated in terms of identification accuracy. A repeated measurement was required because the initial result was inconclusive. Individual library-match values for the tested samples were not available in the original experimental record.

The observations show that the Raman response depended on the properties of the analyzed material and the quality of the acquired spectrum. Within the tested sample set, the principal limitation was the fluorescence background observed for the unknown liquid sample.

3.4. Radiological Measurement of ^{137}Cs

During measurements of a low-activity ^{137}Cs control ampoule with an activity of approximately 3.5 kBq, different dose-rate readings were obtained at the two tested distances. At 30 cm, the measured values ranged from 0.32 to 0.35 μSv·h^{-1}, whereas at 5 cm they ranged from approximately 1.8 to 1.9 μSv·h^{-1}. These values represented total instrument readings and were not corrected for background radiation.

The measurement therefore only demonstrates that the instrument produced clearly different dose-rate indications at the two tested positions. Because only two distances were evaluated, the experiment was not intended to characterize the detailed dependence of dose rate on distance.

Within the specific test procedure, the output of the device did not provide unambiguous information on the identity or category of the radionuclide. This observation applies specifically to the tested configuration and measurement procedure and should not be interpreted as evidence of a general inability of the PM-1401K-3 product line to perform radionuclide identification. Technical documentation for the device series also describes spectrometric and radionuclide-identification capabilities [25].

The relationship between the measured dose rate and the distance from the ^{137}Cs reference source is illustrated in Figure 6.

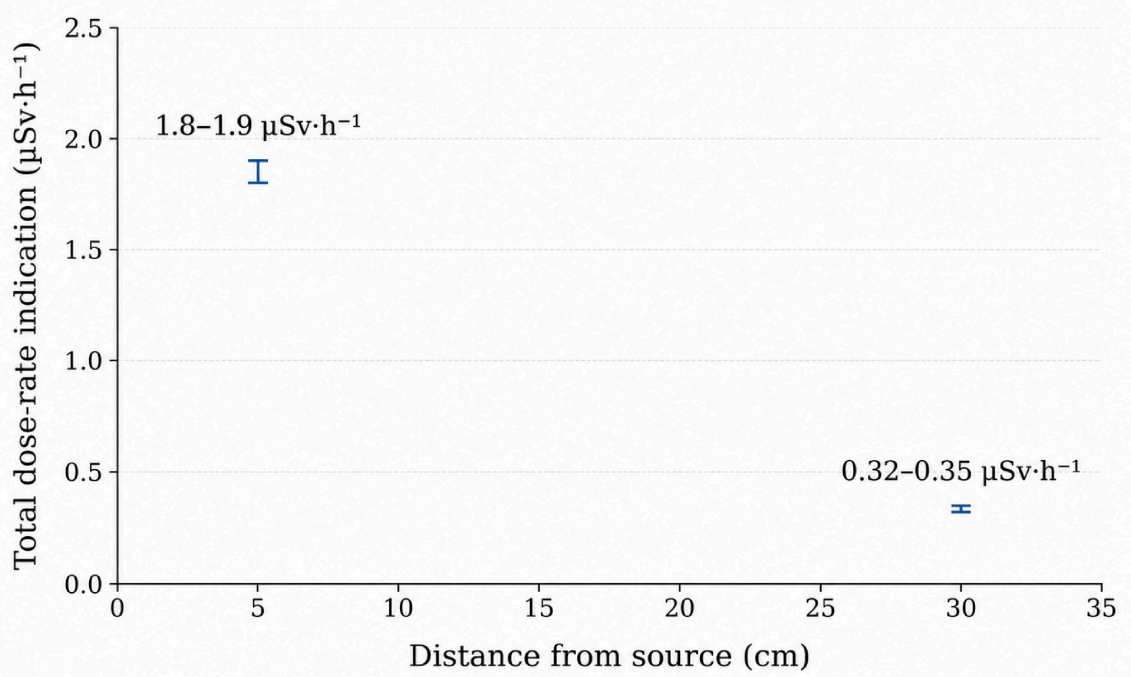


Figure 6. Reported intervals of total dose-rate indication at 5 cm and 30 cm from the ^{137}Cs control source. Vertical intervals represent the reported minimum-to-maximum values, not standard deviations, confidence intervals, or measurement uncertainties. No mean values are shown, and the readings were not corrected for background radiation (prepared by the authors).

Table 4 summarises the observations obtained with the four reference technologies and the principal limits of their interpretation.

The reported times describe different endpoints and are not directly comparable. These observations concern stand-alone instruments and do not establish integrated COMBI-CBRN performance. Reported intervals are descriptive ranges, not confidence intervals or measurement uncertainties.

Table 4. Summary of reference-device observations and interpretation limits (prepared by the authors).

Instrument	Main Observations	Interpretation Limits
MultiRAE Lite	Two units; PID VOC: 180–230 ppm isobutylene equivalent; CO: ≤15 ppm; ΔO_2: −0.3 percentage points; stabilisation: ~15 s.	CO/O_2 changes not attributed to the source; detection probability and repeatability not established.
LCD 3.3	GB output during technical-gasoline exposure; alarm onset: ~8–12 s; recurrent alarm cycling.	Source-inconsistent classification; cause and false-positive rate undetermined.
Progeny ResQ	Five samples; acquisition: ~10–15 s; unknown sample: low-confidence output requiring repeat measurement.	Unknown identity unverified; complete identification records unavailable; accuracy not calculated.
PM-1401K-3	Dose rate: 0.32–0.35 $\mu Sv \cdot h^{-1}$ at 30 cm; 1.8–1.9 $\mu Sv \cdot h^{-1}$ at 5 cm.	No background correction or uncertainty estimate; radionuclide identification not evaluated.

3.5. Functional Coverage of Integrated Architecture

The reference-device observations illustrate the distinct information roles considered in the architecture. Multi-gas monitoring provided atmospheric channel indications, IMS produced a chemical classification requiring further investigation, Raman analysis illustrated sample-dependent spectral interpretation, and the radiation monitor recorded dose-rate differences between two measurement positions. These findings inform the allocation of complementary functions and the interpretation requirements of the proposed architecture.

The proposed architecture was therefore not conceived as a replacement of the individual physical detection principles by a single universal sensor, but as a functional integration of complementary technologies.

Biological sample collection was not experimentally evaluated. The proposed biological module supports collection and transfer for laboratory analysis rather than field detection or identification. Radionuclide identification using the proposed RIIDEye X module was likewise not tested.

Table 5 applies the assessment rules to the available observations. The entries concern the tested scenarios rather than general instrument performance. Where the retained records do not satisfy a rating rule, NE is reported instead of an inferred score.

The NE classifications for integrated-system performance remain unchanged by the software-verification results. Section 3.7 addresses implementation of the interpretation policy and does not provide missing measurements of detection capability, response time, stability or operational usability. The synthetic results are classified as S and reported separately.

The reported response intervals are descriptive observations with different endpoints and cannot be used to calculate an integrated response time. Functional complementarity is assessed at the design level through the distinct tasks of atmospheric monitoring, chemical screening, solid/liquid analysis, radiological assessment, and biological sample collection. Experimentally demonstrated improvement through integration remains NE.

The key result of the system-level assessment is therefore the identification of the need for complementarity and cross-verification rather than the demonstration of superior performance of a COMBI-CBRN prototype that has not yet been constructed.

Table 5. Application of the assessment framework to the available experimental records.

Observation or Function	Supported Assessment	Unresolved Assessment
MultiRAE response near the vapour source	Detection category 1 for the observed source-exposure scenario; approximately 15 s to reported stabilisation	Detection probability, specificity, quantitative repeatability, and formal response-time category: NE
LCD 3.3 output during technical-gasoline exposure	Source-inconsistent GB classification; stability category 0 for the recorded alarm cycling; approximately 8–12 s to alarm	Cause of classification, general false-alarm rate, and source-verified identification accuracy: NE
Progeny ResQ output for the unknown liquid	Identification category 1 for the low-confidence output; approximately 10–15 s per acquisition	Correct identity, accuracy, and instrument acceptance-score assessment: NE
PM-1401K-3 dose-rate readings	Detection category 1 for the tested source and geometries	Background-corrected response, quantitative uncertainty, and radionuclide-identification outcome: NE
Operation in protective equipment	No standardised usability assessment available	Operational-usability category: NE
Integrated COMBI-CBRN operation	Proposed functions and integration requirements only, classified as P	System-level performance categories: NE

3.6. Synthesis of Experimental Findings

The results of the four experimental procedures revealed three recurring characteristics of the current detection process.

First, obtaining comprehensive information may require the use of multiple stand-alone devices. This was directly observed during the multi-gas measurement, in which two different MultiRAE Lite configurations were required.

Second, the high specialization of a single detection principle may introduce interpretative limitations. In the tested scenario, the IMS device displayed a GB classification inconsistent with the nominal technical-gasoline source and exhibited recurrent alarm cycling. Independent sample characterisation was unavailable, preventing attribution of the response to a specific interference mechanism. Raman analysis produced an inconclusive result for the unknown liquid sample in the presence of pronounced fluorescence background.

Third, quantitative indication of a hazard and qualitative identification of its source represent different levels of information. The radiological experiment produced clearly different dose-rate readings at the two tested distances, but radionuclide identification was not experimentally evaluated.

Biological detection or identification was also outside the experimental scope; the biological branch of the proposed architecture is limited to safe sample collection and transport for subsequent laboratory analysis.

These observations inform the proposed allocation of complementary functions and the requirement to investigate ambiguous outputs using analytically applicable methods. They do not demonstrate the effectiveness of cross-verification in an integrated system.

3.7. Results of Synthetic Rule Verification

All 29 primary synthetic verification cases passed (29 passed, 0 failed), with the audited implementation producing the expected decision signatures in every case (Table S2). All 87 supplementary verification checks also passed (87 passed, 0 failed; Table S3), and all eight additional boundary-test functions satisfied their predefined assertions (8 passed, 0 failed; Table S5). No verification failures were observed within the evaluated test suite.

The primary cases evaluated the retention of raw alarms without accepted identity evidence, the rejection of unsupported evidence escalation, the distinction between class-level and identity-specific support, and the preservation of unresolved conflicts despite majority support for another identity. The supplementary checks reused the primary test inputs and did not constitute 87 independent scenarios. Their scope was limited to the evaluated decision-signature properties and trace structure. The 60 deterministic reorderings performed in boundary test B08 involved a single six-record dataset and did not represent independent scenarios.

Removing individual safeguards changed selected decision signatures. Disabling validity checks affected three cases, sample association two, analytical applicability one, repeated-acquisition requirements three, and the known common-failure restriction one (Figure 7; Table S4). Two cases illustrate the significance of these safeguards for interpreting sensor outputs. In T13, the second analytical contribution was marked as invalid. With validity checking enabled, this contribution was excluded from identity corroboration, leaving the evidence level at $L(X) = 1$ while retaining the validity-fault flag (Table S2). Disabling the validity check changed the decision signature, demonstrating the importance of excluding invalid measurements from identity evidence. In T09, the second method examined a different object. The complete implementation retained $L(X) = 1$, whereas disabling the sample-association requirement allowed the evidence level to increase to $L(X) = 2$ despite the absence of a documented link between the samples. These cases illustrate how the safeguards prevent unsupported corroboration when measurement validity or sample association is not established. Their demonstrated effects are limited to the synthetic verification cases and do not establish operational performance.

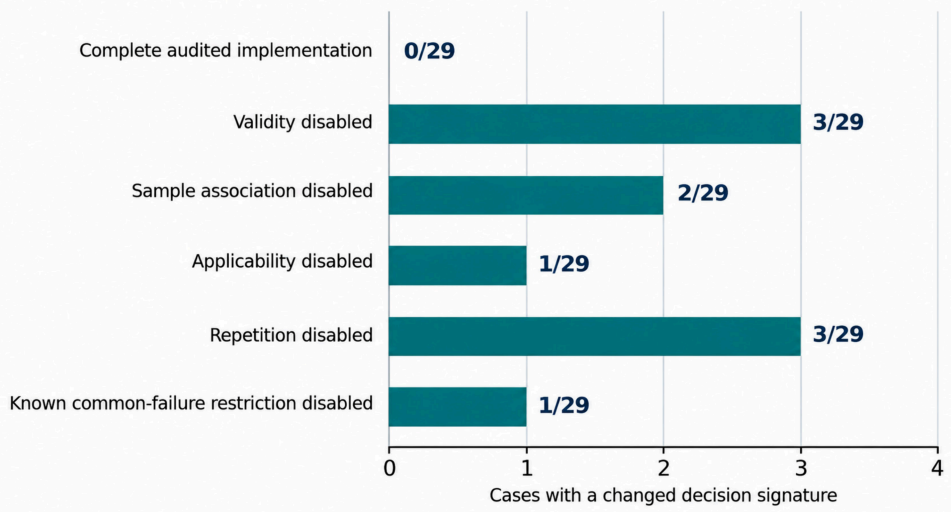


Figure 7. Effect of safeguard removal on decision outputs.

The additional boundary tests examined selected dependency-aggregation cases, the prevention of corroboration by two devices using the same analytical principle, the preservation of identity conflicts, and the stability of the decision signature under the tested reorderings (Table S5).

The results support consistency between the audited implementation and the authored expectations under the stated assumptions. They do not establish that the interpretation policy is analytically optimal, independently validated or suitable for operational deployment.

4. Discussion

The results of this study highlight a fundamental challenge in the initial CBRN reconnaissance conducted during fire and rescue operations: individual detection technologies provide different yet complementary types of information, and none of the tested methods alone provided a complete picture of the nature of the hazard. This finding supports the underlying premise of the study that integrating multiple detection principles based on different physical mechanisms has the potential to increase the information value of the initial incident assessment [8,9]. Similar integrated approaches combining sensor networks, data integration, and decision-support functions have been proposed for high-risk operational environments, including scenarios involving CBRN hazards [9]. The objective is not to replace specialized analyzers with a universal sensor, but rather to combine rapid indication, subsequent identification, and verification procedures.

4.1. Complementarity of Detection Principles

The multi-gas detector experiment demonstrated that even a relatively common scenario involving the presence of organic vapors may require the simultaneous use of two differently configured devices. PID-based VOC readings ranged from approximately 180 to 230 ppm, expressed as isobutylene equivalent, while changes in CO and O_2 concentrations were recorded simultaneously. Two MultiRAE Lite units with different sensor configurations were required to obtain all three types of information. From an operational perspective, the limitation therefore does not lie in the inadequate functionality of an individual device, but rather in the fragmentation of sensor coverage across multiple configurations.

This fragmentation motivates the proposed coordination of measurement functions. Previous studies have discussed multi-sensor and multimodal approaches for combining complementary information [30–33]. In COMBI-CBRN, the corresponding design requirement is to retain the meaning, provenance, and limitations of each output within a common record. Whether this arrangement reduces instrument changes, improves interpretation, or shortens reconnaissance must be evaluated through comparative tasks; these outcomes were not measured in the present study.

The LCD 3.3 observation illustrates a classification inconsistency requiring investigation. Exposure to the technical-gasoline source was followed by a GB output and recurrent alarm cycling. The available records do not identify the responsible compound or distinguish among chemical interference, sampling effects, and other instrument-specific causes. The observation therefore supports the need to investigate unexpected classifications, rather than a general conclusion about IMS reliability. Published IMS studies also show that complex mixtures and confounding compounds can affect classification and target response [34,35].

The interpretation of complementary outputs depends on their analytical scope. An elevated PID response indicates ionisable vapours but cannot confirm or reject a particular IMS agent classification. A negative gas channel that does not target the candidate agent is likewise not evidence of its absence. The proposed rules therefore preserve a valid hazard alarm while distinguishing it from evidence supporting the reported identity. Independent verification requires adequate sensitivity, an applicable analytical principle, and a documented sampling relationship.

4.2. Difference Between Detection and Identification

The results also confirmed the need to distinguish between the indication of a hazard and the identification of a specific substance or source. These two levels of information have different operational significance during an incident response, particularly because initial hazard assessment must support subsequent tactical and protective decisions [36].

Multi-gas channels and Raman analysis provide different types of information. Gas channels indicate atmospheric conditions within their specified measurement scope [17–19], whereas Raman spectroscopy can provide a molecular classification of a targeted solid or liquid sample [23,24]. Neither output should be interpreted without its analytical limitations.

Five samples were examined in the Raman procedure, but a complete dataset of sample-level accepted identifications, numerical match values, and independently verified identities was unavailable. An identification-success percentage or accuracy estimate is therefore not calculated. The low-confidence output for the unknown liquid documents an inconclusive result under the tested conditions; it does not establish whether the proposed match is correct.

The IMS and Raman cases support the identification of interpretation requirements, but their limited chemical diversity does not support general estimates of false-positive risk or identification accuracy. Such estimates require additional independently characterised samples, defined interferents, and appropriate controls.

A similar distinction was observed in the radiological measurement. Reducing the distance from the ^{137}Cs control source from 30 cm to 5 cm resulted in a pronounced increase in the measured dose rate, demonstrating the ability of the reference device to clearly indicate a change in the radiation field. Radiometric measurements provide quantitative information on radiation-field intensity and are widely used for assessing spatial variations in radioactive contamination and associated radiological conditions [37]. However, dose-rate information alone does not provide the same level of information as gamma spectrometric analysis, which enables radionuclides to be characterized based on their energy spectra [27–29,37]. Combining quantitative information on radiation-field intensity with qualitative information on radionuclide identity therefore represents another example of functional complementarity and can provide a more comprehensive basis for radiological hazard assessment [37,38].

4.3. Significance of the Proposed Architecture for Operational Decision-Making

The proposed workflow separates immediate hazard indication, targeted identification, and further verification. Gas and radiation channels provide initial indications within their respective measurement scopes. IMS and Raman analysis contribute different forms of chemical information, but do not automatically verify each other because their sample phases and analytical targets may differ. Additional verification is requested only through a method applicable to the disputed claim. Biological suspicion leads to a separate sample-collection and laboratory-analysis pathway [39].

Such an arrangement reflects the nature of initial operational decision-making during a CBRN incident. During the initial phase of the response, the incident commander does not necessarily require complete laboratory characterization of the material. The immediate priorities are to determine whether the environment presents an acute hazard, identify the most probable type of threat, establish the required level of protection, and determine whether the available information requires further specialized verification. In crisis-management environments, timely acquisition and integration of relevant information are essential for supporting situational awareness and operational decision-making [36,39,40].

Figure 8 presents the proposed operational workflow of the complete architecture. The standalone implementation evaluates a restricted interpretation component using supplied synthetic records, as shown in Figure 3. It does not implement instrument interfaces, physical sample linkage, transport-delay correction or the complete operator workflow. The software results therefore verify selected interpretation requirements without demonstrating the integrated operation depicted in Figure 8.

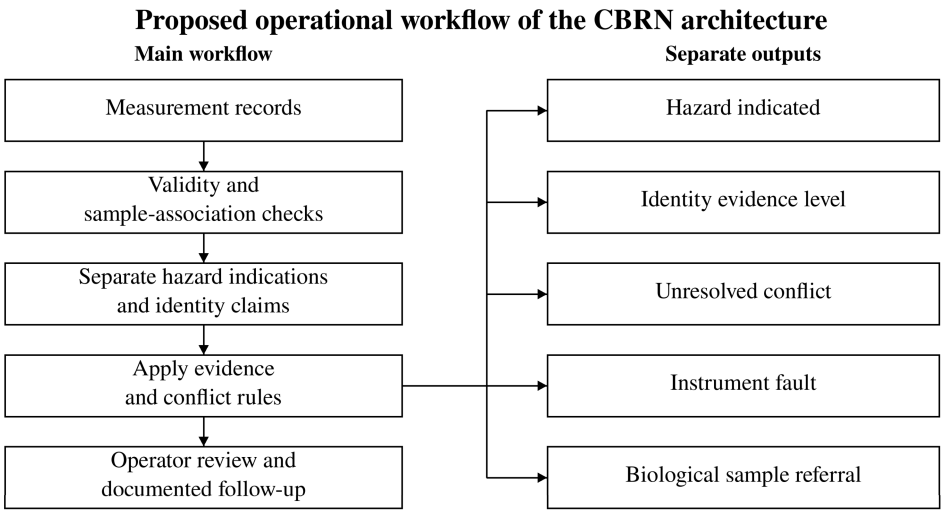


Figure 8. Proposed workflow for presenting hazard indications, identification evidence, unresolved conflicts, and instrument faults within a common reconnaissance record (prepared by the authors).

4.4. Environmental Interferences

The stable indoor observations do not establish performance in smoke-contaminated or rapidly changing incident environments. Temperature, humidity, condensation, aerosol loading, and mixed vapours should therefore be treated as additional validation variables. The following discussion distinguishes limitations relevant to the selected technologies from proposed failure mechanisms whose effects on COMBI-CBRN remain unmeasured.

Published IMS studies have demonstrated that non-target compounds and environmental interferents can complicate discrimination and produce false-positive responses [22,35]. For the proposed architecture, humidity-related changes in ion chemistry, overlapping responses from combustion products, and suppression of target signals are candidate mechanisms requiring controlled investigation. These mechanisms could affect both false-positive and false-negative outcomes, but their occurrence and magnitude cannot be inferred from the present measurements. The technical-gasoline observation neither identifies the responsible compound nor quantifies the effect of smoke or humidity on LCD 3.3 alarm behaviour.

Raman interpretation depends on the acquired spectral quality and measurement configuration [24]. In the present experiment, fluorescence was observed despite the use of 1064 nm excitation, and the unknown liquid produced a low-confidence result. This observation does not establish the source of the fluorescence or its behaviour under fire-scene conditions. For the proposed standoff configuration, smoke along the optical path is expected to attenuate or scatter light, while deposits and condensation may compromise sample presentation. These are anticipated limitations requiring tests with the selected module. The Progeny ResQ observations cannot quantify Pendar X10 performance.

Gas-channel outputs must be interpreted within their sensor-specific scope. The MultiRAE documentation recognises cross-sensitivity, including the response of a CO sensor to VOCs, and specifies configuration-dependent sampling and maintenance requirements [19]. In a combustion atmosphere, an apparent increase in a target-gas reading may therefore include a contribution from other compounds. Proposed validation should separately examine mixed-gas responses, humidity and condensation, sensor contamination, and sample delivery through tubing and filters. Changes in response magnitude, baseline, or recovery should not be attributed to a particular mechanism without appropriate controls. Agreement among channels alone does not establish a substance identity.

Environmental validation should distinguish analytical interference from sampling-system effects. Direct sensor-inlet exposure should be compared with exposure through

the complete sampling assembly. Target-only, interferent-only, blank, and target-plus-interferent trials should include post-exposure blanks to assess carry-over. Endpoints should comprise response changes, time to usable output, baseline recovery, false-positive and false-negative proportions, and inconclusive-result frequency. Challenge conditions should remain within the operating limits of the selected modules when normal analytical performance is being assessed.

Challenge levels must be specified using the intended reconnaissance task and the module-specific operating limits. Outside-limit tests assess fault handling or survivability rather than normal analytical performance. No numerical degradation factor is assigned because the required environmental measurements are unavailable.

Further testing should examine airflow, smoke, dust, and mixed chemical challenges using documented exposure conditions. Air velocity should be measured at the sampling location, aerosol challenges characterised by particle-size distribution and loading, and target and interferent concentrations independently monitored. Smoke and dust should be assessed separately because their composition and effects on optical access, sensor response, and filter loading may differ.

The stand-alone reference instruments should first be tested independently of the proposed sampling assembly. Corresponding complete-path tests should then distinguish analytical interference from sample-delivery losses or delays. Blank, target-only, interferent-only, and combined exposures should include recovery checks and synchronised records of environmental conditions, instrument outputs, and sampling status.

4.5. Operational Requirements and Technical Trade-Offs

Protective clothing and associated equipment impose additional ergonomic, thermal, and operational constraints on firefighters [41–43]. Whether a combined equipment arrangement reduces handling demands must therefore be assessed through user tasks rather than inferred from the number of included sensors. The approximate 20 kg value in the original design is an unverified total-mass target, not evidence of suitability for sustained carriage or operation.

A complete mass and power budget must include the enclosure, batteries, pumps, sensors, electronics, analytical modules, tubing, filters, consumables, and accessories. Integration also requires compatible calibration, communication, decontamination, and fault-management procedures. Adding functions may increase carried mass, maintenance demands, and the consequences of common-component failures.

Power characterisation should distinguish continuous monitoring from intermittent analytical tasks and account for start-up demand, pump operation, communication, and module-specific duty cycles. Operating endurance must be measured for a stated configuration and task sequence. A nominal supply voltage does not establish energy demand or battery endurance. Testing must also determine whether a power or communication failure in one component interrupts other measurement functions or compromises the event record.

COMBI-CBRN should therefore not be regarded as a single monolithic detector. It is more accurately characterized as a modular sensing and identification platform operating within a common operational workflow. The Raman instrument, radionuclide identifier, and biological sampling kit remain task-dependent modules. The appropriate allocation between carried equipment, a transport unit, and remotely positioned instruments requires operational evaluation.

4.6. Positioning Relative to Existing Integrated Systems

RAID-XP provides a commercial reference for combined chemical–radiological monitoring. Manufacturer documentation describes IMS-based CWA/TIC detection together with gamma-radiation, dose-rate, and accumulated-dose functions, including standalone and vehicle-mounted operation [44,45]. These capabilities are already realised in commercial hardware.

COMBI-CBRN extends the intended workflow to an industrial-gas array, targeted Raman analysis, proposed radionuclide identification and biological sample collection. These technologies are established individually. Moreover, experimentally evaluated multisensor fusion has been investigated in systems such as EU-SENSE [17]. COMBI-CBRN is therefore not presented as the first multisensor CBRN concept or a generally superior fusion method.

The contribution examined here is an application-specific specification linking module functions, evidence eligibility, sample association and conflict handling, accompanied by executable rules and traceable verification records (Tables S1–S5). Table 6 summarises the functional comparison with RAID-XP. The safeguard-removal analysis evaluates this implementation internally and is not a benchmark against commercial systems or alternative fusion algorithms.

Table 6. Functional and design comparison between RAID-XP and the COMBI-CBRN concept (prepared by the authors).

Aspect	RAID-XP [44]	COMBI-CBRN Concept
Functional scope	CWA/TIC monitoring; gamma dose and dose rate	Proposed gas, IMS, Raman, radiological, and biological-sampling functions
Sampling strategy	Continuous chemical monitoring; no gas sample required for radiation measurement	Pumped gas core with separate targeted analytical and sampling tasks
Modularisation	Combined chemical–radiological instrument	Gas core and task-dependent modules; final IMS integration unresolved
Inlet design	Internal flow-path details not specified in the cited webpage	Proposed hose, filters, and sensor paths; tube branch requires characterisation
Gas-sensor positions	Number not specified in the cited webpage	12 proposed sensor positions
Total gas-core pump flow	Value not specified in the cited webpage	1–1.5 L·min^{-1} design assumption
Targeted Raman working distance	Raman function not described in the cited webpage	Approximately 0.3–2 m for the selected instrument [26]
Mass	Numerical mass not specified in the cited webpage	Approximately 20 kg unverified target; complete mass budget unavailable
Intended use	Standalone or vehicle-mounted chemical–radiological monitoring	Initial fire and rescue atmospheric and material assessment
Development status	Commercial hardware	Conceptual hardware architecture; standalone interpretation software evaluated using synthetic records

A quantitative mass comparison is not supported because the cited RAID-XP webpage does not provide a numerical mass and the COMBI-CBRN value is an unverified target. No weight or portability advantage is claimed. The available inlet information also does not support a quantitative comparison of flow balance, carry-over, or pressure losses.

The additional numerical entries describe the proposed configuration and the documented working distance of the selected Raman instrument; they are not measurements of

integrated COMBI-CBRN performance. Specifications not reported in the cited commercial documentation are treated as unavailable information rather than absent capabilities.

Unresolved tasks include representative sample delivery, compatible flow requirements, carry-over prevention, instrument interfaces, physical and temporal sample association, independent review of the interpretation policy, and usability verification. These remain requirements for future integration. No matched comparison of detection performance, response time, workload or reliability was performed.

A quantitative performance comparison requires equivalent endpoints measured under matched conditions. Detection limits, classification error rates, response times, endurance, and task efficiency cannot presently be compared on that basis.

4.7. Sampling-System Risks and Verification Requirements

A shared inlet can align the nominal sampling location of several gas channels, but it also introduces common failure mechanisms. A contaminated hose, blocked filter, or manifold fault may affect several channels simultaneously. Physical carry-over and backflow must be distinguished from chemical cross-sensitivity within a sensor.

For a parallel manifold under steady flow, with negligible leakage and volumetric flow rates expressed at the same reference conditions, the flow balance is:

$$Q_{pump} = \sum_{i=1}^{n} Q_i + Q_{\text{bypass}} \quad (2)$$

Here, Q_i denotes an individual branch flow. Equal branch flows are not assumed. Each branch must satisfy the operating requirements of its sensor or analytical element. A stable total flow does not establish adequate flow in every branch. Prototype testing must therefore measure individual branch flows across different hose configurations, filter loads, and indicator-tube operating states. Deviations from validated branch-flow limits must generate a fault indication.

An initial estimate of transport delay within an individual branch is:

$$t_{branch,i} = \frac{V_i}{Q_i} \quad (3)$$

V_i denotes the internal volume downstream of the flow split. Transport through the shared inlet adds a separate delay determined by its volume and flow. These estimates neglect mixing, adsorption, and desorption and require verification using measured step responses. Time to a usable output also includes sensor response and processing; it cannot be determined by summing the response times of the separately tested reference instruments.

Cross-contamination and backflow should be investigated through alternating challenge and blank exposures, including pump and valve transitions. Residual responses must remain below a predefined blank limit before a subsequent measurement is accepted. Tubing adsorption and memory effects should be assessed by comparing direct-inlet and complete-path exposures, followed by clean-air recovery. Target-specific limits are required for analyte transmission and recovery time. Short sampling paths, candidate low-sorption materials, and branch isolation are proposed mitigation measures whose effectiveness remains to be demonstrated.

Filter clogging should be evaluated under controlled aerosol loading while recording differential pressure and individual branch flows. A fault indication must occur before any branch leaves its validated flow range. Filters and conditioning materials also require target-specific transmission tests under dry and humid conditions, since adequate flow alone does not demonstrate representative analyte delivery. Leakage and condensation should be examined through leak tests and temperature–humidity transitions, with predefined leakage limits and measures to prevent or detect liquid accumulation.

These tests are critical requirements for future prototype validation, not completed experiments. Acceptance limits must be specified before testing from the selected modules and intended analytical tasks. An independent reference measurement at the sampling inlet should accompany synchronised records of flow, pressure, environmental conditions, and sensor outputs. If the selected functions cannot share an acceptable sampling arrangement, separate paths or pumps will be required. A common pump therefore remains a design option rather than a demonstrated system capability.

4.8. Study Limitations

The principal limitation is the absence of an integrated COMBI-CBRN prototype. Instrument observations concern separate reference devices, whereas software results concern a standalone interpretation component evaluated using synthetic records. Representative sample delivery, hardware compatibility and integrated analytical performance have not been demonstrated.

The measurements were conducted under stable indoor conditions. Smoke, substantial airflow, temperature and humidity transitions, and defined interferent mixtures were not investigated. The environmental discussion identifies plausible mechanisms but does not quantify their effect on the selected modules.

The original records do not include complete replicate-level numerical data, raw spectra, numerical identification scores, or independent reference characterisations for every sample. Baseline, integration-time, and uncertainty information are also incomplete for the radiological procedure. These omissions prevent formal estimates of repeatability, identification accuracy, false-alarm probability, or background-corrected source response.

The assessment framework was applied retrospectively. Its ordinal categories and proposed decision rules have not been validated as predictors of operational benefit. Manufacturer information and design requirements cannot replace missing experimental evidence.

Finally, neither the usability of the proposed arrangement in protective equipment nor its total mass, power demand, decontamination procedure, and integrated fault behaviour has been demonstrated. These limitations prevent claims of superiority over stand-alone equipment or commercial integrated instruments.

Software verification has additional limitations. The cases and expected outputs were authored from the proposed policy and do not provide independent analytical reference truth. Validity, acceptance, applicability and sample association are prescribed metadata whose correctness is not established by the software. Dependency labels are an implementation convention, and unknown dependency information does not itself prevent a computed $L = 2$. Agreement with expected outputs therefore does not prove analytical independence or correct field identification.

Conflict checks concern eligible incompatible specific identities under a single-identity task assumption. Mixture interpretation, temporal association and transport-delay correction are outside the scope. The supplementary trace check addresses record counts and exclusion fields rather than complete raw-data integrity. Independent domain review and testing with instrument-derived records remain necessary.

4.9. Future Research

The first development task is a functioning gas-sensor core with measured branch flows, pressure losses, transport delays, and raw channel outputs. Direct-inlet and complete-path exposures should distinguish sensor behaviour from sampling artefacts. Target, blank, interferent, and mixed exposures are required to evaluate detection and carry-over.

Further software development should begin with independent domain review of the policy and implementation conventions documented in Table S1, particularly unknown

dependencies, repeated acquisitions and conflicting outputs. The reviewed policy and implementation should be versioned, the verification suite rerun, and additional cases derived from instrument-generated records evaluated. Subsequent integration must establish instrument interfaces, documented sample linkage and appropriate temporal handling before comparative operational testing.

Analytical validation should use independent reference measurements and test cases separate from those used to select acceptance thresholds. Trial counts should be chosen to provide the required precision for detection and error-rate estimates. Detection probability, false-positive and false-negative proportions, inconclusive-result frequency, time to usable output, and recovery should be reported with their denominators and uncertainty.

The IMS test set should include defined target challenges, chemically distinct non-target substances, representative mixtures, and clean-air controls. Alarm events should be distinguished from independently initiated exposure trials so that alarm cycling is not counted as multiple independent false-positive events.

The Raman test set should include independently characterised materials covering relevant sample types, mixtures, fluorescence backgrounds, and packaging conditions. Each acquisition should retain the sample identifier, spectrum, reported classification, quality information, and applicable acceptance rule. Correct, incorrect, and inconclusive outcomes should be reported separately, with inconclusive results retained in the trial totals.

Numerical measurements should retain individual results for repeatability assessment and an uncertainty budget appropriate to the measurement configuration. Categorical identification outcomes should instead be evaluated using trial-based error estimates and confidence intervals.

Environmental and sampling challenges should address the mechanisms and verification requirements described in Sections 4.4 and 4.7. Subsequent user trials should compare the proposed arrangement with the current stand-alone workflow using matched tasks in protective equipment. Where functional scope permits, a commercial integrated arrangement should provide an additional comparator. Each task must specify the required analytical outputs so that faster completion is not achieved by omitting a measurement or verification step.

Total task time should be measured from a predefined common starting condition to delivery of the required reconnaissance record, including inconclusive results and necessary follow-up. Instrument readiness and set-up time should be reported explicitly. Identification outcomes, critical errors, handling actions, instrument changes, assistance requirements, carried mass, and interruptions caused by faults should be assessed alongside elapsed time. Task order should be counterbalanced, and unresolved or failed tasks should remain in the reported results. Figure 9 summarises the proposed development and validation sequence.

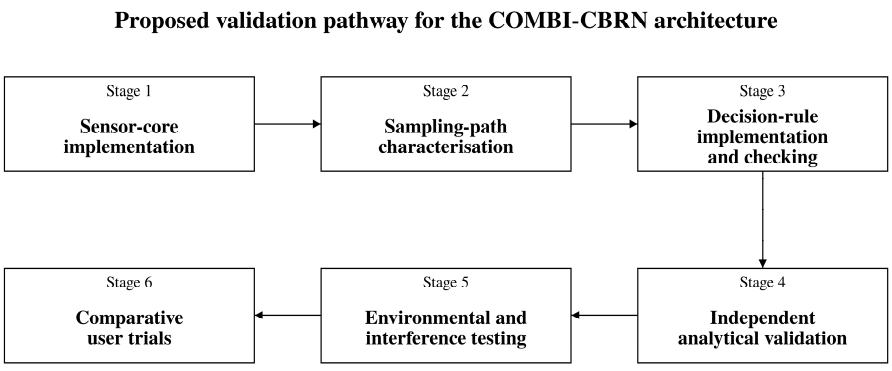


Figure 9. Proposed development and validation sequence. Each stage requires documented acceptance criteria before progression to operational evaluation.

5. Conclusions

This study presents an application-specific conceptual architecture for modular CBRN reconnaissance and a standalone implementation of its interpretation rules. Exploratory observations from separate reference instruments illustrate relevant interpretation limitations but do not establish integrated-system performance.

The audited implementation matched the authored expected decision signatures in 29 synthetic cases, satisfied 87 supplementary checks and passed eight additional boundary test functions. Safeguard-removal comparisons demonstrated that selected validity, association, applicability, repetition and dependency restrictions affect the outputs of the constructed suite. The supplementary tables document the evaluated cases, expected and actual decision outputs, and additional verification results.

These results support implementation consistency within the evaluated scope. They do not establish detection accuracy, analytical independence, operational reliability or superiority over existing systems. The biological component remains a sample-collection function rather than demonstrated on-site biological identification. Independent policy review, evaluation using instrument-derived records, physical prototype development and comparative analytical and user testing are required to establish the practical value of the architecture.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/electronics15225375/s1. The accompanying supplementary document contains Table S1: Interpretation rules and corresponding synthetic verification cases (prepared by the authors); Table S2: Comparison of expected and actual decision outputs for the primary synthetic verification cases (prepared by the authors); Table S3: Results of supplementary software verification checks; Table S4: Effect of individual safeguard removal on decision outputs; and Table S5: Results of additional boundary tests.

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Abbreviations

The following abbreviations are used in this manuscript:

CBRN	Chemical, biological, radiological, and nuclear
COMBI-CBRN	Proposed integrated multi-sensor CBRN detection architecture
CWA	Chemical warfare agent
EC	Electrochemical

HaZZ	Fire and Rescue Corps of the Slovak Republic (*Hasičský a záchranný zbor*)
IMS	Ion mobility spectrometry
LEL	Lower explosive limit
NA	Not applicable
NE	Not evaluable
PID	Photoionization detector
RIID	Radioisotope identification device
TIC	Toxic industrial chemical
VOC	Volatile organic compound

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