



Original Research Article

Intelligent Measurement and Condition-Monitoring Framework for Underground Aviation Fuel Hydrant Networks in Saudi Airports

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Abstract: The underground aviation fuel hydrant systems have to tightly contain hydrocarbons, ensure that the fuel quality remains strict, and are difficult to reach because of the physical limitations involved. They are also influenced by the changes that take place when aircraft are refuelling. For these reasons, the method needed to monitor such networks is different from that applied to long-distance oil pipelines. This article looks at the research carried out between 2020 and 2025 on a number of topics including pipeline leak detection, structural health monitoring, fibre-optic sensing, acoustic emission, hydraulic analytics, sensor fusion, machine learning, and digital twins. On the basis of this research it proposes a framework tailored for airports in Saudi Arabia. The framework follows a step-by-step procedure: the pressure and flow data establish the hydraulic context, while acoustic, vibration, fibre-optic, hydrocarbon-sensitive and corrosion sensors each contribute separate evidence. Edge analytics are used to filter out operational noise, and then a fusion stage combines all the data to estimate the presence, location, severity and degree of degradation of any leak, as well as how confident the estimates are. A digital model links these results to the asset's history, inspection records, maintenance work and operational data. The framework places particular emphasis on the buried pipes underneath the aprons, the hydrant pits, the branch connections, the interfaces between the soil and concrete, access to the sensors, controlling false alarms, and distinguishing between the normal changes that occur during refuelling and abnormal leaks. The review also connects the framework to the EI 1560 best practices and to Saudi Vision 2030, an initiative which aims at achieving reliable, safe, environmentally responsible and digitally capable airports as air traffic increases. The key point is that Saudi airports should not depend on single-sensor leak detection; rather, a risk-based, multi-physics, data-fused approach is more reliable for providing early warnings, enabling condition-based maintenance, reducing product loss, and improving the predictive management of the hydrant network.

Keywords: Aviation Fuel Hydrant Systems; Leak Detection; Structural Health Monitoring; Fibre-Optic Sensing; Acoustic Emission; Sensor Fusion.

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1. INTRODUCTION

Aviation fuel hydrant systems represent the last stage of fixed infrastructure linking airport fuel

storage with the delivery of fuel to an aircraft by means of mobile units or hydrant servicers. At big airports, ring mains and their branches are buried

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under the aprons, since digging there would be disruptive, access is limited, and even a small release of a hydrocarbon could have environmental, fire-safety, operational, and reputational repercussions. For this reason the Energy Institute considers hydrant systems to be a safety- and fuel-quality-critical component of the aviation fuel supply chain and stresses the significance of reliable operation, regular inspection, maintenance, commissioning, and keeping the systems clean. The difficulty of monitoring is greater in Saudi Arabia as airport development is taking place on a national scale. According to the Saudi Aviation Strategy, by 2030 there will be connectivity to more than 250 destinations via 29 airports, 330 million passengers per year and 4.5 million tonnes of air cargo. With more aircraft movements, larger aprons, new terminals and greater fuel throughput, both the importance of having hydrant systems available and the consequences of undetected deterioration increase. Research into pipeline monitoring has moved on very quickly, but the majority of the studies focus on long transmission pipelines, water distribution networks, gas distribution systems, subsea pipelines, or laboratory setups. Recent reviews indicate that the available methods include external sensing, computational techniques, acoustic methods, analysis of pressure and flow, and combinations of these technologies, with no single method being universally superior. Airport hydrants differ in a number of important ways. Their network layout includes loops, short branches, pits, isolation valves, low points, and frequent connections. The flow stays intermittent and depends on demand rather than being continuously steady. Changes in hydraulic signatures occur when refuelling begins or ends, more than one stand can operate at the same time, and the use of pumps or control valves leads to legitimate temporary occurrences. Moreover, a large part of the pipe is covered by concrete pavement, which limits physical access and alters the way acoustic or temperature signatures propagate.

The technical issue at the heart of the matter is therefore more extensive than simply detecting leaks. It is necessary to have an intelligent measurement system which not only picks up on abnormal conditions as well as describes the condition of the assets, identifies the probable source, estimates the level of confidence, maintains fuel quality, and assists in making maintenance decisions. It is important to note that a binary alarm may be technically accurate yet operationally inadequate if it is unable to tell the difference between a refuelling transient and a leak, to identify the area affected, or to explain why several sensors give conflicting readings. Current research is increasingly in favour of using multi-sensor fusion, machine learning, distributed fibre sensing, and digital-twin concepts as

methods of combining detection, localization, quantification and prediction. The fact that such developments have taken place provides an opportunity to create a specific framework for underground aviation fuel networks rather than simply importing a general pipeline algorithm unchanged.

2. Aim, Scope and Review Objectives

This study intends to develop an intelligent measurement and condition-monitoring framework for underground aviation fuel hydrant networks at airports in Saudi Arabia based on existing evidence. It does not involve the design of a new type of physical leak detector in isolation; rather, the review looks at how various measurement technologies and analytical methods can be combined to form a practical integrity system that can progress from baseline monitoring to predictive asset management.

The synthesis is guided by four objectives. The first is to identify the failure mechanisms and the observability requirements which are particularly relevant to buried airport hydrants, such as small leaks, releases from the joints or valve pits, corrosion-caused loss of wall thickness, the risk of water ingress, abnormal pressure behaviour, and sensor drift. The second objective entails comparing the various technologies—hydraulic, acoustic, fibre-optic, direct-hydrocarbon, and corrosion-monitoring—on the criteria that are important in an airport context, namely sensitivity, localization, coverage, the difficulty of retrofitting, maintainability, immunity to normal operational transients, and the ability to provide condition information. The third objective is to design a layered sensor-fusion and digital-twin architecture that enables raw measurements to be converted into alarms rated for confidence and health indicators. The fourth objective is to suggest a step-by-step implementation approach for Saudi Arabia that is in line with EI 1560, the Saudi Aviation Strategy, and the Vision 2030 priorities relating to safety, sustainability, operating efficiency, and technology capability.

3. REVIEW METHODOLOGY

A narrative review in an organised manner was chosen since the available literature includes a mixture of experimental arrangements, field examples, simulation studies, review articles, standards, and policy documents. A statistical meta-analysis would be inappropriate because there is no standardisation among the studies regarding leak sizes, pipe materials, the fluids being transported, burial conditions, sensor spacing, sampling rates, alarm definitions, and the performance criteria. Despite this, the review process was made transparent by applying the PRISMA 2020 guidelines

for identification, screening, eligibility, and reporting. The protocol focused on literature published between 2020 and 2025 and gave priority to peer-reviewed articles from journals listed in Scopus or Web of Science, also including authoritative sources on aviation fuel and Saudi policy when the scholarly literature did not specify the operational or strategic requirements.

The search included combinations of terms relating to pipeline or hydrant systems and leak detection, condition monitoring, acoustic emission, distributed acoustic sensing, distributed temperature sensing, fibre Bragg grating, pressure transient, flow balance, sensor fusion, machine learning, corrosion monitoring, digital twin, underground pipeline, aviation fuel, airport hydrant, and Saudi aviation. Preference was given to publisher records and indexed literature from the databases linked with Elsevier, Springer, Wiley, Taylor & Francis, MDPI, Optica, and those related to IEEE. The technical evidence base was further enhanced through incorporating EI 1560, a case study on airport jet-fuel hydrants, the Saudi Aviation Strategy, the Vision 2030 Annual Report, and the GACA sustainability information.

A study was included only if it made a direct contribution to one or more of the following framework functions: abnormal-event detection, leak localization, inference of leak size or severity, long-distance or distributed sensing, buried-pipeline observability, corrosion or degradation assessment, multi-sensor fusion, real-time analytics, or digital condition representation. Research was excluded if it was published outside the 2020–2025 period, if it did not provide a sufficient methodological description, if it dealt with unrelated rotating machinery without any transferable relevance to sensing, or if it merely repeated earlier leak-detection taxonomies. The final reference set consists of 30 sources. The evidence was coded thematically rather than being assessed by a single performance score, since an algorithm which shows strong accuracy in a laboratory setting might still be inappropriate for use under an operating apron if it requires dense wired access, a stable flow, or operates in a noise environment different from that found at an airport.

4. Underground Aviation Fuel Hydrant Networks as a Monitoring Problem

A buried hydrant system should be seen as a combination of hydraulic, structural, electrochemical, and environmental aspects. The hydraulic part consists of pumps, isolation devices, loops, branches, hydrant pits, valves, and aircraft demand points. The structural component comprises the pipe wall, welds, flanges, joints, supports, and the interfaces where construction tolerances or repeated loading might

cause stress to concentrate. The electrochemical aspect is determined by the condition of the coating, the soil environment, cathodic protection, and the starting or continuing of corrosion. The environmental aspect covers the soil or backfill, the concrete pavement, groundwater, temperature, and the routes by which escaped fuel could migrate. It follows that an effective monitoring system must keep a close eye on more than one physical domain. Leak signatures vary from one case to another; a sudden break will cause a clear pressure transient and a quick difference in the amount of fluid on hand, while a leak through a pinhole may result in only a slight hydraulic disturbance. Research into acoustic emissions has found that small leaks can produce detectable transient elastic energy, but the same research also shows that noise and the way the signals propagate make interpretation difficult. Studies on buried pipelines using distributed acoustic sensing show that leakage can be detected by looking at both the deformation of the surrounding soil and the vibrations associated with the fluid, the sensitivity being influenced by the distance between the pipe and the fibre, the direction of the leak, the pressure, and the type of burial medium. Another method is active distributed temperature sensing, which observes changes in the thermal behaviour of the surrounding porous medium and has proven promising for detecting and locating underground leaks. These results are applicable to hydrants since concrete and soil do not simply conceal the pipe; they modify the way in which the energy from a leak reaches a sensor.

The operation of an airport involves a particularly dense number of confounding factors. The vehicles used for servicing aircraft produce vibrations. The hydrant valves are frequently opened and closed. The pump schedules, the pressure-control valves, and the fact that refuelling takes place at the same time lead to transients which could be similar to fault signals. The day-night temperature changes and the intense solar heating of the pavement affect the pits and sensors near the surface. Maintenance work can result in temporary hydraulic arrangements. Therefore, a reliable system should learn to recognise these normal states rather than regard any departure from a fixed baseline as showing a leak. The actual aim of the design is thus discriminability – that is, the ability to tell the difference between a hazardous or degrading situation and the normal variation of the airport with enough confidence to warrant taking action. The topology also has an effect on the localization problem; in the case of a linear arrangement, arrival-time differences or the pressure responses at the boundaries can indicate the value of one coordinate. In a looped hydrant network, however, several paths can link the same hydraulic nodes and demand

changes at several aircraft stands can take place simultaneously. The more complex the topology, the more valuable multi-sensor evidence becomes. It has already been demonstrated that transient-based fusion enhances localization when the individual measurements contain only weak or noisy evidence, and that pressure-and-flow fusion based on Dempster-Shafer reasoning improves the reliability of the decision when the sensors give conflicting results. This evidence for airports indicate that zone-level reasoning—which combines the topology, the operating state, and the different sensor modalities—should be used rather than depending on a single threshold at a fuel-farm boundary.

5. Measurement Technologies for Hydrant Condition Intelligence

Hydraulic pressure and flow measurements should continue to form the core of a hydrant monitoring system since they directly reflect how the network is operating and are already something that fuel-system operators are familiar with. Methods based on mass or volume balance, pressure-point analysis, the negative-pressure-wave technique, and model-based residuals are able to identify occurrences when the hydraulic disturbance exceeds the level of uncertainty associated with measurement and modelling. Studies involving the use of intermediate pressure sensors explain why arrangements that rely only on boundaries may fail to detect low-pressure events whose characteristics disappear before they reach an inlet or an outlet. Variational-mode-decomposition methods can help in extracting the inflection points of negative-pressure waves from noisy signals. In the case of hydrants, this means that it is not necessary to install a sensor on every pipe segment, but rather that sensors should be placed at hydraulically significant nodes such as at the pump discharge, at major loop junctions, at remote extremities, at high-consequence branches, and at selected stand groups. It is essential to have proper time synchronization since localization depends on comparing how the event develops throughout the network. Hydraulic sensing is a cheap and highly interpretable method, but it does have some limitations. It is impossible to detect small seepages since they can fall below the meter's level of uncertainty; simultaneous refuelling can hide a variance in the balance; and a pressure transient shows only the system's response rather than the actual release mechanism. Data-driven approaches can help with classification. Artificial neural networks, when trained using pressure and flow data, have shown accurate leak localisation under controlled conditions, and attention-based LSTM models are able to pick up on temporal relationships and give more weight to measurements close to a leak. However, such models should be used as aids to decision-making and not as black-box substitutes for

hydraulic logic. For use at an airport it is necessary to have transparent trends regarding the features, a measure of alarm confidence, and a fallback rule set so that the system stays operational even if a model update or the communication failure occurs.

Acoustic emission and vibration monitoring offer a complementary perspective since the escape of pressurized fluid and structural discontinuities causes the production of elastic and vibrational energy. A reference study from 2023 shows a useful signal-processing approach: obtain the acoustic-emission channels, divide the data into segments, extract features in both the time and frequency domains, and then use machine-learning classifiers to identify leaks. In other studies, dependence on fixed thresholds has been reduced by means of multiscale statistical tests, event tracking, vulnerability indices, wavelet scalograms, and convolutional models. Work involving deep learning and wireless accelerometers also demonstrates that spectrogram-based methods are able to distinguish between different pipeline states in noisy environments. These techniques are particularly suitable for use at hydrant pits, valve chambers, accessible manifolds, or at key branch locations where it is possible to fit sensors without having to excavate the whole network. The main problem from an acoustic point of view is transferability. The amplitude of the signal and its frequency content depend on the material of the pipe, its diameter, the pressure, the geometry of the joint, the quality of the mounting, the surrounding concrete or soil, and existing background vibrations. It cannot be assumed that a classifier which has been trained on a stainless-steel laboratory loop will be able to apply its learning to a buried aviation-fuel main. Although continuous wavelet methods and convolutional networks are able to learn complex signatures, operation at an airport requires site-specific commissioning data that cover normal refuelling procedures, the transitions between pumping states, vehicle traffic, maintenance noise, and intentionally simulated safe anomalies. The aim is to create an acoustic evidence channel such that its level of confidence increases whenever the signal is physically plausible and is supported by other sources.

Distributed fibre-optic sensing is especially useful in cases involving long sections that are buried and need to be continuously monitored in terms of space. With distributed acoustic sensing it is possible to turn an optical fibre into a dense array of vibration detectors; distributed temperature sensing or the use of actively heated fibre can show thermal anomalies; and fibre Bragg gratings can give discrete, high-sensitivity measurements of pressure, strain, temperature or vibration. Experimental studies have shown that distributed acoustic sensing can be used

for detecting pinhole leaks in buried soil and that active distributed temperature sensing can be applied to the identification and location of underground leaks. Weak-FBG arrays have been employed for combined temperature-vibration monitoring over long distances along pipelines, and pressure-sensitive FBG systems have enabled the localisation of negative-pressure waves. These methods are unaffected by electromagnetic noise and allow a large number of sensing points to be obtained using only a small number of interrogator locations.

Fibre systems cannot be simply retrofitted. Before they are installed, attention must be paid to the routing of the optical cable, the mechanical coupling, the use of protective conduits, the access risers, the position of the interrogator, the repair strategy, and the calibration. A fibre located several metres away from a pipe may experience a different soil response than one that is directly bonded to the structure. As a result, the newly built aprons at the Saudi airport present a different opportunity versus existing facilities in that the sensing conduits can be incorporated as part of the civil engineering work, thus keeping future access intact and enabling distributed measurements without having to carry out repeated excavation of the pavement. In contrast, existing airports might only have reason to install fibres along high-consequence areas, crossings, or major loops as part of their planned rehabilitation.

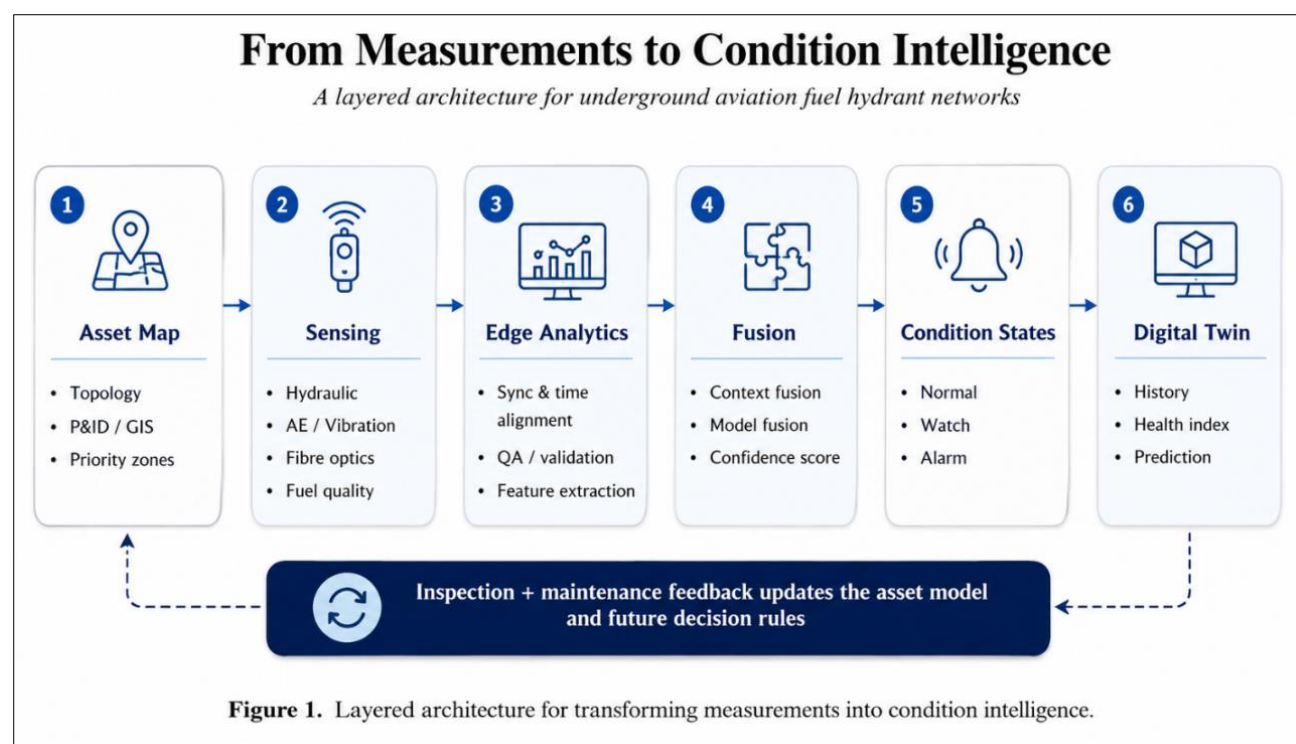
Direct hydrocarbon sensing overcomes a drawback of indirect methods since, unlike them, it detects the presence of fuel that has escaped rather than inferring hydraulic or structural effects. A case study carried out at Abu Dhabi International Airport in 2022 refers to an hydrocarbon sensing cable system that was installed for the purpose of monitoring an underground network of Jet A-1 fuel, which is buried under concrete, and this system includes alarms, location data, logging facilities, and integration with SCADA. Although this does not constitute peer-reviewed performance evidence and must not be regarded as such, it does show the practical feasibility of the approach and the advantages of using continuous sensing via accessible conduits. In the case of Saudi hydrants, hydrocarbon-sensitive cable or point sensors are particularly appropriate in areas such as pits, sleeves, drainage interfaces, and zones where fuel leakage is likely to move. Condition monitoring should also examine the factors upstream of leakage. Corrosion, the deterioration of the coating, abnormalities in the cathodic protection, wall thinning, and repeated

structural loading can lead to a progression from a latent defect to an active failure. Distributed fibre measurements together with machine learning have been used to identify and quantify pipeline corrosion, and recent reviews of structural-health monitoring stress the move from periodic inspections towards continuous or hybrid condition assessment. With regard to hydrants, the permanently monitored cathodic protection parameters, the selected corrosion probes, the pit inspections, the non-destructive examinations, and the past integrity records should all be incorporated into the same asset model as the leak sensors. The resulting question is therefore not merely 'Is this section escaping at this moment?' but 'Is this section becoming more likely to fail, and what evidence supports that conclusion?'

6. Proposed Intelligent Measurement and Condition-Monitoring Framework

The framework suggested has six functional layers. The first of these is the physical asset model, which represents in the form of a geospatial network pipe segments, diameters, materials, joints, valves, pits, branches, elevations, isolation boundaries and consequence zones. The second layer concerns measurement: pressure, flow, valve status, pump state, acoustic or vibration channels, distributed fibre channels, direct hydrocarbon sensors and corrosion indicators together with environmental measurements are all time-synchronized according to a common operational clock. Heterogeneous coverage is intentionally incorporated by the architecture since it is not necessary for every segment to have every type of sensor; rather, risk and observability decide where the density of instrumentation is increased.

Layer three involves edge conditioning; before raw signals are used for diagnosis, they are checked for dropout, saturation, drift, timing errors, and an implausible rate of change. When it comes to hydraulic streams, they are filtered in such a way that fast transients are retained. Acoustic channels are windowed and then transformed into statistical, spectral, or time-frequency features by means of methods that have been endorsed by recent AE research. Fibre streams are given spatial indexing so that ongoing anomalies can be compared with the same physical section over time, and local processing also decreases the communications load allowing the first-line alarms to withstand temporary failure of the central analytics platform.



Layer four involves multi-physics fusion. Rather than having one algorithm decide whether there is a leak, the system produces evidence statements such as hydraulic imbalance, localised pressure transient, acoustic anomaly, distributed-vibration anomaly, thermal anomaly, direct hydrocarbon presence, corrosion deterioration, or unusual pit condition. Each of these statements is given a confidence score which takes into account the quality of the signal, the condition of the sensor, spatio-temporal reliability and how well the statement corresponds to the current operating state. Fusion can be carried out using probabilistic methods, Bayesian methods, Dempster-Shafer methods, or ensemble learning. The literature backs up the idea that multiple independent measurements are better than a single sensor at improving the accuracy of localization and reducing uncertainty. In the case of an airport, the most important fusion rule is practical in that if physically different sensors strongly agree, the event should be escalated more quickly than if the same sensor is triggering repeated alarms from closely correlated duplicates.

Layer five transforms the combined evidence into condition states; a normal state calls for no action, an advisory state notes a weak but persistent deviation for the purpose of engineering review, a state may lead to a targeted inspection or to pressure testing when a suitable operational window is available, and an alarm state indicates high-confidence evidence of an active release or rapid deterioration and triggers the airport's standard emergency and isolation

procedures. However, these labels are merely framework concepts and should not be taken as replacements for operator procedures or regulatory thresholds, since their purpose is to avoid the analytics system from treating all uncertainty as if it were a simple red-or-green indication.

Layer six involves the digital representation of the condition. Research into digital twins has shown that physical sensing, probabilistic modelling, simulation, damage detection, localization, quantification, and prediction can all be combined into a single environment that is continuously updated. For a hydrant network, the digital representation should not start off as a high-fidelity three-dimensional visualization; its initial purpose is to enable asset traceability, which means that each section has attached to it the design data, the inspection history, the sensor history, the records of repairs, the possible failure modes, and a current health score. Hydraulic simulation can then be linked to actual measurements; the predicted and measured responses can be compared; uncertainty can be propagated; and maintenance priorities might be established. Visualization is of only limited use when it supports these decisions.

The framework also requires governance. Model versions, training data, alarm overrides, sensor calibrations, and maintenance actions should be auditable. Cybersecurity boundaries must separate integrity analytics from systems that can command pumps or valves unless a dedicated safety assessment authorizes tighter integration. Human

factors are equally important. Operators need concise explanations such as “pressure discrepancy plus localized hydrocarbon sensor confirmation at Zone H-14” rather than a black-box probability without context. Engineering teams need access to trends and raw data for post-event analysis. This division among operational clarity as well as engineering depth is essential for trustworthy automation.

7. Comparative Technology Synthesis and Deployment Logic

When deciding where to place the sensors, both hydraulic observability and the possible consequences must be considered. In the case of a simple arrangement, synchronized pressure and flow data should be obtained from the discharges of the fuel farm, from the main loop sectors, from the critical junctions, from the remote extremities, and from some of the pits. Acoustic or vibration sensors should then be placed at valves, at pit manifolds, at weld clusters, or at other accessible sites where local structural energy is likely to couple effectively. There should be direct hydrocarbon sensing in any areas where leaked fuel is likely to accumulate or flow and where the environmental consequences are severe. Fibre-optic lines are preferred in instances where the

civil engineering works have already exposed the corridor or when a new apron is being constructed. Corrosion and cathodic-protection data should be recorded for each section so that a leak alarm can be understood in the context of the known degradation.

The commissioning campaign is just as significant as the hardware itself, and the system has to be able to record typical normal states such as no-flow standby, single-aircraft refuelling, simultaneous refueling, pump changes, valve switching, pressure tests, maintenance operations, and exposure to extreme environmental conditions. In order to check the timing and sensor response controlled non-release tests can be carried out; where regulations and safety procedures permit, safe surrogate experiments or dedicated test loops can generate fault-like signatures without it being necessary to introduce fuel into the environment. Machine-learning models should be trained and validated using data that are specific to the airport, and their performance should be reported separately with regard to detection, localization, false alarms, missed events, and confidence calibration; a single accuracy figure is not sufficient for a monitoring system which has safety implications.

Table 1: Comparative synthesis of measurement modalities for airport hydrant condition intelligence

Modality	Primary evidence / coverage	Airport strengths	Principal limits and recommended role
Pressure & flow	Hydraulic state; point/zone coverage	Interpretable, familiar, useful for transients and balance	Small leaks may be masked by demand and meter uncertainty; use as network backbone
Acoustic / vibration	Elastic waves and pipe-wall vibration; local to regional	Fast response; suitable at pits, valves and accessible manifolds	Sensitive to coupling and apron noise; use as corroborating local evidence
Distributed acoustic sensing (DAS)	Continuous vibration along optical fibre	Long spatial coverage; useful for buried corridors	Performance depends on fibre placement and soil/concrete coupling; best when designed into civil works
Distributed / active temperature sensing	Thermal response of pipe surroundings	Can identify persistent buried leakage and spatial trends	Thermal confounders and installation geometry matter; combine with hydraulic context
FBG pressure / strain / temperature	High-sensitivity discrete optical measurements	EMI immunity, multiplexing, targeted precision	Requires interrogator and robust packaging; deploy at high-value nodes or integrated cable routes
Hydrocarbon cable / point sensors	Direct contact with escaped hydrocarbon	High semantic confidence; practical at pits and migration pathways	Response requires fuel to reach sensor; not sufficient alone for early network-wide diagnosis
Corrosion / cathodic protection	Degradation precursor and protection performance	Supports risk-based inspection and failure prevention	Not an immediate leak alarm; integrate with segment health history

8. Saudi Vision 2030 and Airport Implementation Roadmap

The Saudi Aviation Strategy is now organising the monitoring of its infrastructure in such a way that it becomes necessary to do so as the

infrastructure expands. By 2030 the strategy intends to have a greatly expanded passenger and cargo system serving 29 airports. As the airports are growing, the hydrant networks become longer, more interconnected, and harder to inspect because the

ground has to be dug up. Intelligent monitoring can help in separating the need for network growth from the requirement to carry out inspections by focusing maintenance on locations based on evidence, by detecting anomalies earlier, and by keeping a digital record of the condition of the assets throughout their lifetime. There is therefore a link to Vision 2030 in that a reliable fuel infrastructure enables airport capacity, while data-driven integrity management contributes to the wider modernisation of transport and logistics.

Environmental performance provides another link. The GACA has described the environmental sustainability of civil aviation as involving reductions in emissions and pollution, the conservation of resources, and an improvement in environmental management, specifically in relation to Vision 2030. Even though preventing the release of Jet A-1 by itself does not result in the decarbonisation of aviation, it does prevent contamination of the soil and groundwater, loss of the fuel, the necessity of carrying out clean-up operations, and disruption. Monitoring also increases accountability by creating a time-stamped record of the condition of the system and of the responses it has made. In the case of fuel assets of high consequence, environmental stewardship is closely connected with technical integrity.

The implementation should be carried out in stages, not by making one single purchase of technology covering the entire airport. In the first stage the digital asset register should be established, the drawings and the boundaries for isolation checked, the existing instrumentation reviewed and baseline integrity indicators defined in accordance with EI 1560 maintenance practice. In the second stage, multi-physics sensing should be tested on one typical loop, the loop including accessible pits, buried pavement sections and various levels of refuelling demand. In the third stage the validated sensor packages and the analytics should be extended to the priority areas using standard interfaces and common data models. In the fourth stage predictive health scoring and digital-twin functions should be introduced once there is sufficient historical condition data. Table 2 provides an overview of this roadmap and links each stage to measurable operational outcomes.

Proper localization in Saudi Arabia should involve people, and when it comes to procurement raw-data access must be insisted upon together with documented interfaces, calibration procedures, cybersecurity measures and support throughout the entire lifecycle. This will help to prevent vendor lock-in and will also contribute to the development of local expertise as the airport infrastructure expands.

Table 2: Phased implementation roadmap for Saudi airport hydrant monitoring

Phase	Technical scope	Success measures	Strategic contribution
1. Baseline and asset intelligence	Verify network topology, isolation boundaries, drawings, EI 1560 maintenance data, pressure/flow instrumentation and integrity history	Complete digital asset register; synchronized data; known sensor quality	Creates auditable safety and reliability foundation
2. Representative multi-physics pilot	Instrument one loop with hydraulic, acoustic, selected fibre or hydrocarbon sensing; capture normal operating states	Detection and localization performance; false-alarm workload; maintainability; operator usability	Builds Saudi-specific evidence before scale-up
3. Risk-based scale	Standardize validated sensor packages, interfaces, SCADA/analytics integration and high-consequence zone coverage	Coverage of priority zones; response time; reduced unnecessary excavation; stable alarm confidence	Supports growing airport capacity and operational resilience
4. Predictive condition management	Fuse corrosion, inspection, maintenance and live measurements into health scoring and digital-twin functions	Earlier maintenance decisions; traceable degradation trends; calibrated uncertainty	Advances digital capability, local expertise and environmental stewardship under Vision 2030

An being able to detect only final failure. In the case of airports, the studies must combine data on cathodic protection performance, inspection observations, the records of repairs, hydraulic stress cycles, and the continuous sensor readings into segment-level degradation models. Although remaining-life estimates should be used with caution, ordinal health states can still be of use for risk-based

inspections provided that the uncertainty is made clear.

It is important to carry out research into interoperability and lifecycle economics since a sensor which is technically good may still fail to work properly in actual operation if replacement parts, interrogators, software licences, or specialist skills

are not available over the entire lifetime of the asset. Comparative trials should therefore consider the total installed cost, maintainability, calibration frequency, the data infrastructure, the workload resulting from false alarms, the amount of excavation avoided, and also detection correctness. The Saudi airports could speed up their learning by introducing a common validation procedure for pilots and by having their operators share their non-sensitive performance data. Individual technology trials could then become part of a national body of evidence on intelligent fuel-infrastructure management.

10. CONCLUSIONS

The technique which should be employed for monitoring underground aviation fuel hydrant networks has to take account of the particular conditions in which they operate, since the networks are situated beneath safety-critical airside infrastructure, are subject to varying aircraft demand and hydraulic transients, and must provide for both containment and fuel quality. Research carried out from 2020 to 2025 has resulted in considerable advances in the areas of pressure and flow analysis, acoustic-emission processing, distributed fibre-optic sensing, sensor fusion, machine learning, corrosion assessment and digital twins. The literature also indicates that it is unreasonable to expect any one technique to be able to reliably carry out detection, localisation, severity estimation and degradation forecasting under all operating conditions.

The review thus presents condition intelligence as a layered, multi-physics system in which hydraulic measurements set out the operational context, while acoustic, fibre-optic, hydrocarbon-sensitive, and corrosion measurements offer independent evidence; edge processing is employed to guarantee the quality of the signal; fusion enables the different observations to be turned into states that are assessed in terms of confidence; and a digital condition model connects the current signals with the asset's history and maintenance record. The architecture is deliberately designed to be modular so that the high-value areas of existing Saudi airports can be retrofitted and new airport developments can include sensing access as part of the civil engineering work.

This method likewise aligns clearly with the strategic aims. As noted in EI 1560, safe and reliable operation and maintenance of hydrants are emphasized, and the Saudi Aviation Strategy and Vision 2030 call for large-scale growth, improved safety, high operating efficiency, environmental accountability and digital capability. Intelligent hydrant monitoring contributes to achieving these aims by reducing the time between an anomaly occurring and the response being made, by focusing

inspections on areas where evidence is present, by avoiding unnecessary excavation, by keeping the product intact, and by creating auditable knowledge about the assets. In the short term, the most worthwhile action is not to purchase the most advanced algorithm available on the market; rather, it is to set up a common asset model, to establish synchronized baseline measurements, and to design a carefully planned pilot study in which various sensing methods can be tested under real operating conditions at Saudi airports. The evidence gathered from this pilot study can then be used to determine the appropriate balance among coverage, sensitivity, maintainability and cost when carrying out a nationwide deployment.

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