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Fuel Leak Detection in Aircraft Fuel Systems: A Review of Sensing Methods and the Gap Between Available Technology and Operational Practice

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Abstract

Fuel leakage remains one of the more demanding failure conditions in transport aircraft operation. A leak reduces the usable fuel available for the remainder of the flight, creates an ignition hazard around hot engine surfaces, and can be mistaken for an indication fault or a routine imbalance during the period in which it is developing. A considerable body of sensing research has grown around this problem. Optical fibres coated with hydrocarbon-sensitive materials, vapour detectors of several chemistries, acoustic monitoring of pressurised lines, residual generation from a system model, and classifiers trained on recorded flight parameters have all been proposed and demonstrated at various levels of maturity. This paper reviews those approaches and organises them into three families according to what each one actually measures. It then places them alongside the way leaks are recognised in service, which published investigation reports show to be largely dependent on crew interpretation of fuel quantity behaviour, periodic consumption checks, and occasional visual confirmation. The comparison exposes a discontinuity: laboratory response times are reported in seconds, whereas recognition in documented occurrences has taken tens of minutes and in several cases involved an initial misinterpretation of the indications. The review argues that the limiting factor is no longer sensitivity but the ability to survive the fuel tank environment, to keep nuisance alarms low enough that crews trust the annunciation, and to satisfy certification expectations for equipment installed in a flammable zone. Directions that follow from this reading are set out at the end.

Keywords: aircraft fuel system; leak detection; optical fibre sensing; fault detection and isolation; flight safety; condition monitoring

Abbreviations

AAIB	Air Accidents Investigation Branch	**FDI**	Fault detection and identification
ASRS	Aviation Safety Reporting System	**NASA**	National Aeronautics and Space Administration
BEA	Bureau d'Enquetes et d'Analyses	**NTSB**	National Transportation Safety Board
FAA	Federal Aviation Administration	**OTDR**	Optical time domain reflectometry
		SNR	Signal-to-noise ratio

Introduction

The fuel system of a transport aircraft is distributed across the wings, the centre section, and the pylons, and it operates over a wide range of temperature, pressure, and structural loading. Fuel is stored in integral tanks formed by the wing structure itself, transferred between tanks by pumps and valves, and delivered to each engine through feed lines that cross the pylon interface. Every joint, coupling, seal, and access panel in this arrangement is a potential leakage path, and the number of such features on a large aircraft is substantial.

A leak is consequential for three separate reasons. The first is range. Fuel lost overboard is fuel that will not be available at the destination, and if the loss is not recognised the aircraft may continue towards an airport it can no longer reach; the Air Transat event over the Atlantic remains the reference case for this outcome [14]. The second is fire. Fuel released near an engine nacelle or in a pylon bay encounters surfaces that operate well above the autoignition temperature of kerosene [16]. The third is diagnostic ambiguity. A slow leak first presents itself as a discrepancy between what the fuel quantity system reports and what the flight plan predicted, and that same discrepancy can equally be produced by a quantity indication fault, an unbalanced transfer, or an error in the planned burn. Resolving which of these is occurring takes time, and fuel continues to be lost while it is being resolved [15].

The significance of the fuel system within the wider reliability picture is supported by

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statistical analysis of accident and incident records. A National Aeronautics and Space Administration (NASA) study of system and component failures found that a substantial proportion of the accidents examined involved the engine or fuel system, and that a comparable proportion held across a much larger set of incident records [5]. Research into automatic detection has responded from several directions at once. Some groups have pursued sensors that respond directly to the presence of fuel outside its intended containment [1, 3]. Others have treated the problem as one of estimation, comparing measured fuel state against what a model of the system predicts and declaring a fault when the difference persists [6]. More recently, work has drawn on recorded and simulated operational data and applied statistical learning to the same discrepancy [24]. These lines of enquiry are rarely discussed together, and their relative standing is therefore difficult to judge.

This paper has three aims. It brings the principal detection approaches into a single classification and describes what each one measures and where its limits lie. It then summarises what published investigation material shows about the way leaks are actually recognised during flight. Finally it compares the two, and argues that the obstacles now standing between laboratory demonstration and installed capability are environmental durability, alarm credibility, and certification, rather than sensitivity to fuel itself. The scope is confined to fixed-wing transport aircraft; ground refuelling infrastructure and storage tank monitoring are mentioned only where the underlying sensing principle carries across.

2. Scope and Method of Review

The material reviewed here was assembled from two distinct bodies of literature, since the question addressed spans both engineering research and operational evidence.

For the sensing and diagnostics literature, searches were conducted in Scopus, IEEE Xplore, Science Direct, Springer Link, the NASA Technical Reports Server, and Google Scholar. The search strings combined a leakage term with an application term and a sensing term, in the form of fuel leak or leak detection, combined with aircraft, aviation, aerospace or fuel tank, combined with sensor, optical fibre, fault detection or machine learning. Patent literature was searched separately in Google Patents and Espacenet under the classifications covering aircraft fuel systems and leak testing, because a considerable part of the applied work in this field appears as patents instead of journal articles. The period considered was 1990 to 2026, with earlier items admitted where they establish a sensing principle still in use.

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For the operational evidence, published investigation reports and safety reporting material were drawn from the National Transportation Safety Board (NTSB) investigation database [19], the NASA Aviation Safety Reporting System (ASRS) [18], the Air Accidents Investigation Branch (AAIB) of the United Kingdom [17], the French Bureau d'Enquetes et d'Analyses (BEA) [13], the Federal Aviation Administration (FAA) lessons learned collection [14], and manufacturer safety publications [16]. Items were retained where the occurrence involved a fuel leak during flight and where the report described how the condition was first noticed.

Records were included if they addressed detection of fuel leakage in an aircraft or in a directly comparable fuel containment system, and if they reported either a sensing principle with supporting results or an occurrence with a described detection sequence. Records were excluded if they addressed fuel quantity measurement without reference to leakage, if they concerned automotive evaporative emission control alone, or if they were secondary summaries of work already included. Two limitations of this approach should be stated at the outset. Voluntary reporting material cannot be used to infer how frequently a condition occurs, since submission is not a random sample of events [18], and it is used here only to characterise how detection happened rather than how often. In addition, manufacturer and operator monitoring data are proprietary and were not available, so the operational picture is drawn from published investigations alone.

3. The Fuel System and Where Leaks Originate

Figure 1 shows the arrangement in schematic form, with the locations that recur most often in leakage events marked. Wing tanks are formed by sealing the structural box, so the containment boundary is the airframe itself and its sealant. Feed lines run inboard from each tank towards the engines, crossing the pylon interface where relative motion, thermal cycling, and maintenance disturbance all act on the joints. Investigation of one event traced the leak to a flange in the main fuel line between the pylon and the engine, on an aircraft that had undergone engine removal during maintenance some months earlier [13], and a separate case was attributed to incorrect installation of a seal in the coupling between a fuel tube and a high-pressure fuel pump [12]. A cross feed line connects the two sides so that either engine can be supplied from either tank, and its valve is normally closed.

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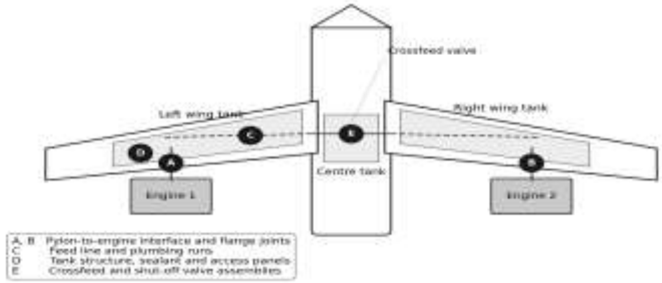

Figure 1. Schematic arrangement of a typical transport aircraft fuel system, showing the locations most frequently associated with leakage events.

Five regions are marked in the figure. Positions A and B lie at the pylon-to-engine interface, where the feed line crosses from a fixed structure to one that moves relative to it and where couplings are broken and remade during engine maintenance. Position C denotes the feed line and plumbing runs that carry fuel inboard from the tanks. Position D covers the tank structure itself, including the sealant along the wing box joints and the access panels cut into the lower skin. Position E is the crossfeed and shut-off valve assembly on the centreline. These five account for the majority of leakage paths, and they differ in an important way for detection: A, B and E sit in compartments where hydrocarbon should ordinarily be absent, whereas C and D lie within or alongside the fuel-wetted volume.

Two features of this layout matter for detection. The first is that the cross feed valve, opened in response to an imbalance, will draw from the intact side and feed it towards the leaking side if the imbalance was caused by a leak rather than by unequal consumption. Operating procedures therefore warn against opening the cross feed while a leak is suspected, but the warning only helps if the leak has already been suspected, and in at least one documented case the warning appeared in the flight manual but not on the display the crew was actually using [15]. The second is that most of the leakage-prone geometry is outside the crew's field of view. Confirmation by eye is possible for some pylon and nacelle leaks and impossible for others; in one event a visual inspection of the wings and engines requested from the cabin did not reveal the leak [14]. This places the burden of recognition on instrumentation and on inference from fuel quantity behaviour.

Leak rates span a wide range. At the upper end, one investigation calculated a consumption difference between the two fuel systems of approximately sixty kilograms per minute [12], and another recorded a loss of

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several tonnes over a flight of a little more than two hours [13]. Such rates produce an imbalance rapidly and are correspondingly easier to notice. At the lower end, a weeping joint may release a quantity that is small relative to the resolution and drift of the fuel quantity system, and such a leak may not be distinguishable from measurement noise until it has been running for a long time or has worsened. It is the lower end of this range that automatic detection is intended to address, and it is also the end at which false alarms become most likely.

4. Detection Approaches

The methods proposed in the literature can be grouped by what they observe. Direct sensing responds to fuel that has escaped. Model-based inference responds to a discrepancy between measured and expected fuel state. Data-driven methods respond to patterns in recorded parameters that have previously accompanied leakage. Figure 2 sets out the classification used in the remainder of this section.

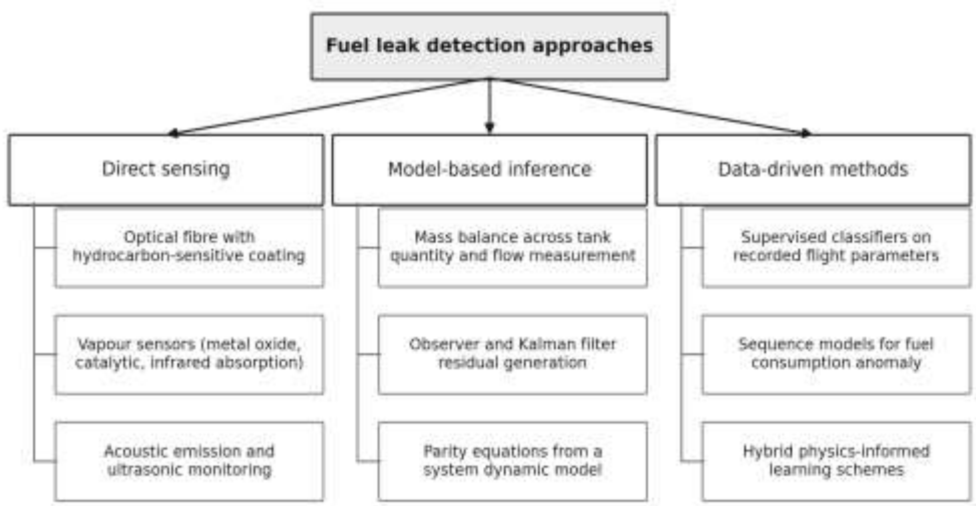

Figure 2. Classification of fuel leak detection approaches by the quantity each family observes.

The three columns of the figure correspond to the three subsections that follow. The left column groups methods that place a sensing element where escaped fuel would reach it. The centre column groups methods that infer a leak from measurements taken elsewhere in the system. The right column groups methods that learn the signature of a leak from recorded or simulated behaviour. The order reflects decreasing directness of observation and, broadly, decreasing maturity for installed use.

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4.1 Optical fibre sensing

Optical fibre has attracted sustained attention for this application, and the reason is largely environmental, not metrological. A fibre carries no current, dissipates negligible power, and therefore does not introduce an ignition source into a flammable zone, which is a decisive advantage over electrically interrogated sensors placed inside a tank [4]. A single fibre can also be routed over a long path and interrogated from a single unit mounted outside the tank, so the sensing element covers a distributed region instead of a single point [1, 2].

Two transduction mechanisms dominate. In the first, the fibre is coated with a polymer that swells when it contacts hydrocarbon. The swelling imposes a microbend on the fibre, the microbend attenuates the guided light locally, and the position of the attenuation is recovered from the return time of the reflected signal using optical time domain reflectometry (OTDR). A distributed sensor built on this principle has been reported to locate events to a precision of about two metres over a sensing length of ten kilometres, with a response occurring within roughly thirty seconds of exposure to the fuel, and has been demonstrated detecting several separate short events simultaneously along one fibre [3]. The underlying transduction mechanism appears in the patent literature in both microbending and evanescent-wave forms [20]. In the second mechanism, the coating is fluorescent and its emission changes on contact with fuel; a system built on this principle operates in separate detection and localisation modes, raises an alarm within seconds of contact, and has been proposed for pipelines, tanks, pumps and valves as well as for airport applications [1]. A related arrangement has been used in ground storage, where a fibre coated with a compound that attracts and retains hydrocarbon interrogates the space beneath a tank floor, with the perforation subsequently localised by applying vacuum to individual bores in turn [21]. Figure 3 illustrates the arrangement common to these designs.

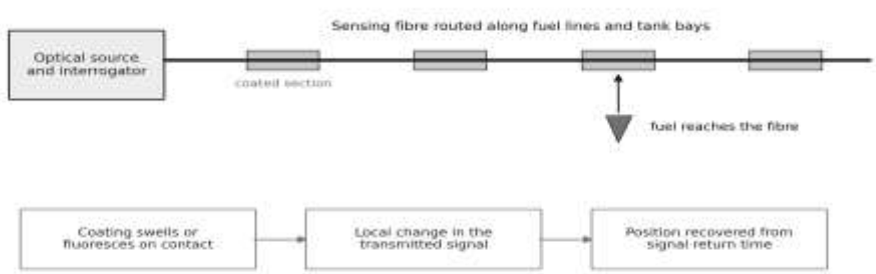

Figure 3. Operating principle of a distributed optical fibre leak sensor with a hydrocarbon-sensitive coating.

The lower row of the figure traces the sequence that follows an escape of fuel. Contact with the coated section alters the coating, either by swelling it or by changing its emission. That alteration produces a local change in the light travelling through the fibre, which the interrogator observes as a departure from the baseline return. Because the interrogator measures the time taken for the disturbed signal to return, the position of the affected section along the fibre is recovered from the same measurement that detected it. Detection and localisation are therefore obtained together, which is the principal advantage of the distributed arrangement over a set of point sensors.

Optical methods have also been applied to related measurements inside the tank. A fibre-coupled sensor system has been developed to determine oxygen, nitrogen and hydrocarbon vapour concentrations in the ullage of a fuel tank, returning readings in about five seconds with up to eight sensor heads served by a single detection unit, and using a low-power solid-state source so that the sensing head introduces no intrinsic ignition hazard [4]. That work was driven principally by tank inerting, not by leak detection, and followed from concern about tank flammability. Its relevance here is that it establishes the practicality of routing optical sensing hardware into a fuel tank and returning quantitative measurements from it, which is a prerequisite for any distributed leak sensing installation. Manufacturer interest in the same direction is visible in patent activity covering the testing and health monitoring of optical sensors installed inside aircraft fuel tanks during production [22].

The limitations are practical, not fundamental. The coating is a consumable in the sense that its response depends on remaining chemically intact over years of exposure to fuel vapour, water and thermal cycling. Reversibility after an exposure event is not guaranteed by every chemistry; one early design depended on the degradation of shear pins by hydrocarbon contact and was therefore inherently single-use [20]. Routing a continuous fibre through a wing box adds installation complexity and creates a new item requiring inspection. Reported detection performance is also established under controlled exposure conditions [3] rather than under the vibration and temperature excursions of flight.

4.2 Vapour and chemical sensing

Point sensors that respond to hydrocarbon vapour offer an alternative that does not require a distributed element. Metal oxide semiconductor devices change conductivity in the presence of hydrocarbons, catalytic elements respond to oxidation at a heated surface, and infrared absorption instruments identify hydrocarbon species by their absorption bands. The same class of sensing has been applied outside aviation, including

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in automotive fuel systems where hydrocarbon concentration measured in the line between tank and vapour canister is used both to confirm depressurisation and to gate the initiation of a leak detection routine [23].

Applying vapour sensing inside an aircraft tank bay raises two difficulties. Devices that require a heated element are not readily accepted in a flammable zone, which removes several of the more sensitive chemistries from consideration unless they are optically interrogated [4]. In addition, hydrocarbon vapour is present in the ullage under normal conditions, so a vapour sensor must distinguish a leak-induced concentration change from the normal variation produced by altitude, temperature and fuel state. This pushes the design towards dry bays and pylon compartments, where background hydrocarbon should be absent and a positive reading is therefore meaningful, and away from the tank interior.

4.3 Acoustic and ultrasonic monitoring

Fluid escaping through a small aperture under pressure generates broadband acoustic emission, and the technique of listening for that emission is well established for pressurised pipework in other industries. Applied to an aircraft, the attraction is that the sensor is external to the fluid path and requires no chemical element, so neither coating durability nor background vapour is a concern. The difficulty is the acoustic environment. Engine noise, airflow over the structure, pump operation and structural vibration all contribute energy in the same bands as the leak signature, and the signal-to-noise ratio (SNR) available in flight is far removed from that of a quiet test cell. No in-flight demonstration of the technique for fuel leak detection was identified in the material reviewed here. The approach is consequently more promising for ground testing and post-flight inspection, where the aircraft is quiet and a pressurised system can be monitored deliberately, than for continuous monitoring during flight.

4.4 Model-based inference

A different strategy accepts the sensors already installed and extracts more from them. Fuel quantity is measured in each tank and fuel flow is measured to each engine, so the quantity remaining can be predicted from the quantity initially present less the integrated flow. A leak breaks this relationship, and the difference between measured and predicted quantity, known as the residual, grows with time. Estimation techniques generate this residual in a form that accounts for sensor noise and for the effects of attitude and acceleration on quantity measurement, and a fault is declared when the residual exceeds a threshold and stays there. Figure 4 shows the structure.

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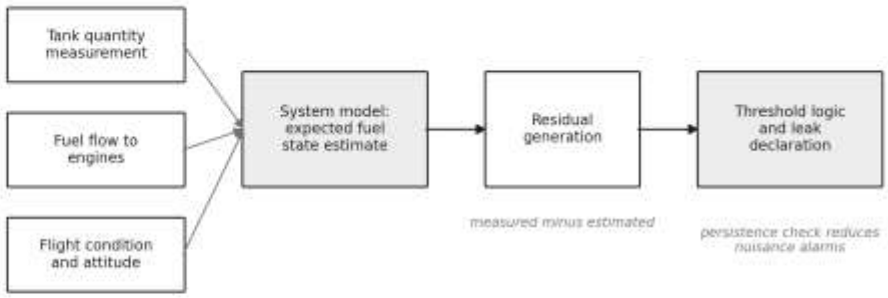

Figure 4. Residual generation and threshold logic in a model-based leak detection scheme.

The three inputs on the left of the figure are measurements already available on the aircraft. Tank quantity and fuel flow supply the mass balance itself, while flight condition and attitude are needed because tank quantity measurement varies with the orientation of the fuel surface. The system model combines these into an estimate of the fuel state that would be expected in the absence of a fault. Residual generation forms the difference between that estimate and the measured state, and the threshold stage converts the residual into a declaration. A persistence check is applied at this last stage so that a brief excursion, such as one produced by a manoeuvre, does not by itself raise an alarm.

Work on an experimental aircraft fuel rig has demonstrated this approach directly. Linear models of the system were used to construct a Kalman filter arrangement for fault detection and identification (FDI), with filter gains tuned and residual thresholds chosen to define the fault condition boundary, and logic added to identify the location of the fault. Performance was improved further by evaluating the residual statistically and by calculating the threshold automatically rather than fixing it in advance. The reported results captured both abrupt faults such as sensor malfunction and actuator failure, which produce large residual deviations, and gradual ones including performance degradation and fluid leaks in the tanks and pipes. Faults of smaller magnitude were captured reliably but over a longer time interval [6].

Related work on fuel system components uses the same principle in a different arrangement. A fuel regulator model predicts flow from the engine controller command while an inverse engine model estimates the flow actually passing through the regulator, and the deviation between the two forms the diagnostic signal [11]. In engine health

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monitoring more broadly, banks of Kalman filters have been applied to sensor and actuator fault diagnostics [7], hybrid formulations combining a nonlinear onboard engine model with piecewise linear state-space models have been developed to maintain estimation accuracy as flight condition and engine health change [8], and integrated schemes have addressed performance estimation and diagnostics together [9]. Comparable multiple-model filter arrangements have been applied to fault diagnosis in other fluid systems [25]. Neural network banks have been proposed as an alternative residual evaluation stage within the same overall architecture [10].

The appeal of this family is that it requires no new hardware in the tank and therefore avoids the certification burden associated with installing equipment in a flammable zone. Its weakness is resolution. The smallest detectable leak is set by the accuracy and drift of the existing quantity and flow instrumentation, and lowering the threshold to catch smaller leaks raises the nuisance alarm rate. The trade-off between the two is the central design problem, and the delayed detection of smaller faults reported in rig work is a direct expression of it [6].

4.5 Data-driven methods

Recorded flight data provides an alternative route to the same discrepancy. Classifiers trained on parameters such as tank quantities, flow rates and imbalance history can learn to separate normal fuel behaviour from behaviour associated with leakage, and sequence models can be applied to the time development of consumption instead of to instantaneous values. Work on leak detection in other thermal plant illustrates both the approach and its principal obstacle. Faced with a shortage of labelled examples, one study generated synthetic data from a high-fidelity dynamic simulation covering normal operation and progressive leak faults under transient conditions, then applied a few-shot learning scheme that stabilised class representations and reported improved accuracy and stability relative to conventional few-shot methods [24].

The scarcity of labelled data is the defining constraint for this family in the aircraft case. Fuel leaks are rare, and the recorded parameter sets available from routine operations contain very few positive examples relative to the volume of normal flight. This makes conventional supervised training difficult and pushes practitioners towards simulation-generated data, transfer from related systems, or anomaly detection formulations that model normality and flag departures from it [24]. A further consideration is that a purely learned model is difficult to argue through certification, because its behaviour outside the training distribution cannot be bounded by inspection. Hybrid formulations that retain a physical

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model and use learning only to sharpen the residual evaluation, in the manner of the neural network residual evaluators proposed for engine diagnostics [10], are more tractable in this respect.

5. Comparative Assessment

Table 1 summarises the families against criteria that matter for an installed system rather than for a laboratory demonstration.

Table 1. Comparison of fuel leak detection approaches.

Approach	What is observed	Localisation	Main strength	Main limitation	Maturity for flight	Ref.
Coated optical fibre	Fuel contacting the sensing element	Yes, along the fibre	No electrical energy in the tank; distributed coverage	Coating durability and reversibility; installation complexity	Demonstrated, not routinely installed	[1, 3, 20]
Vapour and chemical sensors	Hydrocarbon concentration in a compartment	By compartment	Simple to interpret in dry bays	Background vapour; heated elements unsuitable in flammable zones	Selective use	[4, 23]
Acoustic and ultrasonic	Emission from flow through an aperture	By sensor position	No contact with the fluid path	Masked by engine, airflow and structural noise in flight	Ground use	See 4.3
Model-based residual	Difference between measured and predicted fuel state	By tank or feed path	Uses existing instrumentation; no tank hardware	Resolution limited by sensor accuracy and drift	Demonstrated on rigs	[6, 11]
Data-driven	Patterns in recorded flight parameters	Limited	Captures behaviour not represented in a simple model	Few labelled leak events; difficult to certify	Research stage	[10, 24]

Read across the table, the families are complementary and not competing. Direct sensing responds to the physical event and can localise it, but requires hardware in the least convenient location on the aircraft [3]. Model-based inference requires nothing new but cannot resolve leaks smaller than the noise floor of the existing instrumentation [6]. Data-driven methods can capture behaviour that a simplified model omits but lack the evidence base needed to train or to argue them [24]. A practical architecture would use the model-based residual as the always-available layer and add direct sensing in the specific bays where consequences are highest and background hydrocarbon is absent.

6. The Gap Between Reported Capability and Operational Practice

Detection performance in the sensing literature is quoted in seconds [1, 3]. Recognition in service is measured in a different unit. Published investigation material describes leaks identified when a crew compared actual consumption against plan during a routine periodic check, when a fuel imbalance advisory annunciated, when a message indicating disagreement between fuel used and fuel on board appeared [16], or when the condition was reported from outside the aircraft. In one investigated event the difference in consumption between the two fuel systems was of the order of sixty kilograms per minute, and the leak was nevertheless identified around two hours after departure, during what the report describes as a routine hourly fuel check [12]. In another, several tonnes were lost during a flight of a little over two hours [13]. In a further case, a crew asked cabin crew to inspect the wings and engines visually and the inspection did not reveal the leak [14].

Recognition is also not the same as detection. Investigation material records instances in which the indications were seen but interpreted as something else. In one documented case the crew worked from an initial assumption about the source of the low fuel indication and did not establish the true nature of the problem until late in the flight, with the correct action following from the intervention of a third pilot present on the flight deck [15]. In another event the aircraft continued with both engines running for an extended period while the imbalance grew, and the leak was confirmed visually only by a maintenance technician who happened to be on board [16]. A recent report on a diversion following a leak identified delay in crew diagnosis as a contributing factor [17]. The current operational method is described in industry material as a combination of crew checks and automated alerting, and the sequence that results is shown in Figure 5

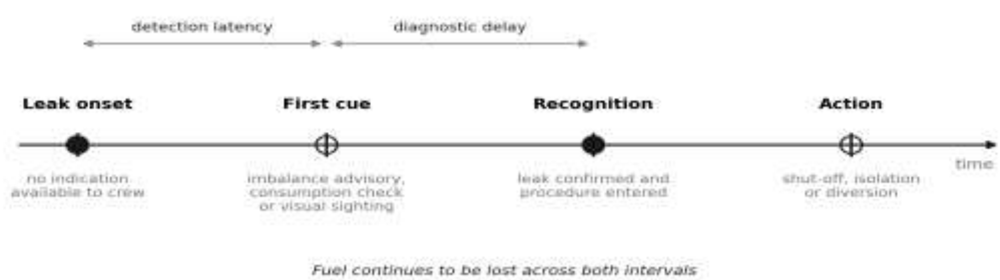

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Figure 5. Sequence from leak onset to crew action, showing the two intervals during which fuel continues to be lost.

Two intervals appear in this sequence. The first runs from the onset of the leak to the first cue that something is wrong. The second runs from that cue to correct recognition and entry into the appropriate procedure. Sensing research has concentrated almost entirely on shortening the first interval [1, 3, 6]. The second is a diagnostic problem, not a sensing one, and the evidence from investigation material suggests it is not small [15, 17]. A detection system that annunciates a leak unambiguously would compress both intervals, whereas one that merely provides an additional indication requiring interpretation would compress only the first.

This has a consequence for how detection performance should be specified. Sensitivity expressed as a minimum detectable leak rate is necessary but not sufficient. What determines operational value is whether the output is trusted and acted upon without an extended period of cross-checking, and that depends on false alarm behaviour. An annunciation that has previously proved spurious will be treated as suspect, and the diagnostic interval will reappear in a different form. The specification that matters therefore combines a detection threshold, a detection time, and a false alarm rate low enough to sustain confidence, with the third being the one least often reported in the sensing literature. Where thresholds are addressed explicitly in the diagnostic literature the difficulty is acknowledged directly: automatic threshold calculation and statistical residual evaluation were introduced in rig work specifically to manage this trade-off [6].

A third constraint sits behind both. Any equipment installed inside or adjacent to a fuel tank must be shown not to constitute an ignition source under normal and fault conditions, and must survive the qualification environment for temperature, vibration and altitude. This requirement explains much of the emphasis on optical methods, whose advantage is stated in exactly these terms by their developers [4], and much of the reluctance to place conventional electrical sensing inside the tank. It is a stronger determinant of what reaches service than incremental improvement in sensitivity.

7. Directions for Further Work

Four directions follow from the preceding discussion. The first is durability evidence for hydrocarbon-sensitive coatings. Published performance is established for fresh material under controlled exposure [3], and what is required for an installed system is response retention after extended exposure to fuel, water and thermal cycling, together with a defined and repeatable behaviour after an exposure event has occurred.

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The second is characterisation of false alarm behaviour under representative conditions. Detection thresholds are widely reported [1, 3]; nuisance alarm rates under vibration, temperature excursion, condensation and manoeuvre are not. Without the second the first cannot be translated into an operational specification, and the operational evidence indicates that credibility of the annunciation is what governs how quickly it is acted upon [15, 17].

The third is combination of direct and inferential methods. A residual generated from existing instrumentation provides continuous coverage of the whole system at coarse resolution [6], while a direct sensor provides fine resolution over a limited region [3]. Treating an elevated residual as a trigger for closer examination of direct sensor output, rather than treating the two independently, would allow a lower effective threshold at an acceptable alarm rate.

The fourth is a shared basis for evaluation. Detection performance is currently reported against whatever leak rates and conditions each experiment happened to use, which makes comparison across the literature unreliable. A defined set of leak rates, locations and environmental conditions, drawn from the range that appears in service [12, 13], would allow methods to be assessed against one another and against what the operational problem actually requires.

8. Conclusion

Fuel leak detection for aircraft has been approached through direct sensing, model-based inference and data-driven analysis, and each family is well developed in its own terms. Optical fibre with a hydrocarbon-sensitive coating offers distributed coverage and localisation without introducing electrical energy into a flammable zone, with reported localisation to a few metres and response within tens of seconds under controlled exposure [1, 3]. Residual generation from existing quantity and flow instrumentation offers continuous coverage without new hardware, at a resolution limited by that instrumentation and with smaller faults detected over longer intervals [6]. Data-driven analysis offers sensitivity to behaviour a simplified model omits, constrained by the scarcity of labelled leak events [24].

Set against operational practice, the position is less advanced than the individual results suggest. Leaks in service are still recognised largely through crew interpretation of fuel quantity behaviour, and published occurrences show both extended intervals before recognition [12] and instances of initial misinterpretation [15, 17]. The obstacles now are environmental durability of the sensing element, false alarm behaviour sufficient to earn crew confidence, and demonstration that equipment placed in a

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flammable zone is acceptable [4]. Progress against these three will determine whether the capability demonstrated in the laboratory becomes capability available in flight, and each of them is addressed less often in the literature than sensitivity is.

Two limitations of this review should be recognised. It draws on published sources only, and manufacturer and operator monitoring data, which would give a fuller picture of how often small leaks are detected and by what means, were not available. In addition, the operational material is descriptive and not statistical: it establishes that recognition intervals of tens of minutes and initial misdiagnosis both occur, but the sources used here do not support an estimate of how frequently they occur. A systematic analysis of occurrence records coded for detection cue and recognition interval would place the argument advanced here on a quantitative footing, and is a natural extension of this work.

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