

VACUUM INTEGRITY AND LEAK LOCALIZATION IN POLYMER COMPOSITE MANUFACTURING

by

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To my wife and children.

Thank you for your patience, encouragement and love throughout this journey. This thesis is as much a reflection of your support as it is of my work.

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Abstract

Vacuum infusion is widely used to manufacture large composite structures where the vacuum integrity of the vacuum bag assembly governs the quality of the resulting laminate. Before resin is infused, manufacturers verify integrity with a vacuum-drop test which confirms whether a leak is present but gives no information about where it is located. When the vacuum-drop test fails, the leak is found by a manual search that is slow, depends on skilled operators and scales poorly to large parts. Published localization methods address this only partially: they infer leak position from flow measured at the vacuum boundary while the pump is operating, rather than from pressure measurements across the part. This thesis investigates whether a distributed array of pressure transducers installed beneath the vacuum film can localize a leak during the vacuum-drop test. Twenty pressure transducers recorded gauge pressure at 1Hz across a $1.86\text{m} \times 1.20\text{m}$ fabric stack through fourteen experiments, spanning ten pinhole positions and two needle diameters with each leak introduced during pump-off vacuum-drop conditions. In all fourteen experiments the PT(s) recording the largest dP/dt gradient was the one nearest the pinhole. The leak region is identified from the spatial pattern of dP/dt across the array. This pattern proved robust to baseline vacuum drift and per-sensor calibration offsets. Although the peak magnitude varied between nominally identical punctures, the identified location did not. The work demonstrates, at laboratory scale, a route to localizing vacuum film leaks during a vacuum-drop test already performed in industry, using low-cost PTs and standard data acquisition hardware.

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Nomenclature

Abbreviations

- CFM Cubic feet per minute
- DAQ Data acquisition
- DLR German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)
- FRP Fiber reinforced plastics
- ID Inner diameter
- OD Outer diameter
- OEM Original equipment manufacturer
- PC Personal computer
- PE Polyethylene
- PMC Polymer Matrix Composite
- PT Pressure transducer
- RTM Resin transfer moulding
- SCADA Supervisory control and data acquisition
- SI International System of Units
- UBC University of British Columbia
- uVic University of Victoria
- VDC Voltage Direct Current

Symbols

- P Gauge pressure, kPa
- t Time, s
- x x-coordinate, cm
- y y-coordinate, cm
- X_i Pinhole location in experiment i , (x, y)
- dP/dt Pressure-time gradient, kPa/s

Chapter 1 Introduction

1.1 Background and Context

1.1.1 Vacuum Infusion

Vacuum infusion is a liquid composite moulding process used for manufacturing small to large structural polymer composite parts, most prominently in the marine, automotive and wind energy sectors. In this thesis the stack of dry fabric reinforcement plies is referred to as fabric stack, the process of placing the fabric stack on a mould is referred to as layup, the fabric stack covered by ancillaries and sealed under the vacuum film is referred to as vacuum bag assembly, and the cured composite is referred to as the laminate. In a vacuum infusion layup, a fabric stack is laid up on a single-sided rigid mould. It is then covered with a peel ply, a flow-distribution medium and a breather, and it is finally sealed beneath a flexible vacuum film bonded to the mould perimeter using sealant tape. A vacuum pump connected to the vacuum bag assembly evacuates air from beneath the vacuum film, drawing the film down onto the fabric stack and compacting it against the mould. Once the fabric stack and ancillaries are positioned and compacted under stable vacuum, liquid resin is then infused under the pressure differential between resin inlet at atmospheric pressure and evacuated cavity beneath the vacuum film, until the fabric stack is fully impregnated and saturated with resin, ready for curing into a composite laminate.

Vacuum infusion has become a widely used process for manufacturing large composite structures where autoclave processing of pre-impregnated reinforcement is impractical or cost prohibitive. Wind turbine blade manufacturing illustrates the scale: modern blades exceeding 100 metres in length are manufactured using vacuum infusion in a single shot, meaning that an entire shell half is infused in a single operation. Tooling and autoclaves suitable for such large parts would be excessively expensive, if available at all. Marine vessel construction, which historically relied on hand layup of wet reinforcement, has shifted toward vacuum infusion for hull and superstructure components above a certain size. The aerospace sector uses vacuum infusion for selected non-primary structures, and the automotive sector uses it for high-volume composite parts in performance vehicles. In these applications process integrity is critical because defects introduced during vacuum infusion can compromise structural performance, increase rework and delay production.

The economic case for vacuum infusion rests largely on the absence of an autoclave. The vacuum infusion process operates under vacuum rather than positive pressures used in autoclaves. The costs of both energy and tooling are substantially lower. The trade-off is that vacuum infusion is more sensitive than autoclave processing to the integrity of the vacuum bag assembly itself. The vacuum film, the seal between the film and the mould, and the connections between the vacuum bag assembly and vacuum pump must all hold throughout evacuation and infusion stages. Any breach in this vacuum bag assembly allows air into the fabric stack, with consequences that the next subsection details.

1.1.2 Role of the Vacuum Film

The vacuum film performs several roles in a vacuum bag assembly, of which two directly govern the quality of the resulting composite laminate. The first is compaction. The pressure differential between atmosphere above the vacuum film and evacuated cavity beneath it drives the film against the fabric stack, increasing the fibre volume fraction of the reinforcement plies and reducing the volume trapped between fibres and fabric plies. Higher fibre volume fractions translate directly into higher specific stiffness and strength of the cured composite laminate, while the suppression of trapped air reduces its porosity. The second is resin transport. The same pressure differential drives resin through the fabric stack during infusion. Both roles depend on the vacuum film maintaining a sealed boundary throughout the process.

A leak in the vacuum film breaches both roles simultaneously. Air ingress occurring through a leak prior to resin infusion reduces effective vacuum level, lowering compaction force on the fabric stack and allowing entrapped air to expand into the fabric stack. During infusion, inflowing air competes with resin flow in the vicinity of the leak, producing visible bubbles in the resin, dry regions in the fabric stack and additional voids in the cured laminate. Resulting laminate degradation was characterized in detail in the recent work of Haschenburger [1] who attributes degradation to a chain of mechanisms. Partial vacuum loss reduces compaction across the fabric stack. Trapped air can no longer be fully evacuated throughout the fabric stack and resin may not completely infuse the fabric stack. The propositions put forth by Haschenburger state the end result concisely: defective vacuum film have the greatest negative impact on component quality among known process disturbances in open-mould composite manufacturing.

1.1.3 Vacuum-Drop Tests and Industrial Practice

Industry practice requires that vacuum film leaks be detected and removed before infusion begins. It relies almost entirely on a single, non-standardized test for this purpose: the vacuum-drop test. The test is straightforward to perform using equipment already present on any vacuum infusion setup. The vacuum bag assembly is evacuated to its working vacuum level, the vacuum pump is then isolated from the assembly by closing a valve. The pressure-time rate of change, dP/dt gradient, inside the sealed assembly is measured over a fixed time. A pressure rise exceeding a defined specification limit indicates that the assembly is not sufficiently sealed for infusion to begin, and a manual search for the leak is then initiated.

Specific thresholds against which the pressure rise is compared vary considerably across the industry. The Composites Research Network at the University of British Columbia publishes a guideline [2] of no more than 2 inches of mercury pressure rise over 5 minutes, or approximately 1.35kPa/min. Published literature reports state varying vacuum-drop thresholds for composites manufacturing, and some guidance documents provide specific acceptance limits in the range of 0.5 to 1.5kPa/min for vacuum infusion [3, 4, 5]. Industrial practice in wind turbine blade manufacturing, where layup dimensions can span tens of metres, applies vacuum-drop thresholds that range from approximately 0.1kPa/min to 5kPa/min, all measured over a set time limit of the order of 5-20 minutes; specific OEM criteria are trade secrets. The methodology developed in this thesis uses an allowable pressure-rise threshold of 1kPa/min during the vacuum-drop test.

The vacuum-drop test is widely adopted because it is simple and typically only requires the vacuum pump and a pressure gauge. It confirms or refutes the integrity of the vacuum bag assembly as a whole, but it provides no information about the number, size, or position of any leaks present. When the test fails, the manufacturer is left with the task of finding the leak by some other method, and that task is the starting point for the work that this thesis addresses.

1.2 Problem Statement

When the vacuum-drop test fails, the manufacturer must find the leak. Industrial practice for this task is still largely manual. Technicians sweep the perimeter of the layup with a stethoscope, an ultrasonic listening device or an acoustic imaging camera that visualizes the source of ultrasonic emissions from leaks against a video image of the vacuum bag assembly. These methods work but

they are time-consuming. Each method requires skilled operators, scales poorly to large components and holds up the production schedule. Modern wind turbine blades exceed 100 metres in length and are produced as two shell halves, each presenting a vacuum bag assembly surface area on the order of $\sim 500\text{m}^2$ that must pass a vacuum-drop test before infusion can begin. Supervisory Control and Data Acquisition (SCADA) systems on the shop floor monitor vacuum pump pressures and flow rates hence they can flag the existence of a leak, but in current practice leak localization across a surface of this size remains a manual task that consumes hours of skilled operator time and can delay an entire production shift. A faster and more automated leak-localization method would therefore have direct industrial value.

Published literature on leak localization methods reviewed in Chapter 2 leaves three concrete gaps relative to the industrial leak localization problem:

1. Methods scale poorly to large laminates and force changes to the manufacturing setup.
2. Sensing happens at the boundary rather than across the fabric stack, so the spatial structure of a leak signature remains unknown.
3. All methods require the vacuum pump to be running during measurement since the flow signal that they obtain is generated by the vacuum pump pulling air through the leak under sustained vacuum flow.

None of the existing methods can operate during the vacuum-drop test phase that industry already uses for leak detection, when the vacuum pump is shut down. These three gaps frame the research question that this thesis addresses.

1.3 Research Objectives

This thesis asks whether a distributed pressure sensing approach can provide leak localization information during the same vacuum-drop test already used in industrial practice. Specifically, it asks:

Can a distributed array of pressure transducers installed beneath the vacuum film identify the presence and approximate location of a vacuum leak from the spatial pressure-rise signature measured during the pump-off vacuum-drop phase?

The thesis decomposes this question into four specific objectives:

1. Develop a distributed PT array that can be installed under the vacuum film, using industrial-grade consumables and acquisition hardware compatible with timescales of industrial vacuum-drop tests.
2. Establish an experimental protocol that introduces controlled vacuum film leaks of known position and size, permits the acquisition of pressure data distributed across the array during vacuum-drop test phase, and supports systematic comparison of leak signatures at different positions.
3. Develop a methodology for distinguishing leak-induced dP/dt gradient signatures in the distributed array from non-leak-related effects, principally edge effects in the gauge pressure field and single-channel sensor faults.
4. Characterize leak localization performance and speed of the methodology across a range of leak positions spanning the centre, edges, corners and cell-centred interior position of the laminate, and compare resulting performance with methods reviewed in Chapter 2.

1.4 Contributions

The work documented in this thesis makes three principal contributions to knowledge on leak detection and localization in vacuum infusion composite manufacturing. These contributions address the gaps identified in Section 1.2 and are supported by experimental results presented in Chapter 4.

1. Leak localization over a laboratory scale fabric stack. The thesis demonstrates leak localization across fourteen experiments spanning ten unique positions. These include repeated tests at centre and corner locations for assessing reproducibility.
2. Area-resolved sensing across the fabric stack. The thesis shows that an array of PTs distributed across the fabric stack can measure local gauge pressure and its rate of increase during a vacuum-drop test. The spatial pattern of the dP/dt field identifies leak position with the PT nearest the leak recording the largest dP/dt gradient. Although the gauge pressure at that PT is often elevated and can support the interpretation in clean single PT cases, it is less reliable than the gradient response because it varies with baseline vacuum

integrity and channel-to-channel offsets. Localization therefore rests primarily on dP/dt gradients rather than gauge pressure.

3. Leak localization during vacuum-drop test phase. The thesis demonstrates that the method operates during the vacuum-drop test phase already used for leak detection. During this phase the vacuum pump is isolated and the vacuum bag assembly remains sealed throughout the measurement.

A methodological note supports these three contributions: gradient-based (dP/dt) analysis used in localization methodology is robust to per-sensor calibration offsets since such offsets cancel in time derivatives. Localization claims supported by dP/dt contour maps presented in Chapter 4 are therefore more robust to sensor calibration uncertainty than claims based on absolute pressure alone.

The three contributions sit alongside methods reviewed in Chapter 2 rather than replacing them. Existing methods generally sense boundary flow while the pump is operating whereas this work senses pressure across the fabric stack during the pump-off vacuum-drop phase.

1.5 Thesis Outline

Chapter 2 reviews the literature relevant to the research question stated above. The chapter establishes the context of vacuum integrity in vacuum infusion and the consequences of vacuum film leaks for laminate quality, surveys the methods used in industrial and laboratory practice to detect the presence of vacuum leaks, reviews the published research on leak localization, and characterizes the pressure and flow phenomena beneath a vacuum film that any distributed pressure-sensing methodology must be able to interpret from leak-induced signatures. The chapter closes with a synthesis of the gap between existing methods and the question that this thesis addresses.

Chapter 3 describes the experimental setup and the protocol used in this work. The chapter specifies the layup configuration, geometry and instrumentation of the twenty PT array, acquisition hardware and sample rate, and controlled pinhole leak induction protocol. It also describes the vacuum-drop test procedure used for verifying layup integrity before each leak is introduced, which serves as the operational context for subsequent measurements.

Chapter 4 presents experimental results across fourteen experiments at ten leak positions of the fabric stack. The chapter develops dP/dt gradient signature analysis methodology in stages, demonstrating progressively how the spatial distribution of the gauge pressure rate field reveals the position of an induced leak and characterizes the methodology's localization performance across the range of tested positions.

Chapter 5 analyzes and discusses the results presented in Chapter 4. The chapter interprets the observed spatial dP/dt gradient patterns across the PT array, compares the behaviour of centre, edge, corner and cell-centred leak positions, and evaluates how quickly leak directionality and localization can be inferred from the measured pressure-rate signatures. It also discusses the influence of non-leak-related pressure variations, including baseline vacuum-drop behaviour, sensor-to-sensor variation, edge effects and proximity to the vacuum line. The chapter concludes by assessing the reliability of the proposed localization methodology and identifying the main experimental factors that affect its interpretation.

Chapter 6 summarizes the principal conclusions of the thesis, identifies the main contributions of the work, discusses the limitations of the experimental methodology, and outlines directions for future development. The thesis closes with a brief reflection on the practical applicability of distributed pressure sensing for industrial vacuum infusion operations.

Chapter 2 Literature Review

Leaks through the vacuum film are a recognised cause of variability in laminate quality [1]. Detection methods used in industry will only confirm that a leak exists; they do not locate it. This thesis asks whether a distributed array of low-cost pressure transducers installed beneath the vacuum film during vacuum infusion layup can localize a leak from its spatial pressure and/or dP/dt gradient signatures measured during the vacuum-drop test phase already used systematically in industry.

The following sections provide the background needed for the leak localization method developed later in the thesis. Section 2.1 revisits the role of vacuum integrity in infusion. Current leak detection practices are surveyed in Section 2.2. Section 2.3 discusses some published attempts at localization. The physical phenomena that create pressure signals are discussed in Section 2.4. Finally, section 2.5 identifies the gap that this thesis addresses.

2.1 Importance of Vacuum Integrity in Vacuum Infusion

Chapter 1 introduced the vacuum infusion process, the roles of the vacuum film and how vacuum-drop tests are conducted in industry. Hindersmann's overview was cited as the standard reference for this family of processes [4]. This section highlights two findings from the literature that are directly relevant to the localization method developed in this thesis.

The first is from Yenilmez et al. [6], who showed experimentally that local compaction pressure on a vacuum infused laminate varies in both time and space during resin injection, during consolidation and in between, with corresponding variation in laminate thickness, as compaction pressure depends on time and position dependent resin pressure as well as on vacuum applied at the manifold. The second finding comes from Haschenburger [1], whose doctoral work examined both the quality effects of vacuum film leakage and the detection of such leaks. That work showed that volumetric flow rate measurements can indicate the presence of a leak, while infrared thermography can be used to identify local cold spots associated with air ingress. This distinction between detecting leakage and localizing its position is central to the present review.

2.2 Leak Detection Methods in Vacuum Infusion

Methods used in industrial practice and laboratory settings for detecting leaks in a vacuum infusion layup are presented by the physical signal on which they rely: pressure, volumetric flow, acoustic emission, thermal contrast, and chemical or optical tracers. The purpose of this section is to establish the landscape of detection methods against which the present thesis is positioned, and to make explicit the distinction between detecting a leak i.e. confirming that a leak exists somewhere in the vacuum bag assembly, and locating a leak i.e. identifying where in the assembly it is. Several of the methods reviewed here extend to localization through the addition of further sensing or analysis steps; those extensions are reviewed in Section 2.3.

2.2.1 Pressure-Based Detection: The Vacuum-Drop Test

The vacuum-drop test is the common method for verifying vacuum integrity in industrial composite manufacturing, and a benchmark against which other methods tend to be compared.

A major drawback is that the vacuum-drop test measures only overall pressure. Leaks can appear from vacuum film, sealant tape, valves, vacuum lines, sensors, ports – these leak sources can all contribute to overall pressure increase. The vacuum-drop test cannot distinguish between a single large leak in the vacuum film and a number of small leaks distributed across the vacuum bag assembly. The test cannot indicate where the leak or leaks are located. Haschenburger [1] notes that current industrial leak detection practices rely heavily on operator judgement, use inconsistent thresholds, and offer no practical way to pinpoint the location of a leak on large parts.

2.2.2 Flow Rate Based Detection

A second signal complementary to pressure is the volumetric flow rate of air through the vacuum line. The principle is straightforward: under steady conditions, a properly sealed vacuum bag assembly should draw negligible air through the vacuum line. A leaking line will draw a flow of air whose magnitude depends on the size and number of leak paths. This is one of the main approaches used in leak detection at the German Aerospace Center (DLR) in Stade. In one published study, Haschenburger, Menke and Stüve [3] fitted flow meters to the vacuum lines of an industrial autoclave layup and showed that the volumetric flow rate exceeds a defined limit once a leak is present. Flow rate and pressure signals are not interchangeable. Flow rate measurements

are taken while the vacuum pump remains connected and operating whereas pressures are measured after the vacuum pump is shut down during a vacuum-drop test. In addition, manifold flow rate is directly related to the air drawn through an active leak path, while pressure changes reflect the combined leakage and volume responses of a sealed vacuum bag assembly, Figure 2.1.

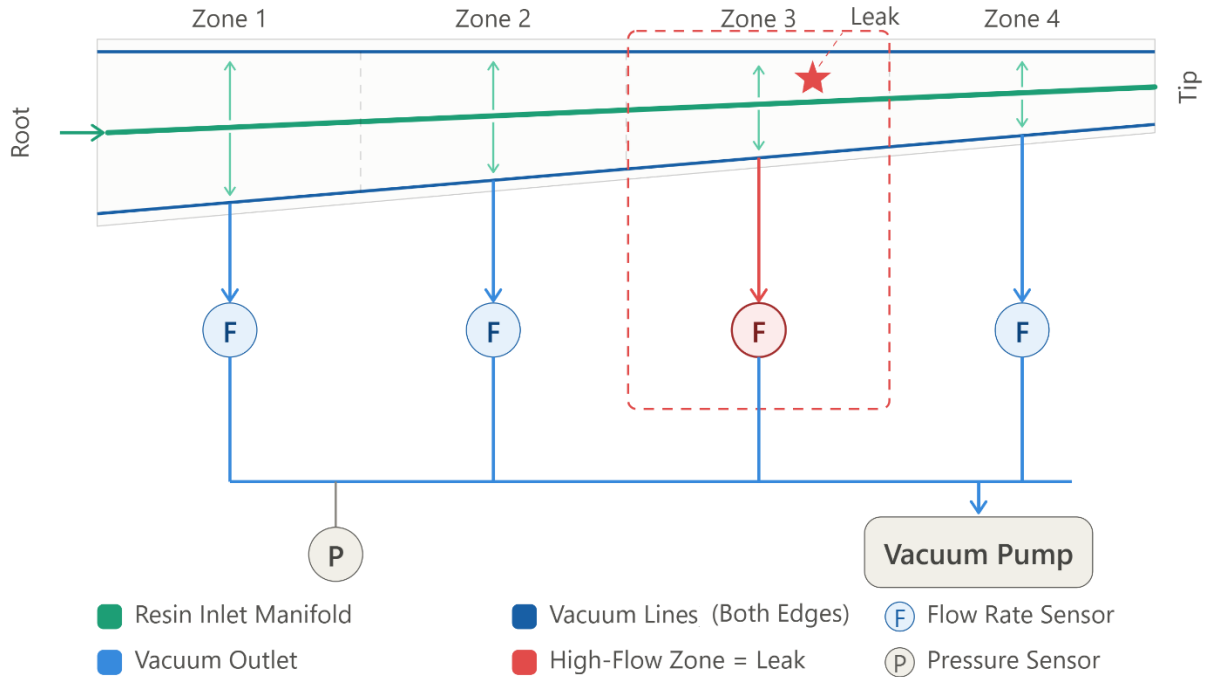


Figure 2.1: Flow rate measurement setup for a wind turbine blade shell infusion

A separate line of work from Najjaran's group at the University of British Columbia (UBC) [5] also builds on flow rate signals but interprets them differently through an electric-current analogy paired with machine learning. This method uses the same flow rate threshold logic as Haschenburger but adds data driven analysis to support localization.

A practical limitation is that flow meters must be selected, installed and calibrated for the expected gas-flow range. Their resolution may also become limiting for small leaks generating low flow rates.

2.2.3 Thermographic Detection

As air is drawn through a leak in the vacuum film, it undergoes an isenthalpic pressure drop. This produces Joule-Thomson cooling that lowers the temperature of incoming air and the vacuum film around the breach [1]. The cool region shows up as a cold spot in a thermal image of the vacuum film surface, which is what lets an infrared camera detect and position a leak from its cold spot signature. Haschenburger uses flow rate detection to narrow the region first, then applies infrared thermography to confirm the leak from its cold spot [1, 3]. As a standalone detection method it tends to fall short: the cooling signature is faint and the camera must be aimed at the leak's region. It works better as a confirmation step, which is how the DLR has used it.

2.2.4 In-Situ Component-Level Detection

So far the focus has been on leaks in the vacuum film and within the sealant tape's boundary. A separate strand of work examines leaks across metal–composite interfaces in FRP laminates. Baumann, May and Hausmann [7] studied the leak behaviour of metallic bushings: pipes that pass through a RTM-made composite laminate while it is under cyclic loading. They built a custom RTM tool with in-situ leak detection that uses hydrogen as a test gas, much like the standardized helium-sniffing test (DIN EN 1779:1999-10) [7]. This narrow field of study shows that leak detection can be tailored to a particular interface within a vacuum bag assembly, and that the detection signal itself can be optimized for the failure mode of that interface.

2.2.5 Summary

The methods in this section can detect leaks but they cannot localize them. As mentioned, thermography can be used as a confirmation step. Haschenburger [1] frames this as a central industrial problem, since commercial detection products are costly, manual, and cannot quickly position leaks on large parts quickly. The next section reviews work that adds sensing or analysis to close this gap.

2.3 Leak Localization

Published work on locating leaks has developed along two lines: one centred at the DLR, the other at UBC. Both lines rest on earlier work on real-time monitoring of the infusion process. Although that earlier work does not directly address leakage, it demonstrates that spatially distributed process measurements can support real-time interpretation and control of vacuum infusion.

2.3.1 Real-Time Monitoring of the Vacuum Infusion Process

During vacuum infusion, variables such as pressure, flow front position, compaction and saturation all change across the fabric stack during infusion. Modi et al. [8] showed that monitoring these changes in real time makes it possible to detect and correct flow disturbances caused by an uneven reinforcement fabric. Their setup paired a low-cost webcam for monitoring the flow front with computer-controlled injection ports that adjusted resin delivery. The primary variable in Modi's work is local saturation, which determines flow front position using optical access through a transparent mould. The present thesis instead uses local gauge pressures as primary variables, read by pressure transducers distributed across the fabric stack. There is no need for a transparent mould, which broadens the range of possible usage conditions to actual industrial moulds, potentially for very large parts.

2.3.2 The DLR Group Line of Work: Flow rate

The most extensive body of published work on leak localization in vacuum infusion comes from the DLR group. Three related methods were reported by this group, each using volumetric flow measured at the vacuum manifold rather than pressure measurements distributed across the laminate.

The first method by Haschenburger, Menke and Stüve [3], runs in two stages. Several vacuum lines are each fitted with a flow meter to monitor volumetric flow. When a reading goes past a preset threshold it flags a leak. The size of the reading hints at leak size; comparing readings between ports gives a rough sense of leak location. Technicians then walk the flagged area with an infrared camera, picking out the leak from its Joule–Thomson cold spot. The two-stage method

held up in industrial-scale autoclave trials and forms the backbone of DLR's industrial work in the field [1, 3].

The second method, also by Haschenburger and colleagues at DLR [9] keeps the front end but swaps thermography for a computational model. Volumetric flow rates at four vacuum ports around the edge of a square vacuum bag assembly are fed into any one of these arrangements: a potential-flow simulation, a numerical regression tying flow rates to port-to-leak distances or a matching method that checks observed flow fractions against pre-calculated values on a discretized grid. Localization accuracy depends on how far apart the ports sit. The method eliminates the need for thermography but it requires a calibrated model of air flow through the reinforcement fabric stack.

The third method by Brauer, Hindersmann and de Wolff [10] brings discrete geometry tools to the same manifold flow signal, and was the first DLR method to be evaluated at industrial scale. It relies on a single physical assumption, that air from a leak follows the path of least resistance to the nearest vacuum connection hence the flow meter at the connection nearest the leak registers the highest reading. A Voronoi diagram [10] is drawn above the vacuum bag assembly, dividing the fabric stack surface area into cells. Each cell has one connection. The cell holding the highest-reading sensor is the predicted location of the leak. A refined variant uses the two highest readings and predicts the two nearest cells. Both were tested on an industrial upper wing cover. The mould measured 5.2m by 16m and was instrumented with ten flow meters on vacuum ports spaced evenly around the perimeter. Leaks were introduced by puncturing the mould with hypodermic needles on a 250mm grid, yielding 413 single-leak samples. The plain Voronoi predictor correctly identified the leak cell in 91.7% of single-leak cases, with a mean Euclidean error of 20.6cm for misclassified cases. The method, dataset, and code were all released openly to enable comparison by other researchers.

This approach is limited by sensor spacing, which reduces localization accuracy in some regions. The method measures flow rate at the manifold which requires the vacuum pump to be connected and running, so it applies only during active evacuation and not during vacuum-drop tests. It also depends on flow meters that must be calibrated, and whose number must increase to improve resolution. Moreover, localization resolution is set by the density of perimeter

connections, so with ten flow meters on an 83m² mould each Voronoi cell spans roughly a square metre hence correct cell identification still leaves a sizable region to search.

Among published approaches, the DLR work is the most mature and the only one tested at industrial scale. All three DLR methods rely on flow rate measurements at the vacuum manifold and infer leak position from how the flow divides across multiple ports. What separates them is how the flow data are read: thermography in the first method, model-based inversion in the second, geometric partitioning in the third. Because sensors are located at the perimeter, achievable resolution is set by port spacing rather than by the physics of the leak itself.

2.3.3 The Najjaran Group Line of Work: Data-Driven and Optical

Najjaran's group at UBC and later University of Victoria (uVic) developed a second line of research [5, 11]. This work also uses volumetric flow rate measurement but pairs it with two complementary refinement techniques: machine learning inversion and Schlieren imaging.

Esmaeili, Cosco, and Najjaran [5] proposed an electrical analogue model where resistances to flow of air through the breather and vacuum film interfaces are represented as an electrical resistor network. The network is solved for flow distribution induced by a leak at any given position, and the simulated flow data is used for training a machine-learning model that estimates leak position from flow rates observed at the manifolds. Simulation quickly generates training data, avoiding extensive physical experiments. The authors note that the resulting model requires a training dataset that captures the flow characteristics of the layup to which it will be applied. Esmaeili later extended the data-driven framework to a broader range of detection and localization scenarios and to the classification of multiple simultaneous leaks [12].

Cosco [11] developed and demonstrated Schlieren imaging, which reveals air-density differences, showing leaks as density gradients against undisturbed air. Cosco showed bench-scale feasibility but noted the need for special optics, controlled lighting, and a clear line of sight which are often impossible to achieve in industrial settings.

The Najjaran work shares with the DLR work a dependence on flow rate measurements at vacuum manifolds, and a requirement for multiple vacuum lines that specifically enable the methods whilst staying compatible with manufacturing requirements. Approaches integrate a

trained machine learning model or a Schlieren optical system. These methods were developed in research settings and have not yet been validated at industrial scale.

2.3.4 Adjacent Work: Distributed Sensing and Pressure-Signature Analysis

Three additional bodies of work address similar phenomena but do not focus on leak localization during polymer matrix composite (PMC) manufacturing by infusion.

Buchinger and Khodaei [13] demonstrated that distributed optical fibre sensing embedded within a vacuum infusion layup can quantify local pressure, fabric stack compaction and fibre volume fraction. The setup uses a closed mould instead of a flexible vacuum film. It focuses on process monitoring rather than leak detection and shows that area-distributed sensing captures spatial details missed by single-point sensors. The optical fibre approach uses a Rayleigh backscattering interrogator with optical fibres embedded in the fabric stack. It raises costs, complicates layup, and requires time and skills beyond those typically available in industrial settings.

Siddig et al. [14] developed a simulation-based methodology for detecting race-tracking in RTM using pressure-time signatures recorded by a network of pressure sensors. Race-tracking happens when resin follows edges or low-resistance channels, causing nearby sensors to show sudden pressure increases. The method creates pressure gradient dP/dt maps from simulations and overlays them across scenarios to reveal common features. It was validated across 242 simulations covering geometries of increasing complexity. The study is computational, not experimental, and does not address vacuum leakage. It assumes that flow disturbances can be detected by pressure sensors and that pressure–time signatures can help locate leaks.

Caglar et al. [15] used optical flow-front detection in a transparent mould together with inverse optimization to map in-plane permeability; their rigid mould targeted permeability and not leak detection, showing that spatial distributions can be recovered from distributed measurements.

2.3.5 Summary

Published leak localization methods fall in one of two groups: the flow rate methods developed at DLR and the flow rate with models methods developed at UBC and UVic. Both infer

leak position from flow imbalances across perimeter manifolds, and neither measure pressures distributed across the fabric stack. Earlier distributed-sensing work [6, 8, 13] shows that such measurement is feasible but was not applied to leak localization.

2.4 Pressure and Flow Phenomena Relevant to Interpreting PT Signals

The leak localization methodology developed in Chapter 4 of this thesis interprets signals from an array of pressure transducers distributed across the fabric stack. Interpreting those signals requires knowledge and understanding of what produces spatial variation of pressure beneath a vacuum film. Three phenomena matter. Compaction of the fabric stack is uneven. Permeability varies in the plane of the fabric. Air follows low-resistance paths. This section returns briefly to literature on distributed sensing introduced in Section 2.3 to establish that the scale at which these phenomena manifest is consistent with the scale of the PT array used in the present work.

2.4.1 Compaction Non-Uniformity

Robitaille and Gauvin [16] proposed a time dependent power-law relation between compaction pressure and fibre volume fraction. In a single-sided vacuum bag assembly, compaction stress carried by the fabric stack at any point is set by the difference between atmospheric pressure above the vacuum film and the cavity pressure beneath it. Atmospheric pressure is constant. Variations in compaction stress come from cavity-pressure changes caused by in-plane fluid flow. The fabric stack resists this flow, and the flow rate depends on fluid viscosity.

This distinction separates two regimes. During resin infusion, high viscosity of the resin produces a large pressure gradient; Yenilmez et al. [6] monitored pressure at five points and observed thickness variation. Under dry evacuation only air flows. Air viscosity is about 10^3 to 10^4 times lower than that of resin, so cavity pressure gradients are minimal after pump shutdown.

Compaction changes gradually as the fabric stack creeps under the applied vacuum. Thickness decreases and fibre volume fraction increases until the material reaches equilibrium. This behaviour mirrors the viscoelastic response described by Robitaille and Gauvin [16]. For the

present work, these compaction-related effects are expected to appear primarily as a settling transient rather than as a dominant spatial leak-localization signature.

The relevance of compaction to leak localization is not that it imprints a spatial pressure signature on the array. A transducer beneath the vacuum film records the local cavity pressure, not the fabric compaction stress. Therefore, in the dry leak free condition, compaction non-uniformity is invisible to the array as a direct spatial signal.

2.4.2 In-Plane Permeability Variation

In-plane permeability quantifies the ease with which a fluid moves in the plane of a reinforcement fabric stack under a pressure gradient [17]. It is most often used as a constant or variable parameter in Darcy's law, and as one parameter in Forchheimer's law for faster flow. Permeability is a second-order tensor that depends on fabric stack architecture, ply orientation, local fibre volume fraction, and saturation within the fabric stack. Permeability is relevant to infusion in a number of ways: it quantifies how resin flows in plane during resin infusion; how air flows into an evacuated dry cavity upon leak, before resin infusion; and how air flows into a saturated cavity and displaces resin upon leak, during or after resin infusion. It should be noted that contrary to the premise of theoretical work defining it, permeability to resin and air may differ for otherwise identical stacks of fabric reinforcements at the same fibre volume fraction v_f .

For a nominally uniform fabric stack, permeability is idealized as constant across the part. However, permeability varies in practice. Variations in fibre orientation, areal density and inter-ply nesting create different local permeabilities [18]. Endruweit et al. [18] used stochastic resin injection simulations based on measured permeability and fibre angle distributions. Modi et al. [8] showed that permeability heterogeneity in fabric stacks can produce unpredicted resin flow fronts. Caglar et al. [15] developed a methodology for mapping the in-plane permeability distribution of isotropic mats by tracking the resin flow front during vacuum infusion. This demonstrates that permeability heterogeneity can be detectable and spatially understood using a flow-derived signal.

Permeability heterogeneity controls how gauge pressure responds locally to disturbances. A leak at a specific location will create a distinct pressure pattern. Where permeability is high, the rise spreads quickly across the array giving a broad, shallow signature. Where it is low, the rise stays local, narrow and steep.

2.4.3 Race-Tracking and Edge Effects

Race-tracking is the term used in liquid composite moulding literature for the preferential flow of resin or air along low-resistance paths in the fabric stack, such as edges, flow-distribution boundaries or ply drops. The phenomenon was originally identified in RTM where it manifests as leading flow fronts at part edges that race ahead of the main central flow front and produce dry spots in the part interior. Agogu   et al. [19] used Monte Carlo simulation to assess variability in RTM filling times, finding that channels near vents can increase dry-spot areas up to thirtyfold. Siddig et al. [14] used simulations to detect race-tracking from pressure-time signatures. Sas,   im    ek and Advani [20] investigated the design of the flow-distribution medium itself as a means of reducing variability that race-tracking introduces to vacuum infusion. The study optimized placement of distribution media around mould inserts where race-tracking is most prominent in vacuum infusion.

The relevance of race-tracking to leak localization is that low resistance channels shape how air, air pressures and air pressure gradient signatures distribute across the array, both during the pump shutdown transient phase and when a leak admits air that travels preferentially along those channels. Race-tracking signatures occur mainly near edges and distribution boundaries. An interior leak shows a different pattern than an edge channel, but a leak near the edge of a fabric stack may produce a signature that overlaps spatially with that of an edge channel. One must treat edge readings cautiously or wait until pump shutdown effects end.

2.4.4 Spatial Scale and the Feasibility of Distributed Sensing

The three physical phenomena reviewed above operate over spatial scales ranging from centimeter for local compaction non-uniformities and ply-edge effects to part scale for race-tracking along part edges and large-scale permeability gradients. The PT array used in the present work is described in Chapter 3. Array spacings of 31 cm horizontally and 24 cm vertically match the scales of large-scale permeability gradients and part edges race-tracking. Therefore, the PT array does not mix part-scale gradients with local signatures. Compaction non-uniformity is not a concern for the PT array used in this work. Furthermore and as established in Section 2.4.1, a transducer beneath the vacuum film records cavity pressure rather than compaction stress, hence centimeter scale compaction features are not measured, regardless of spacing.

The feasibility of distributed sensing across a vacuum bag assembly at this scale is established by the work reviewed in Section 2.3.4. Buchinger and Khodaei resolved local pressure distribution and compaction across a panel using fibre-optic sensors embedded within the fabric stack [13]; their setup used a rigid closed mould, but the present thesis demonstrates that comparable spatial resolution is achievable beneath a vacuum film using pressure transducers, with the trade-off that a pressure transducer records cavity pressure, not compaction stress.

2.4.5 Summary

Non-uniform compaction, permeability variation and race-tracking all influence how pressure evolves beneath the vacuum film. Of the three, compaction acts mostly on timing. Permeability and race-tracking determine where a disturbance might show up across the array.

2.5 Research Gap

Vacuum film leaks are sufficiently common in industry to justify dedicated detection methods. By contrast, leak localization remains largely unaddressed.

Most published localization methods use volumetric flow at the vacuum manifolds as the main signal, and infer leak location from flow imbalances across perimeter sensors. Localization resolution is set by the spacing of these measurement points, which places a practical limit on the size of the vacuum bag assembly over which a leak can be accurately localized.

These constraints define the research gap addressed in this thesis: whether PTs distributed across the fabric stack rather than limited to the perimeter can provide spatial leak localization information during vacuum-drop tests.

Chapter 3 Materials, Equipment and Procedures

3.1 Overview

This chapter describes the materials, equipment and procedures used to study vacuum behaviour and leak localization during vacuum-drop testing. The experimental procedure was developed iteratively beginning with vacuum integrity checks and progressing to controlled pinhole leakage tests using a distributed array of PTs. The materials and equipment were selected to reflect industry practice. All tests reported in this thesis were conducted under dry vacuum conditions without resin infusion so that pressure variation associated with leakage could be isolated from resin flow effects.

Section 3.2 describes the vacuum bag assembly including the mould, fabric stack, vacuum film, ancillaries, vacuum pump, vacuum pot and valve. Section 3.3 describes the pressure measurement system, PT layout, data acquisition hardware and controlled pinhole creation method. Section 3.4 presents the experimental protocol used for fabric stack preparation, vacuum evacuation, vacuum-drop testing and induced leak creation. The experimental setup is shown in Figure 3.1.

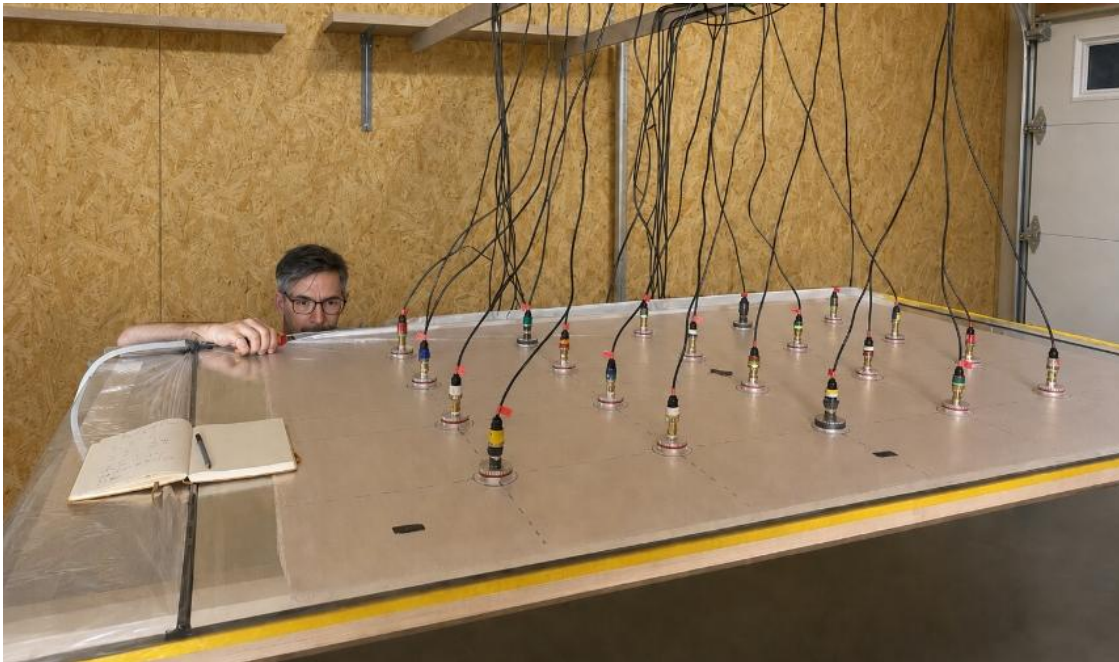


Figure 3.1: Experimental setup

3.2 Physical Elements of the Vacuum Bag Assembly

The vacuum bag assembly consists of a stack of reinforcement fabric layers referred to as fabric stack, laid on a mould and under a sealed vacuum film and ancillaries. Fabric stacks were prepared on a flat glass mould covered with vacuum film and sealed using industry-standard sealant tape. Spiral wrap distributed vacuum beneath the vacuum film.

Vacuum was generated using a single-stage vacuum pump connected to a vacuum pot. The vacuum pump evacuates air from under the sealed vacuum film. Vacuum pots are used systematically for protecting pumps from ingress of excess resin; one was integrated here to replicate real processing conditions even as no resin was used in this thesis. Vacuum was distributed to the fabric stack through flexible hose and spiral wrap. Inline valves and clamps enabled isolating the pump during vacuum experiments. Figure 3.2 provides an overview of the vacuum bag assembly including hardware. Figure 3.3 shows the top view of the vacuum bag assembly along with the hardware. Early testing revealed that unnecessary fittings and junctions increased the risk of leaks; consequently the vacuum bag assembly was simplified by eliminating all non-essential components. Detailed descriptions of all individual components appear in subsequent subsections.

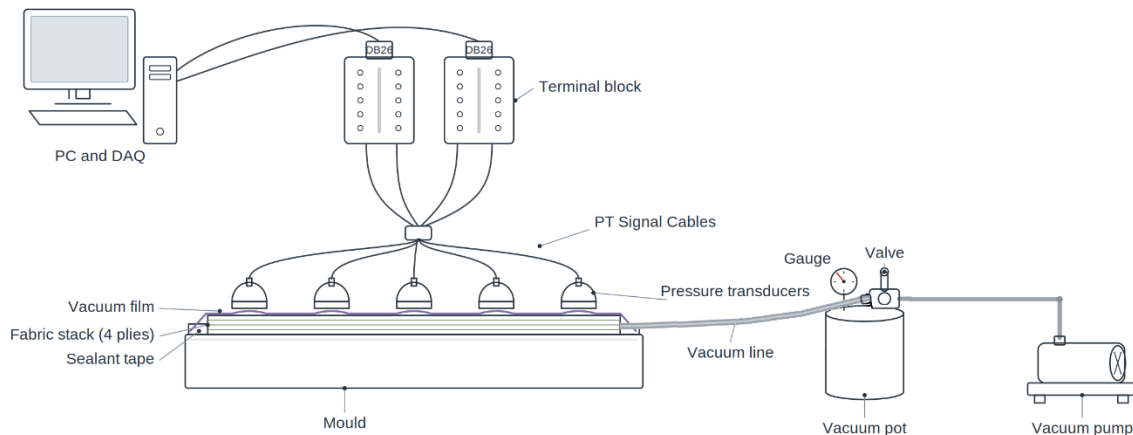


Figure 3.2: Sketch of vacuum bag assembly including hardware

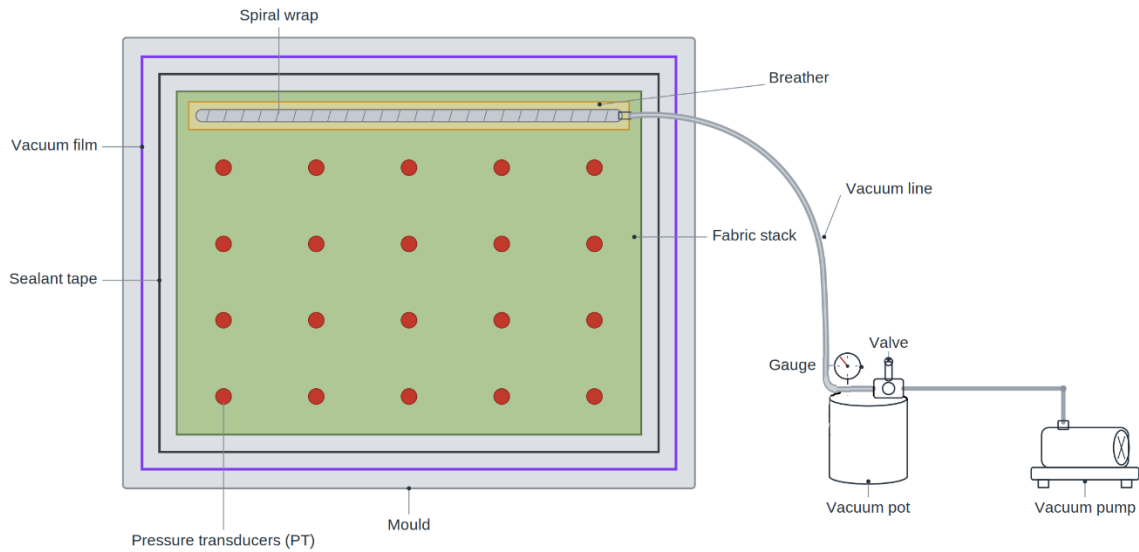


Figure 3.3: Top view of vacuum bag assembly

3.2.1 Mould

The mould consisted of a 12.5mm thick tempered glass plate measuring 2.4m in length by 1.29m in width, resting on a frame of 90mm by 40mm (2" x 4" nominal) spruce studs supported by two Bora Speedhorse XT adjustable sawhorse legs, Figure 3.4. It was designed with the capability to be used for manufacturing composites. The plate provided sufficient stiffness for dry vacuum bag assembly tests and was transparent, allowing visual inspection of the fabric stack and vacuum film seal during setup.



Figure 3.4: Mould

3.2.2 Reinforcement Material

Woven E-glass fabric suitable for vacuum infusion served as reinforcement material for all fabric stacks, Figure 3.5. A 300g/m² balanced plain weave (0°/90°) E-glass fabric was used as it is common in composites manufacturing. Its permeability and compaction behaviour are representative of typical layups. The fabric was laid up in uniform stacks featuring four plies. The fabric stack measured 1.2m by 1.86m.

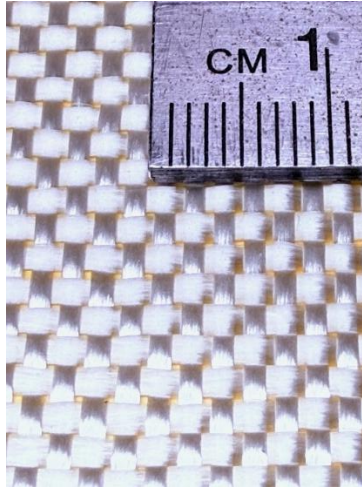


Figure 3.5: E-glass woven fabric, 300g/m²

3.2.3 Vacuum Film and Moulding Ancillaries

Polyethylene-based vacuum film Airtech Stretchlon™ series was used for all experiments described in this thesis, Figure 3.6. The vacuum film's high elongation helped it conform to the mould and fabric stack geometry, reducing bridging near edges and sealant-tape regions where leaks commonly occur.

Breather fabric Stretch Flow P 2000 is a highly permeable non-woven material positioned beneath the vacuum film and above the layup, Figure 3.7. Its primary purpose is to maintain a continuous low-resistance pathway for air and volatiles to escape from the fabric stack into the spiral wrap. In dry vacuum experiments conducted for this thesis, breather fabric facilitates air removal and supports reliable vacuum hold.

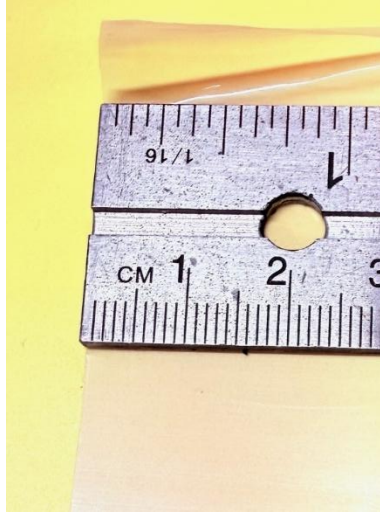


Figure 3.6: Vacuum film

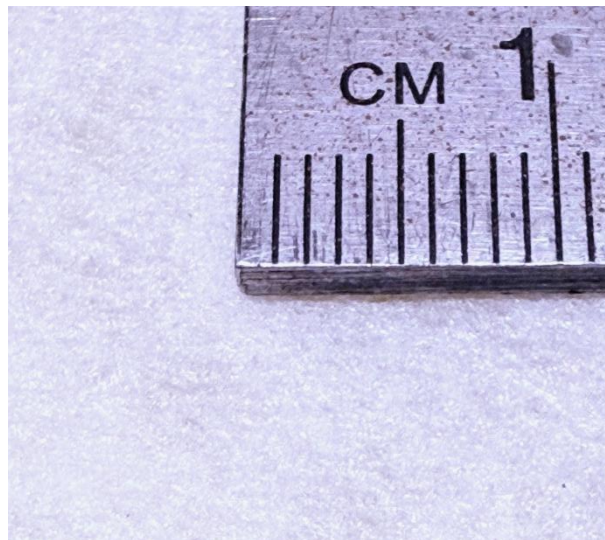


Figure 3.7: Breather fabric

Sealant tape Tacky Tape™ was used in all experiments for achieving an airtight seal, Figure 3.8. Tacky Tape™ is a butyl-based sealant tape standard in vacuum infusion. It was applied as a continuous bead along the mould and stack perimeter, with no overlaps.

Double-faced adhesive tape Tesa™ was used for positioning and securing the breather fabric, spiral wrap and vacuum tubes, Figure 3.8. Short strips were positioned strategically to prevent shifting or wrinkling of ancillaries during vacuum film application and air evacuation.

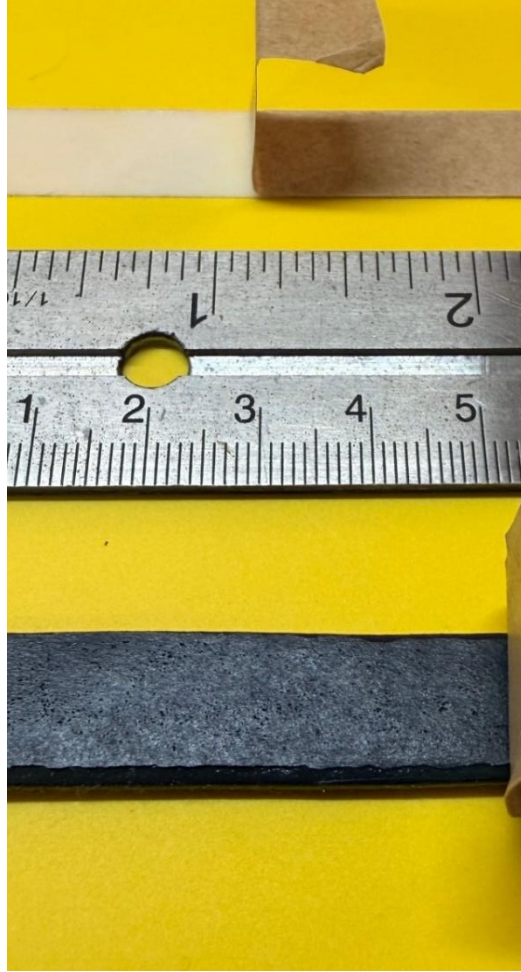


Figure 3.8: Double-faced adhesive tape (top) and sealant tape (bottom)

Polyethylene (PE) spiral wrap with a 12mm outer diameter (OD) was used for vacuum distribution and manifolding, forming a vacuum manifold along the perimeter of fabric stack and enabling air evacuation beneath the vacuum film, Figure 3.9. Additionally, 12mm OD PE vacuum tubing served as the primary pathway to connect the fabric stack to the vacuum pot and vacuum pump.

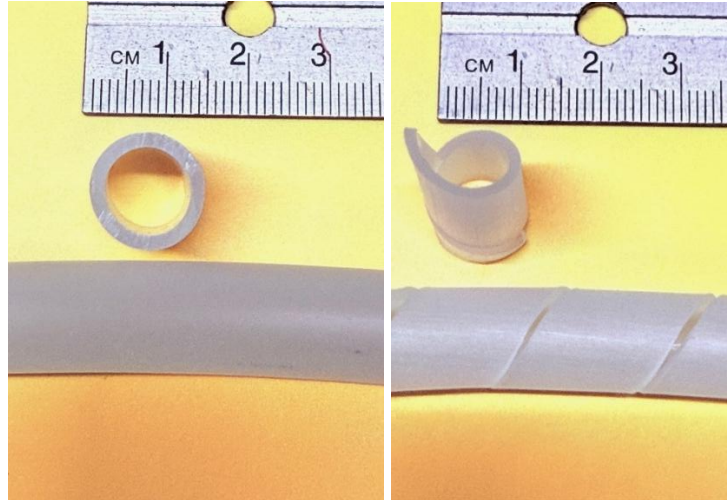


Figure 3.9: Vacuum tubing (left) and spiral wrap (right)

3.2.4 Vacuum Pump and Vacuum Pot

A single-stage Vevor 99.1 L/min (3.5 CFM) rotary vane vacuum pump was paired with an 11.4L (3 gallon) stainless steel vacuum pot, Figure 3.10. The pump reaches vacuum levels in the 1–10kPa absolute range corresponding approximately to –100kPa to –90kPa gauge pressure. The 11.4L stainless vacuum pot has a silicone-gasketed lid that held vacuum without measurable leakage over the test window.



Figure 3.10: Vacuum pump (left) and vacuum pot (right)

3.2.5 Valve

The vacuum line was isolated using a manually operated quarter-turn ball valve (Figure 3.11). The valve contained several threaded interfaces and polymer sealing surfaces which made it a potential source of leakage. Thread sealant was therefore applied at threaded joints. The valve was retained because similar manually operated valves are commonly used in production infusion setups and its inclusion made the experimental setup more representative of industrial practice. Its potential contribution to system leakage was considered during baseline vacuum-drop testing.



Figure 3.11: Quarter-turn ball valve

3.3 Pressure Measurement and Controlled Leak Creation

3.3.1 Pressure Transducers

Local vacuum levels were measured using Forunkeen 0-5 V DC 85Y PTs labelled PT1 to PT20 installed at discrete locations under the vacuum film, Figure 3.12. Each PT had an accompanying certificate showing specifications and calibration, Figure A.1. The PTs were arranged in a 5 by 4 grid over the fabric stack. The spacing between columns was 31cm and the spacing between rows was 24cm. Sealing at PT interfaces was critical as early experiments identified fittings as potential leak sources. Vacuum valves were used for connecting and sealing PTs to the fabric stack, Figure 3.13.

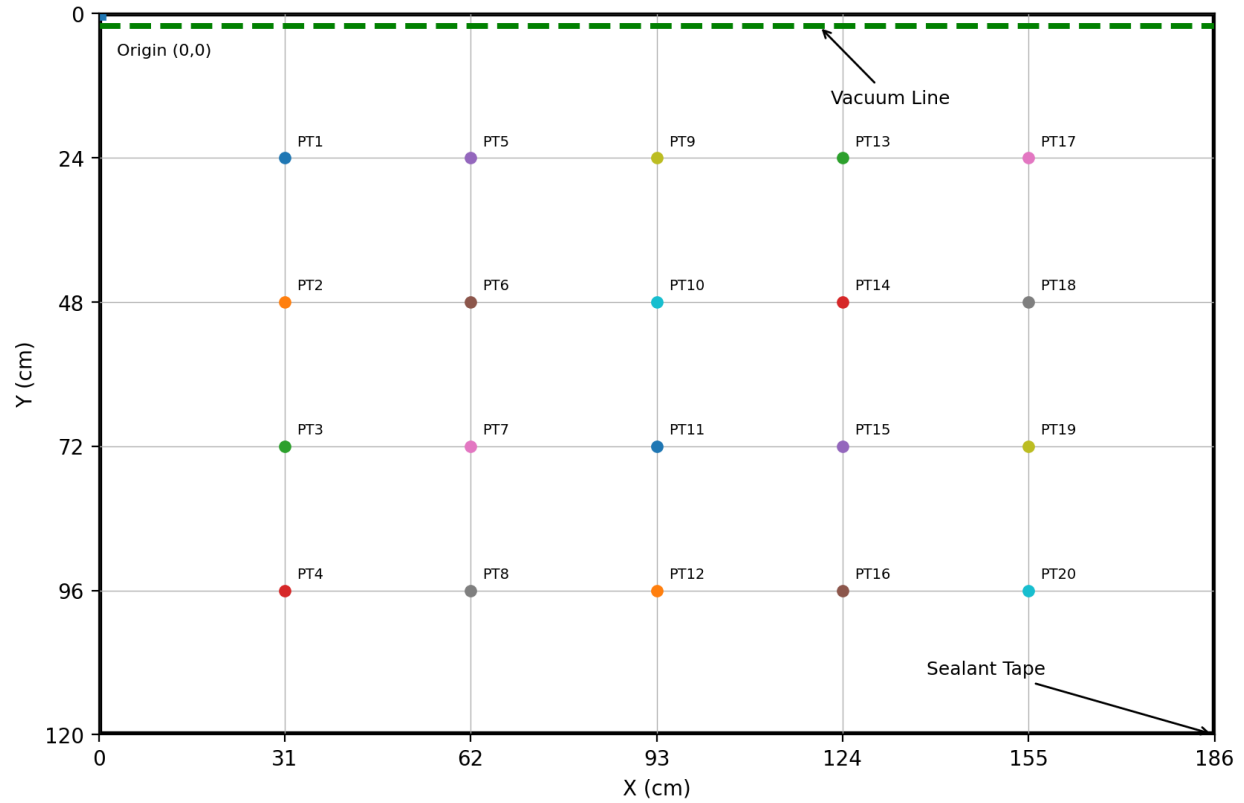


Figure 3.12: Locations of PTs over fabric stack

Twenty PTs were used to monitor the pressure distribution across the vacuum bag assembly during each test. Each PT had a measurement range of 0 to -100kPa , an analog output of 0–5VDC, and a stated accuracy of $\pm 1\text{kPa}$. The PTs provided a nominally linear voltage response over the calibrated pressure range, with the output voltage converted to pressure using a linear calibration relationship. Prior to testing, the PTs were checked against known reference conditions corresponding to atmospheric pressure and full vacuum, and the resulting calibration relationship was applied during post-processing.

The PTs were connected to a multi-channel data acquisition system and sampled at a rate of 1Hz. Although the data acquisition system recorded measurements from all twenty channels within each sampling interval, the channels were internally scanned in rapid succession rather than measured by dedicated simultaneous analog-to-digital converters. As a result, a small time offset existed between individual channel measurements within a scan cycle. This offset was considered negligible relative to the timescale of the vacuum-drop tests, which occurred over several minutes.



Figure 3.13: PT with vacuum valve assembled (left) and PT disassembled (right) having PT (top), 6mm (1/4" NPT) female pipe coupling (middle), vacuum film connector plates (bottom)

3.3.2 Needles for Controlled Pinhole Creation

Pinholes were punctured into vacuum films using sterile single-use medical acupuncture needles of diameters 0.25mm (32-gauge) and 0.14mm (42-gauge), Figure 3.14 and Figure 3.15. Although needle diameter provides a controlled nominal leak size, the actual effective leak area may vary slightly due to vacuum film elasticity, local stretching, puncture angle and partial resealing after needle removal. For this reason, leak size is reported by needle diameter and interpreted as a method-repeatable, rather than size-repeatable, induced defect method rather than an exact orifice area. Each pinhole was created by inserting the needle perpendicularly through the film and extracting the needle with the entire insertion–removal process lasting approximately one second.

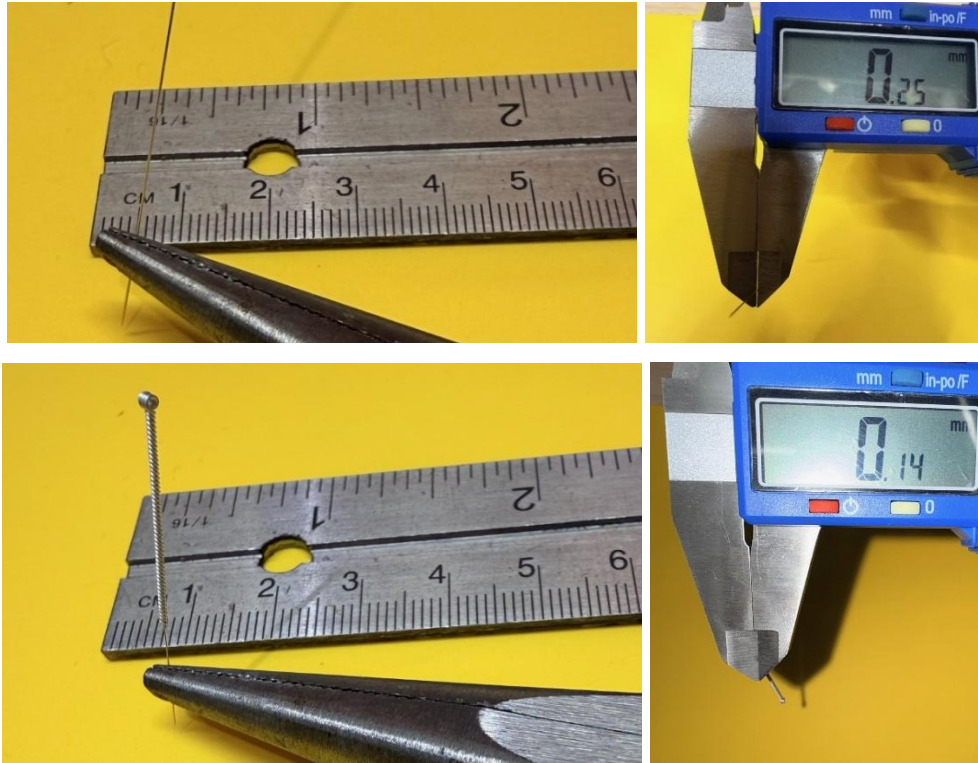


Figure 3.14: Needles used for puncturing pinholes: 0.25mm diameter (top), 0.14mm diameter (below)

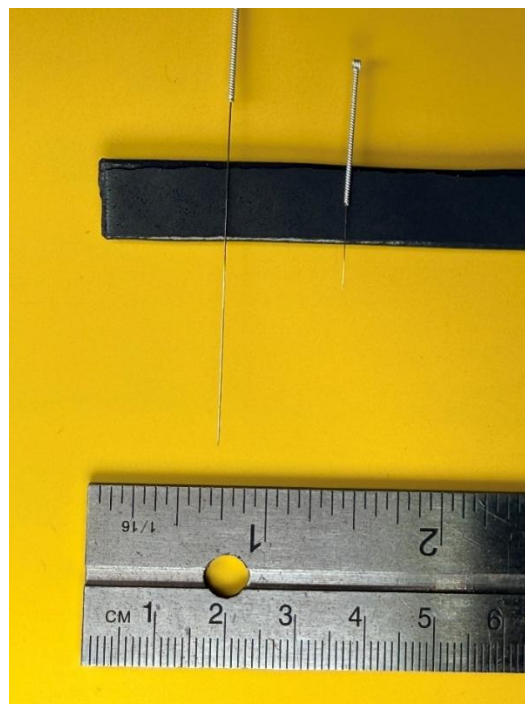


Figure 3.15: Needles compared, 0.25mm diameter (left), 0.14mm diameter (right)

3.3.3 Data Acquisition Hardware

All PTs were connected to a National Instruments SCB-68 terminal block. The data acquisition (DAQ) board used a data acquisition rate of 1Hz. The DAQ board interfaced with a personal computer (PC) for real-time pressure monitoring and data logging.

Data acquisition was conducted using LabVIEW™ which allowed individual channel sampling control across all twenty PTs and logged directly to file. Early experiments used a sampling frequency of ~100Hz with the aim of ensuring capture of transient effects. Analysis of data files confirmed that a reduced rate of 1Hz offered a strong compromise between adequate vacuum leak detection, minimizing data volume for experiments that would last over 120 minutes, and improving workability and interpretability.

All datasets were exported to Microsoft Excel for post-processing including signal calibration, analysis and visualization of pressure–time responses. Digital calibration was performed using the vacuum pot pressure gauge as a reference, at 0kPa and –100kPa. Linear correction factors were applied to each PT to align outputs with reference measurements. Subsequently, PT1 was designated as the control sensor, and all remaining PTs (PT2–PT20) were normalized relative to PT1 to eliminate systematic offsets.

A standardized acquisition protocol was implemented with all experiments. Post-processing normalization ensured inter-sensor consistency and enabled reliable comparisons of pressure fields and gradients in space and time. The correction procedure improved consistency between channels and enabled meaningful comparison of pressure fields and dP/dt gradients.

3.3.4 Absolute Pressure and Gauge Pressure

Pressure is defined as a force exerted per unit area and is commonly expressed in SI units of Pascals (Pa):

$$P = \frac{F}{A} \quad (3.1)$$

where P is pressure (Pa), F is force (N) and A is area (m^2).

In vacuum engineering and composite manufacturing processes such as vacuum infusion, pressure measurements may be expressed in two different reference systems: absolute pressure

and gauge pressure. Absolute pressure P_{abs} is measured relative to a perfect vacuum, which represents the theoretical state where no gas molecules are present. In contrast, gauge pressure P_g is measured relative to surrounding atmospheric pressure. The relationship between these quantities is expressed as:

$$P_{abs} = P_g + P_{atm} \quad (3.2)$$

where P_{abs} , P_g and P_{atm} are absolute, gauge and atmospheric pressure respectively. At sea level, atmospheric pressure is approximately $P_{atm} \approx 101.3 \text{ kPa}$ and average atmospheric pressure within the Ottawa area on experimental days was $P_{atm} = 99.0 \text{ kPa}$ [21]. Thus, if a vacuum gauge reads -90 kPa (P_g) the corresponding absolute pressure is:

$$P_{abs} = (-90 \text{ kPa}) + 99.0 \text{ kPa} = 9 \text{ kPa} \quad (3.3)$$

Absolute pressure always remains positive whereas gauge pressure may be either positive or negative depending on whether the pressure is above or below atmospheric pressure.

In this work, PTs are used for monitoring spatial pressure distribution and temporal pressure variations beneath the vacuum bag assembly during leak events, prior to and after controlled punching of the bag. Because sensors measure gauge pressure, recorded signals reflect relative pressure changes to atmospheric pressure. When a leak is introduced, atmospheric air enters the system causing measured gauge pressure to increase; gauge pressure values move toward 0kPa.

All pressures reported in this work are gauge pressures unless stated otherwise. Therefore, during a leak event an increase in gauge pressure corresponds to a loss of vacuum.

By monitoring the rate of pressure increase, also referred to as loss of vacuum, and comparing signals from multiple sensors, it becomes possible to detect and localize leaks within the system. Experiments conducted in this work focus on gauge pressures recorded across space and time.

A common source of confusion in vacuum measurements arises from the interpretation of negative pressure values. A vacuum pressure gauge displaying a reading near -100 kPa does not indicate negative absolute pressure. It indicates that the pressure inside the vacuum bag assembly is approximately 100kPa below the surrounding atmospheric pressure, Table 3.1.

Table 3.1: Examples and interpretation of pressure measurements

Atmospheric Pressure (kPa)	Gauge Pressure (kPa)	Absolute Pressure (kPa)	Interpretation
101.3	0	101.3	Atmospheric pressure
101.3	-50	51.3	Partial vacuum
101.3	-90	11.3	Strong vacuum
101.3	-100	1.3	Near full vacuum

All recorded values represent pressure differences relative to atmospheric pressure rather than absolute pressures under the vacuum film.

3.4 Experimental Measurement Protocols

The experimental procedure followed in this work is aligned with industrial practice and aims at evaluating vacuum integrity and induced leak behaviour systematically. Figure 3.16 shows a cross-section of the vacuum bag assembly used throughout the campaign. The process flow illustrated in Figure 3.17 outlines the sequential experimental steps followed for each experiment, from fabric stack preparation to pinhole creation.

3.4.1 Fabric Stack Preparation

The first experimental step ensures that the fabric stack and vacuum bag assembly are assembled in a controlled and repeatable manner.

1. Clean mould surface to remove contaminants that may affect sealing.
2. Apply sealant tape along mould perimeter.
3. Layup glass reinforcement plies.
4. Install vacuum ancillaries i.e. spiral wrap and vacuum tubing.
5. Apply and seal vacuum film.
6. Inspect visually for bridging, wrinkles or gaps along perimeter.

This step is essential to isolate system leaks from induced leaks. A system leak is an unintended loss of vacuum arising from imperfections within the vacuum bag assembly itself, such as faulty seals, tubing connections, valves or transducer interfaces. An induced leak is a deliberately created defect, e.g. a calibrated pinhole punctured actively in the vacuum film.

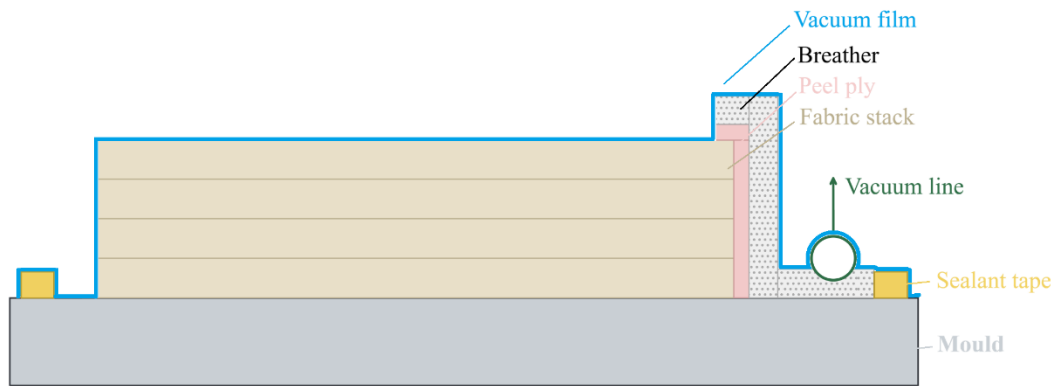


Figure 3.16: Side view of vacuum bag assembly

3.4.2 Pulling of Vacuum

The second step begins once the fabric stack is sealed, with the vacuum bag assembly being activated. The objective of this step is to achieve stable high vacuum prior to integrity testing.

7. Activate DAQ and begin pressure recording.
8. Open vacuum port valve, turn vacuum pump ON and allow vacuum pump to approach at least -95kPa gauge pressure.
9. Verify vacuum film seal.
10. Confirm that all PTs reach consistent steady-state pressure values.

3.4.3 Vacuum-Drop Testing

The vacuum-drop test step is conducted for quantifying the leak rate of the system prior to introducing controlled defects.

11. Prepare a 5-minute timer.
12. Turn vacuum pump OFF.
13. Record pressure values at 1 second intervals.

14. Calculate pressure differences over 5 minutes (kPa/min).

Decision criterion: If pressure increase is greater than 1kPa/min, a leak is present and rework is needed before continuing. If pressure rise is below threshold, system is sufficiently airtight.

This step serves two purposes:

- A. Validation of baseline vacuum integrity.
- B. Establishment of reference decay curve against which induced leaks can be compared.

3.4.4 Pinhole Creation

After confirming vacuum integrity, controlled pinhole defects are introduced to simulate leak scenarios. This step enables quantification of pressure decay response as a function of nominal leak size, and it supports the exploration of spatial localization of leaks.

1. Turn vacuum pump ON.
2. Confirm pressure stabilization.
3. Turn vacuum pump OFF.
4. Mark intended leak location on vacuum film.
5. Select needle gauge e.g., 0.25mm / 32Ga; 0.14mm / 42Ga.
6. Puncture vacuum film and record time of puncture.
7. Continue recording all PT values until atmospheric pressure is reached or predefined stopping criteria are met.

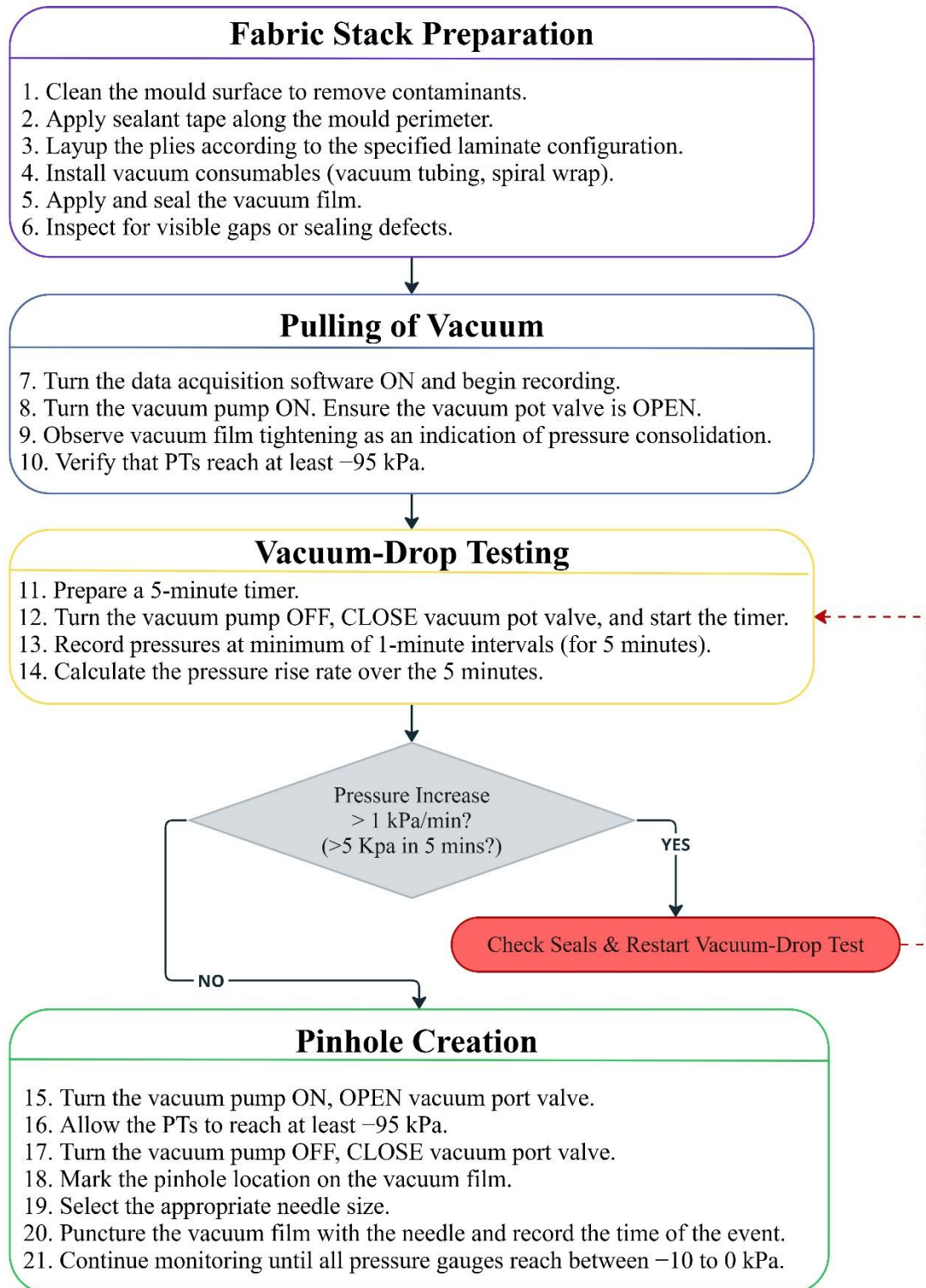


Figure 3.17: Experimental flow chart

Chapter 4 Results

4.1 Overview

This chapter presents and compares the responses recorded using the PT array during controlled pinhole leak experiments, focusing on gauge pressure, rates of pressure changes with space and time, and reproducibility. Pinhole locations changed across the 14 experiments to assess how pressure evolved under different conditions, to test whether the array can locate leaks, and to examine how the vacuum line affects both localization and leak behaviour itself.

Pinhole positions were chosen to cover four cases of interest: the geometric centre of the fabric stack, the point furthest from vacuum line entry, the point nearest it, and several positions in between. Each pinhole was positioned between PTs rather than directly over one so that more than one sensor would pick up signal and localization could be tested.

The campaign began at the geometric centre to confirm that all PTs were working and check overall setup. Two locations were repeated to assess reproducibility: the geometric centre tested once with the 0.25mm needle and thrice with the 0.14mm needle, and the corner farthest from the pump but next to the vacuum line tested with both needle sizes. Two needle diameters were used to produce leaks of different sizes, representing pressure losses observed in industrial settings. Section 4.2 covers the first three experiments made with a 0.25mm, 32-gauge needle. Section 4.3 covers the remaining eleven experiments made with a 0.14mm, 42-gauge needle. Results are read with three questions in mind: how sensitive the method is, how well it detects and locates leaks of different sizes at different positions, and how proximity to the vacuum line shapes the response.

Table 4.1 lists the 14 experiments, indicating needle diameter and pinhole location for each experiment. Figure 4.1 shows a top view of the experimental setup including PT positions, pinhole locations and vacuum line. Departures from the expected pattern at individual locations are noted with each experiment and analysed in Chapter 5.

Table 4.1: Experiment matrix: section, needle size and pinhole location for all experiments

Section	Experiment #	Needle size (mm)	Pinhole location x, y (cm)
4.2.1	1	0.25	X_1 : 93, 60
4.2.2	2	0.25	X_2 : 170.5, 108
4.2.3	3	0.25	X_3 : 170.5, 12
4.3.1	4	0.14	X_4 : 93, 60
4.3.2	5	0.14	X_5 : 93, 60
4.3.3	6	0.14	X_6 : 170.5, 12
4.3.4	7	0.14	X_7 : 93, 108
4.3.5	8	0.14	X_8 : 15.5, 12
4.3.6	9	0.14	X_9 : 93, 12
4.3.7	10	0.14	X_{10} : 46.5, 60
4.3.8	11	0.14	X_{11} : 93, 60
4.3.9	12	0.14	X_{12} : 139.5, 60
4.3.10	13	0.14	X_{13} : 15.5, 60
4.3.11	14	0.14	X_{14} : 46.5, 108

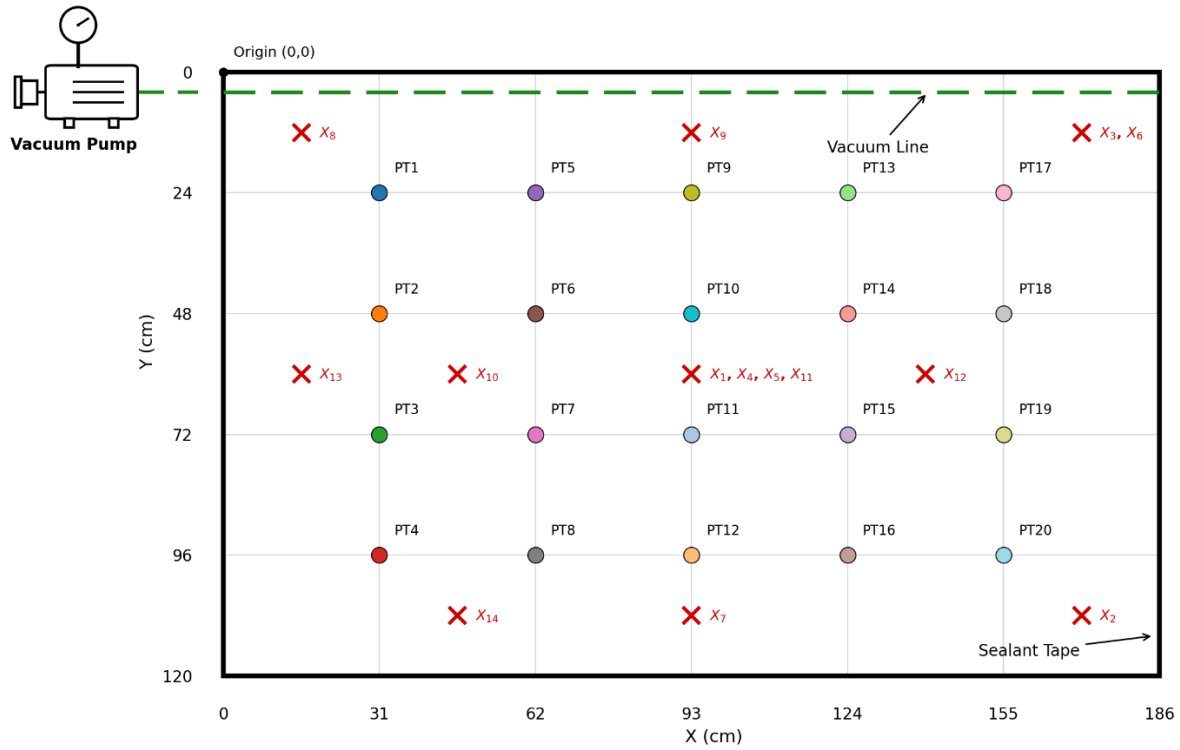


Figure 4.1: Top view of experimental setup including positions of PTs (coloured circles), pinholes (red crosses) and vacuum line (dotted green line)

4.2 Experiments Using 0.25mm Diameter Needle

The first series consisted of three experiments in which pinhole leaks were induced using a 0.25mm diameter, 32-gauge needle. The 0.25mm diameter was selected as a starting point on the basis that it would produce a leak that would be sufficiently larger than baseline system vacuum-drop hence detected unambiguously by the PT array, and generate sufficiently localized pressure rises at PTs nearest to pinholes hence localized unambiguously by the PT array.

4.2.1 Experiment #1

In Experiment #1 a pinhole was punched at location X_1 at the geometric centre of the fabric stack using a 0.25mm diameter needle. Figure 4.2 shows pinhole location relative to PT array and vacuum line.

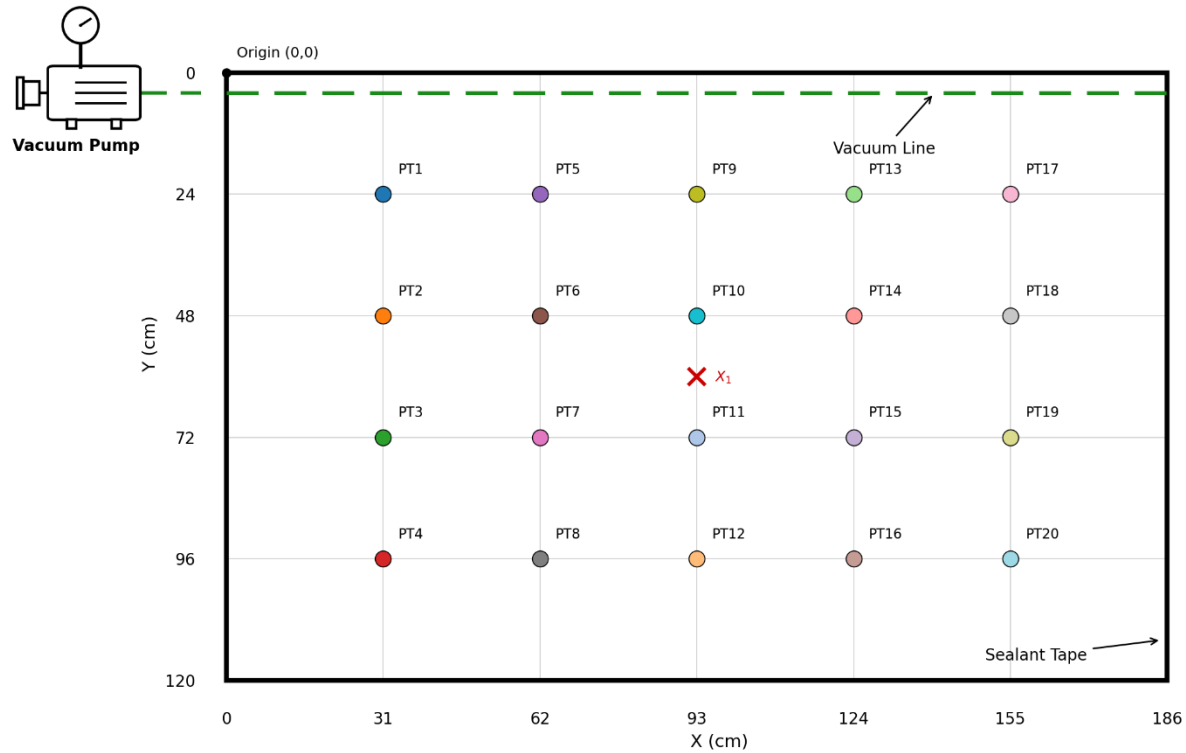


Figure 4.2: Pinhole location, Experiment #1

Figure 4.3 details key events in Experiment #1. Gauge pressures at all PTs varied during the vacuum-drop test and subsequent induced leak event. The vacuum-drop test was conducted from $t = 186s$ to $486s$ with the pump shut off. The vacuum-drop test recorded a 4.36kPa pressure rise

over 5 minutes, corresponding to 0.87kPa/min, which was below the 5kPa in 5 minutes industrial acceptance threshold. The induced leak drove gauge pressures across all PTs to atmospheric pressure by approximately $t = 2800$ s.

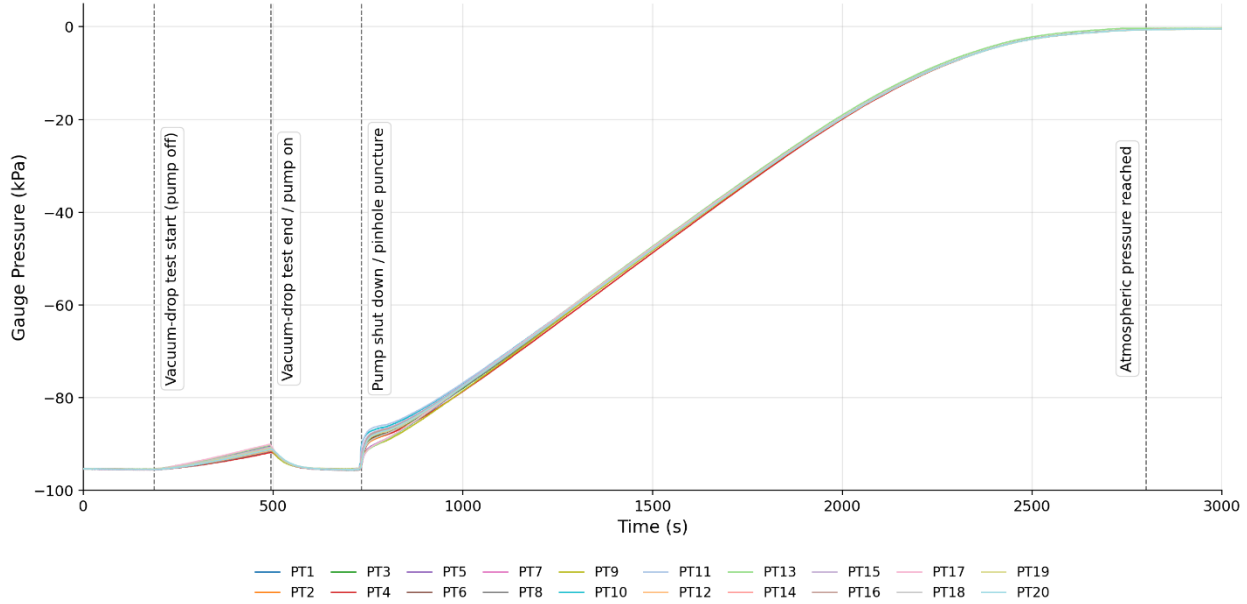


Figure 4.3: Key events, Experiment #1

Figure 4.4 shows pressure rise during the vacuum-drop test for Experiment #1. Five of the top six PTs that led the rise, PT17, PT13, PT1, PT5 and PT9 are located in the row nearest the vacuum line. Three out of five PTs furthest from the vacuum line, PT4, PT8 and PT12 showed the smallest rise.

The leak signature emerged within seconds of test start. Figure 4.5 shows the first 30s of the test, $t = 186$ s to 216s, with raw measurements as dashed traces and second-degree polynomial smoothed curves overlaid. The six PTs that led the rise across the complete test are already separating from the rest of the array by $t = 216$ s.

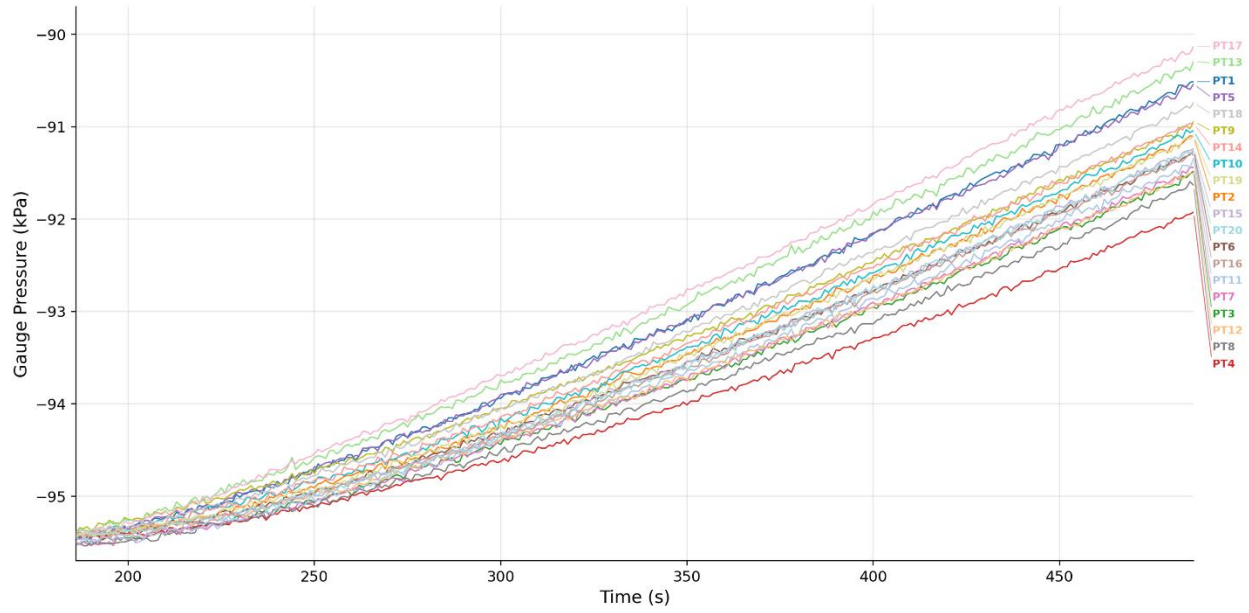


Figure 4.4: Vacuum-drop test, Experiment #1

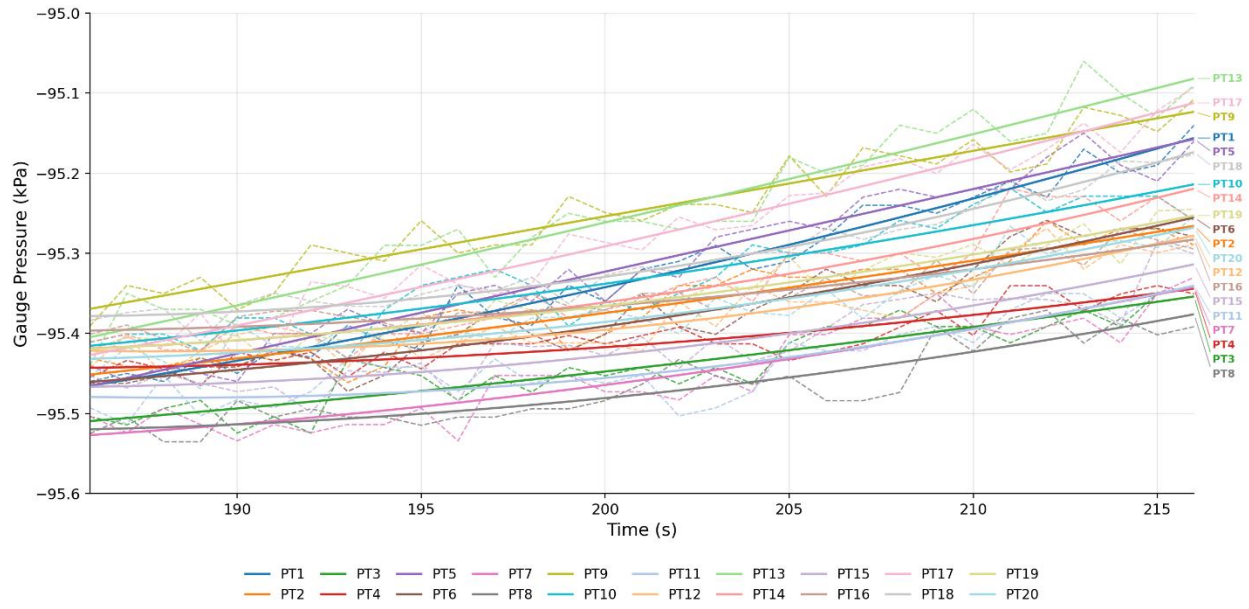


Figure 4.5: Vacuum-drop test, first 30 seconds, Experiment #1

Grouping the PTs by row and plotting row-averaged gauge pressures shows the rows nearest the vacuum line separating first, Figure 4.6 and Figure 4.7. Each curve in Figure 4.7 is the average of the five PTs in one row, raw as dashed traces with smoothed curves overlaid.

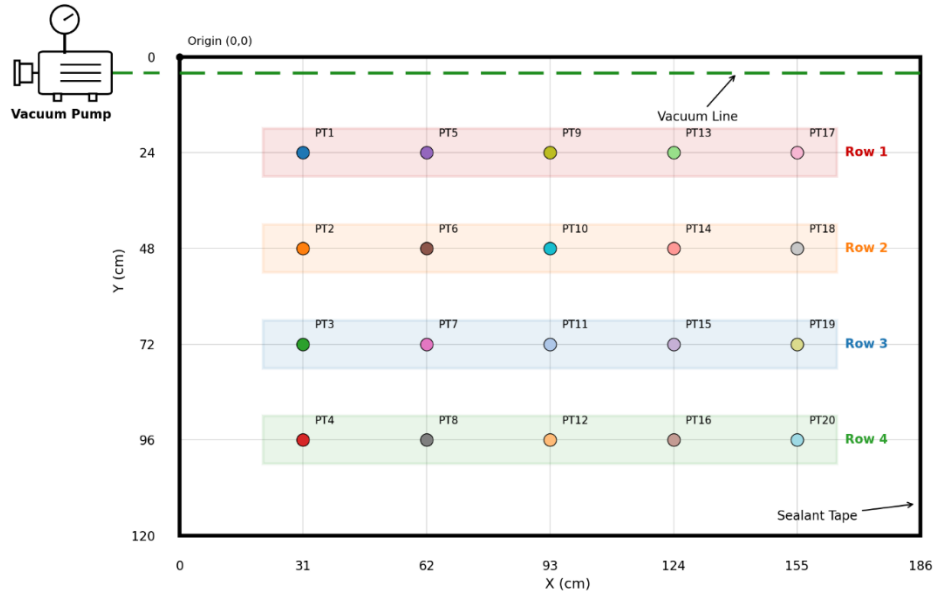


Figure 4.6: PT array layout with each row of five PTs grouped and colour-coded by row, Experiment #1

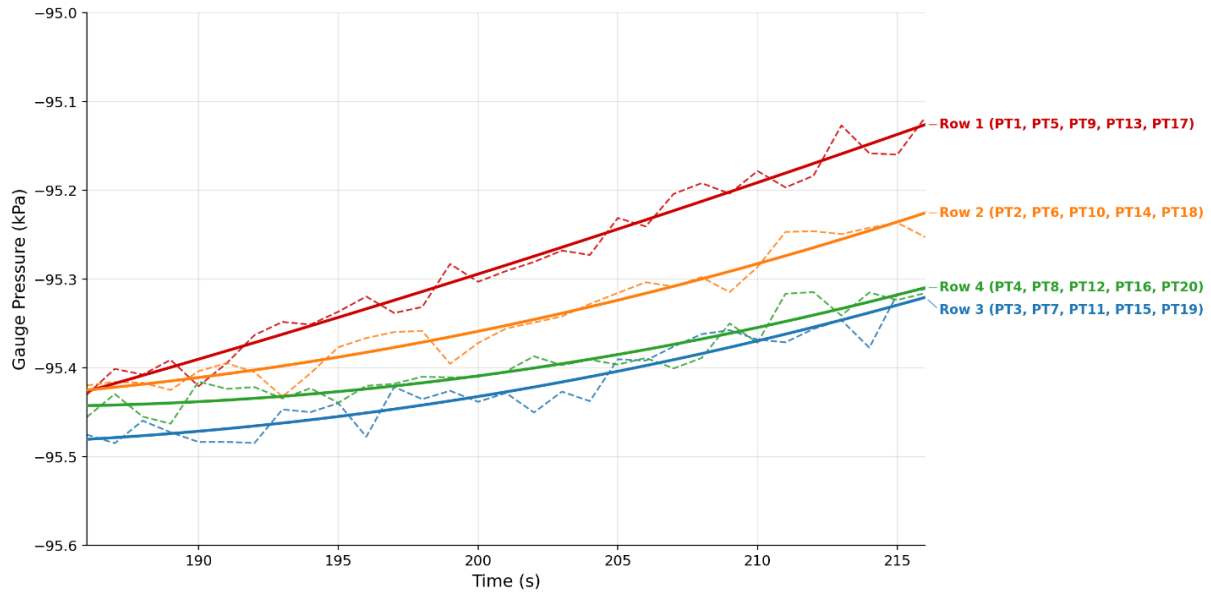


Figure 4.7: Row-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #1

Grouping the same data by column, at four PTs per column, gives the complementary view along the x-direction, Figure 4.8 and Figure 4.9. Each curve in Figure 4.9 is the average of the four

PTs in one column. Column-averaged curves separate far less than row-averaged curves, with Col 5 the highest and Col 1 among the lowest.

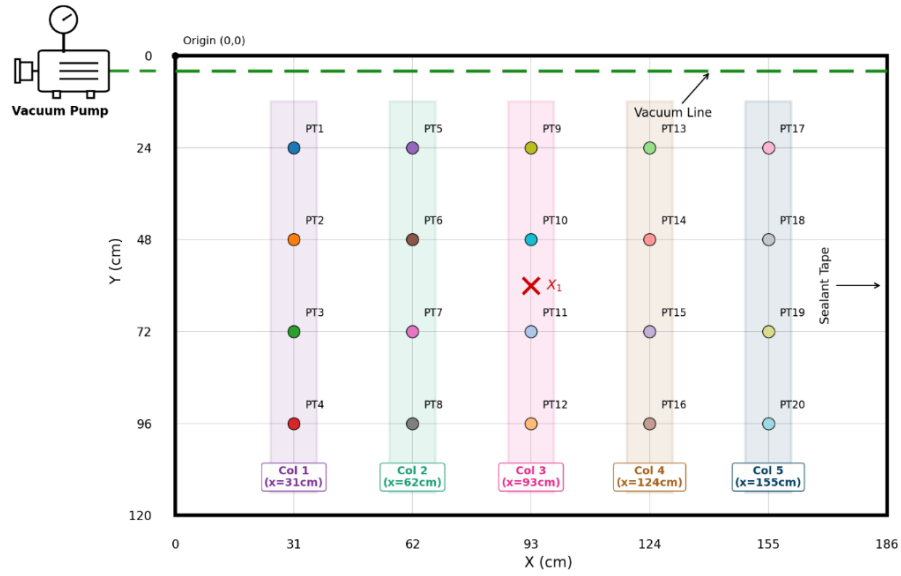


Figure 4.8: PT array layout with each column of four PTs grouped and colour-coded by column, Experiment #1

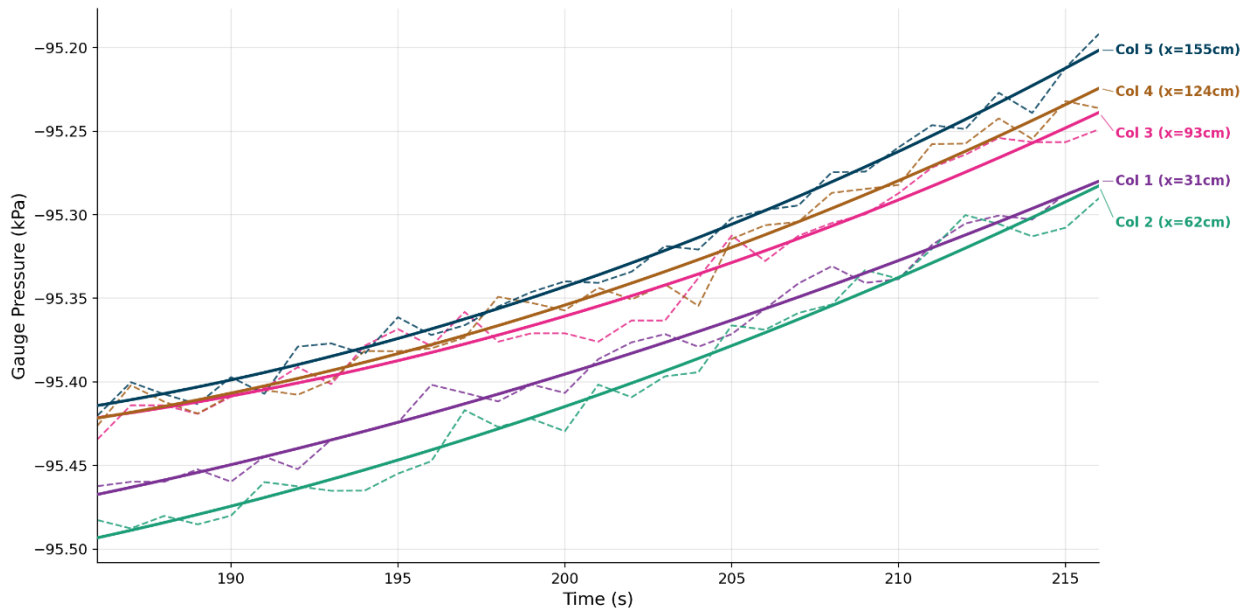


Figure 4.9: Column-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #1

The vacuum pump was restarted at $t = 493\text{s}$ and shut off at $t = 708\text{s}$ to set the pre-puncture baseline. The vacuum film was punctured at X_1 : the needle was inserted at $t = 728\text{s}$ and extracted at $t = 731\text{s}$, Figure 4.10. PT10 and PT11, the PTs closest to X_1 , showed the largest pressure rise on insertion, stabilized briefly as the needle partially sealed the hole, then rose most sharply on extraction (3.20kPa/s). The transient phase spanned $t = 728\text{s}$ to 731s , with steady-state leak phase beginning at $t = 732\text{s}$.

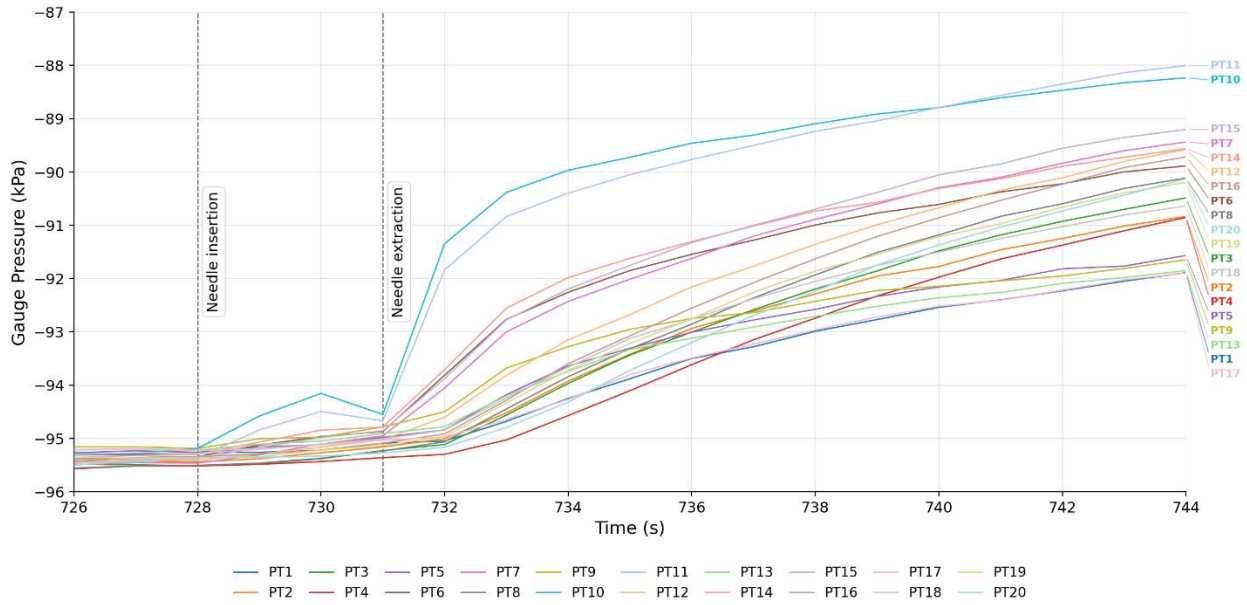


Figure 4.10: Pinhole insertion and extraction effects, Experiment #1

Before puncture the dP/dt field is uniform and near zero across the array, Figure 4.11. The needle is inserted and the gauge pressures rise, peaking at $t = 730\text{s}$ at PT10 and PT11 while the needle is still in the vacuum film, Figure 4.12. At needle extraction a single peak emerges at PT10 and PT11 again, nearest X_1 at the centre, Figure 4.13. One second later the peak gives way to elevated rates at surrounding PTs, Figure 4.14, and by the first second of steady-state leak phase the field is uniform again, Figure 4.15. Each contour map figure includes a red 'Max Scale' box denoting the maximum scale value applied to that figure. Figure 4.16 shows the complete three-second window for Experiment #1, in which PT10 rose first and steepest.

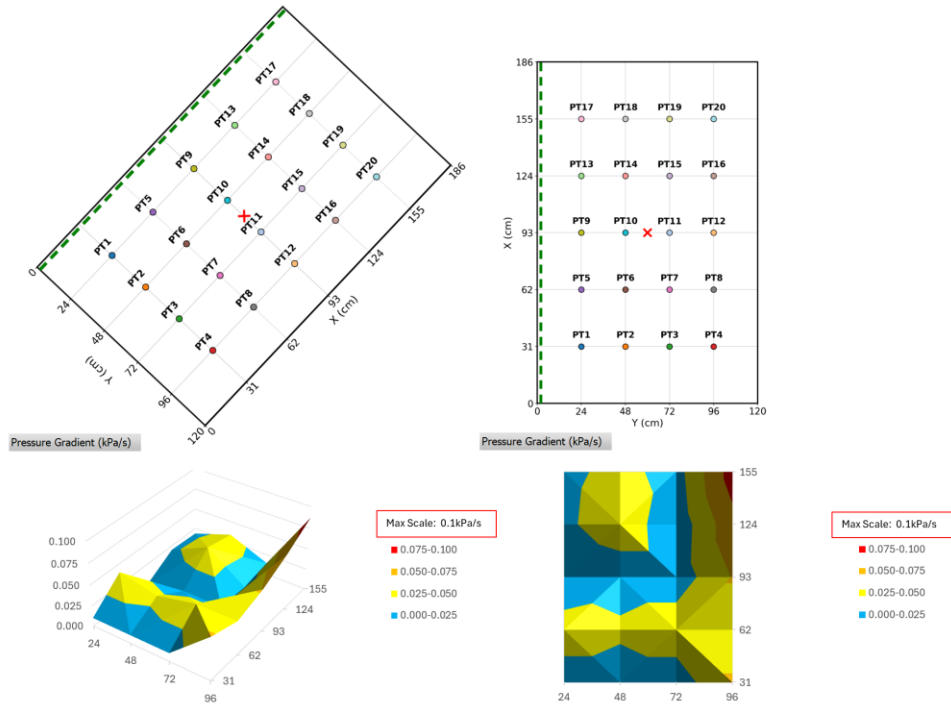


Figure 4.11: Contour map of dP/dt for $t=727-728s$ (pre-puncture baseline), Experiment #1

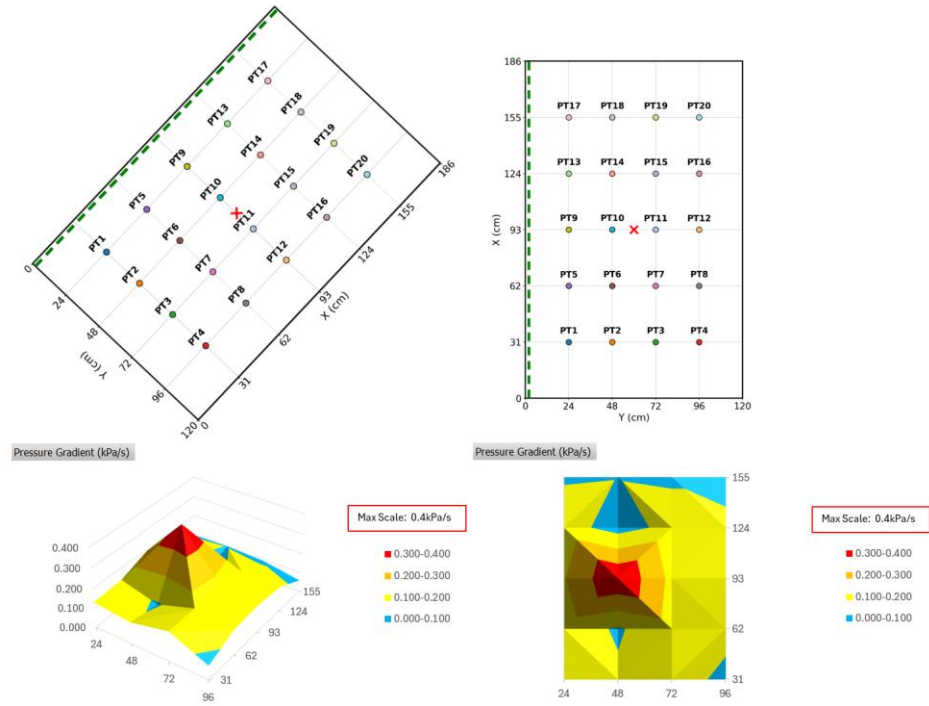


Figure 4.12: Contour map of dP/dt for $t=730-731s$ (2s after needle insertion), Experiment #1

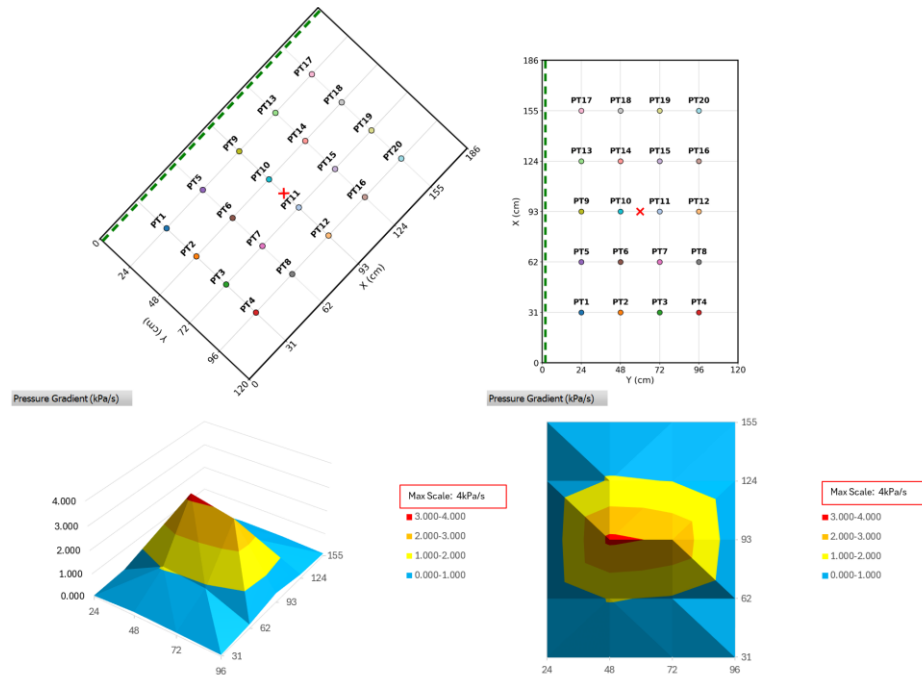


Figure 4.13: Contour map of dP/dt for $t=731-732s$ (needle extraction, peak transient leak), Experiment #1

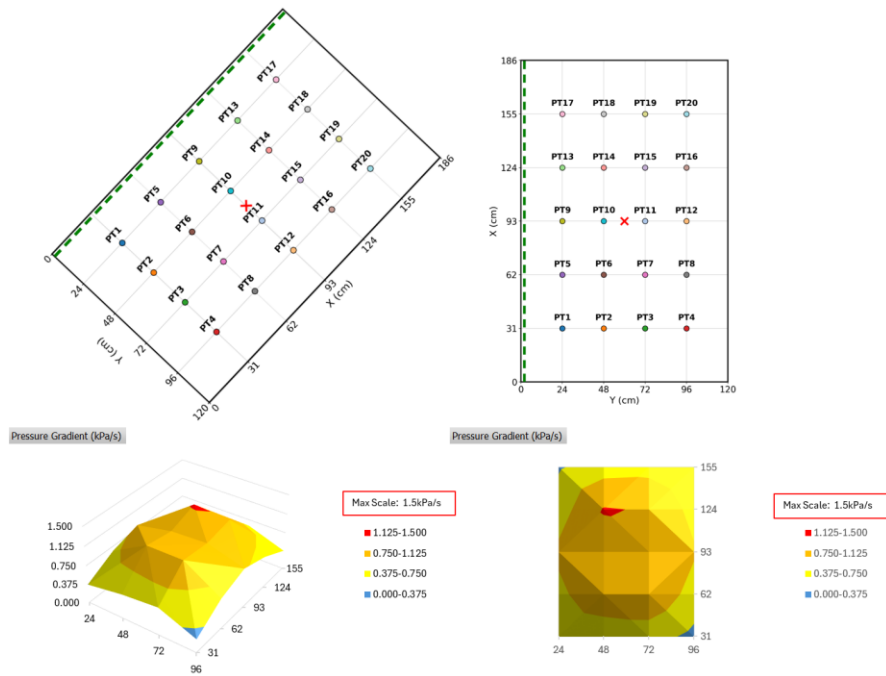


Figure 4.14: Contour map of dP/dt for $t=732-733s$ (first second after needle extraction), Experiment #1

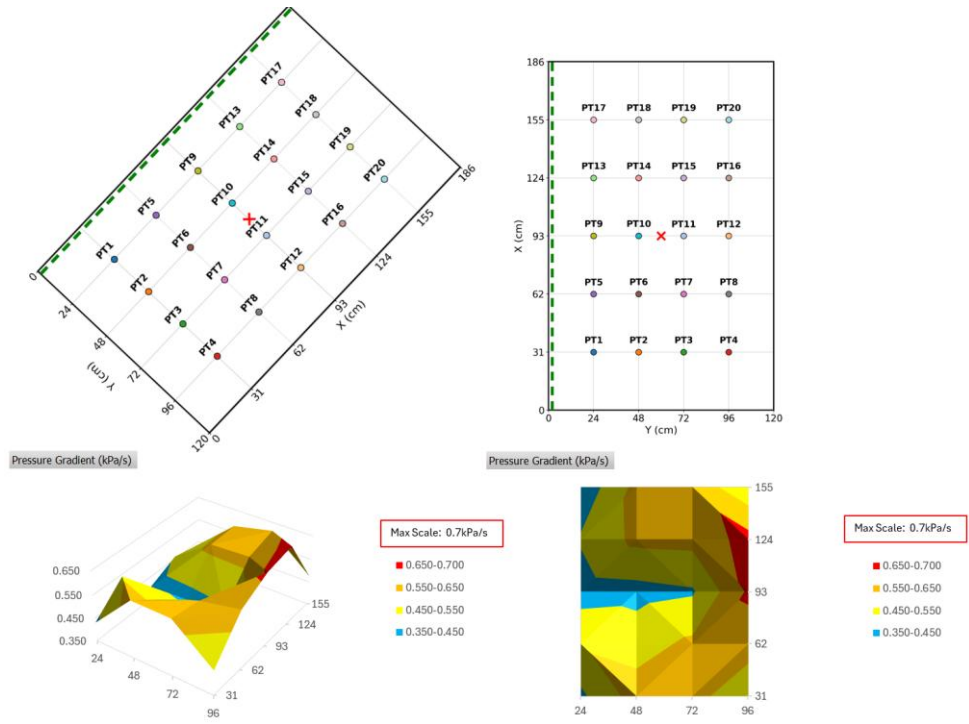


Figure 4.15: Contour map of dP/dt for $t=733-734s$ (steady leak established), Experiment #1

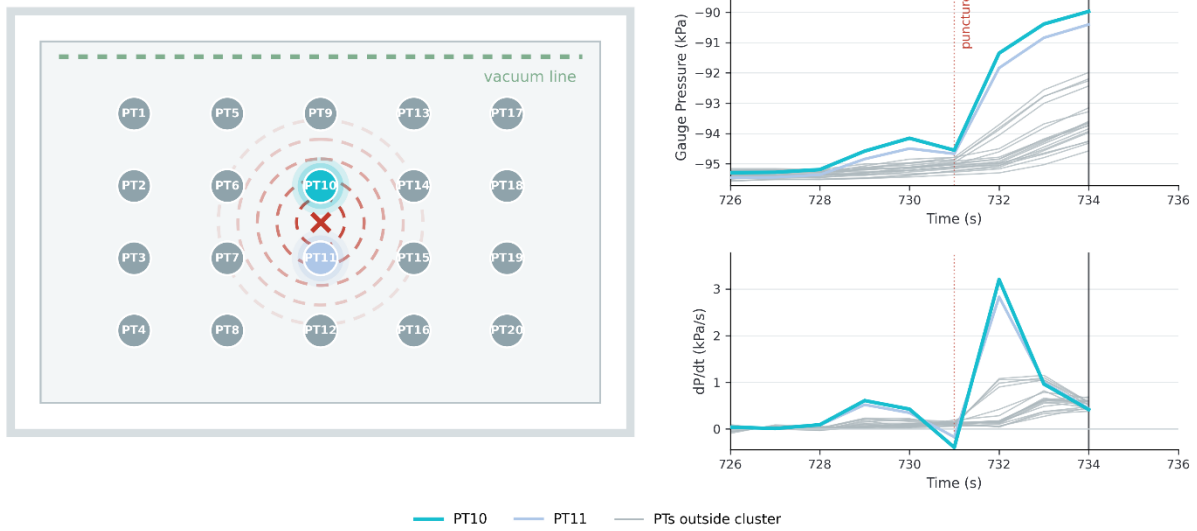


Figure 4.16: Localization window for Experiment #1 ($t=731$ to $734s$)

Considered alongside vacuum-drop test results, data from Experiment #1 indicate that the pressure response arose from two sources: a residual vacuum-line leak detected during the vacuum-drop test and the localized pinhole leak at X_1 observed during and after the puncture event.

4.2.2 Experiment #2

In Experiment #2, a pinhole was punched at location X_2 near the bottom-right corner of the fabric stack using a 0.25mm diameter needle, Figure 4.17.

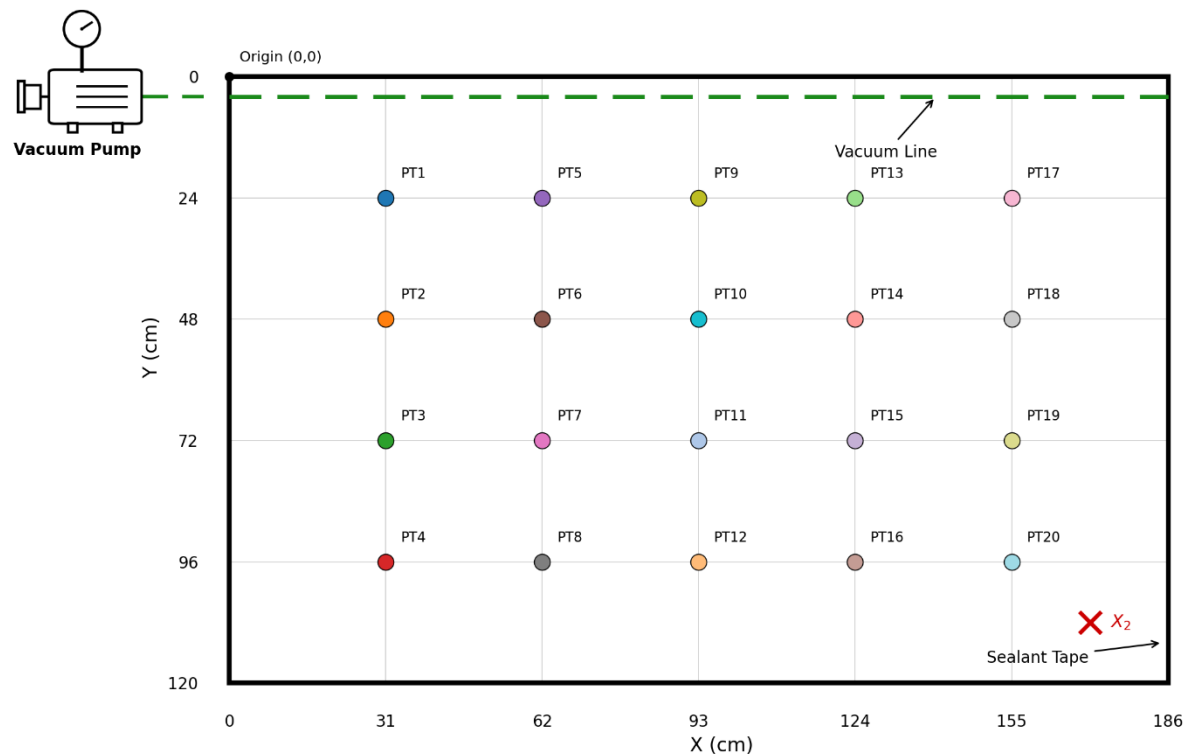


Figure 4.17: Pinhole location, Experiment #2

Figure 4.18 details key events of Experiment #2. The vacuum-drop test was conducted from $t = 30s$ to $330s$ and recorded a $5.53kPa$ rise in array-averaged gauge pressure, exceeding the $5kPa$ in 5 minutes threshold. The induced pinhole response was still localized and substantially larger than the baseline drift hence the experiment was retained. However, the failed baseline vacuum-drop test is treated as a limitation when comparing pressure-rise magnitudes with other

experiments. The induced pinhole leak drove gauge pressures across all sensors to atmospheric pressure by approximately $t = 4000$ s.

The vacuum pump was restarted at $t = 341$ s and shut off at $t = 728$ s to set the pre-puncture baseline. The needle was inserted and extracted within one second at $t = 744$ s, Figure 4.19. PT20, the transducer closest to X_2 , rose at 0.70 kPa/s, roughly three times the next-fastest rate, and remained highest as surrounding PTs followed. The transient phase spanned $t = 744$ s to 747 s, with steady-state leak phase beginning at $t = 748$ s.

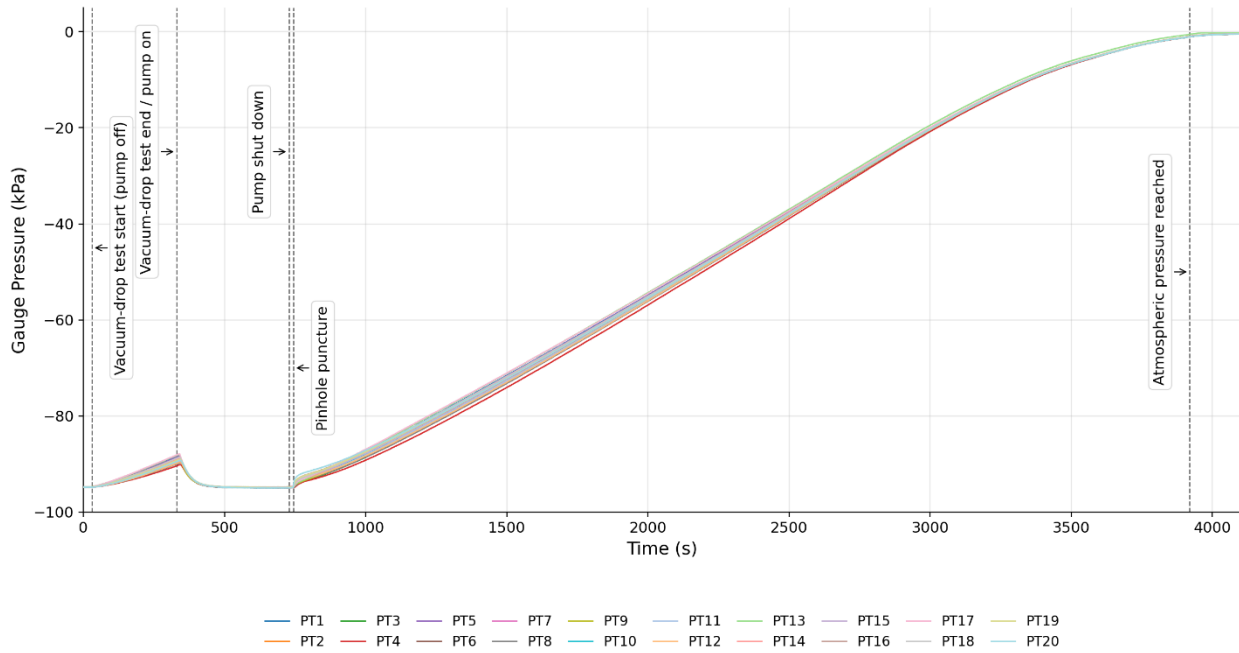


Figure 4.18: Key events, Experiment #2

Before puncture the dP/dt field is uniform and near zero across the array, Figure 4.20 . At the moment of puncture the dP/dt field shows a single peak at PT20, nearest X_2 and confirming the leak location, Figure 4.21. The leak dissipates as corner PTs equilibrate, Figure 4.22. As Figure 4.23 shows, the far-corner pinhole of Experiment #2 was resolved by a single sensor, PT20. Additional supporting figures are provided in Appendices B–E.

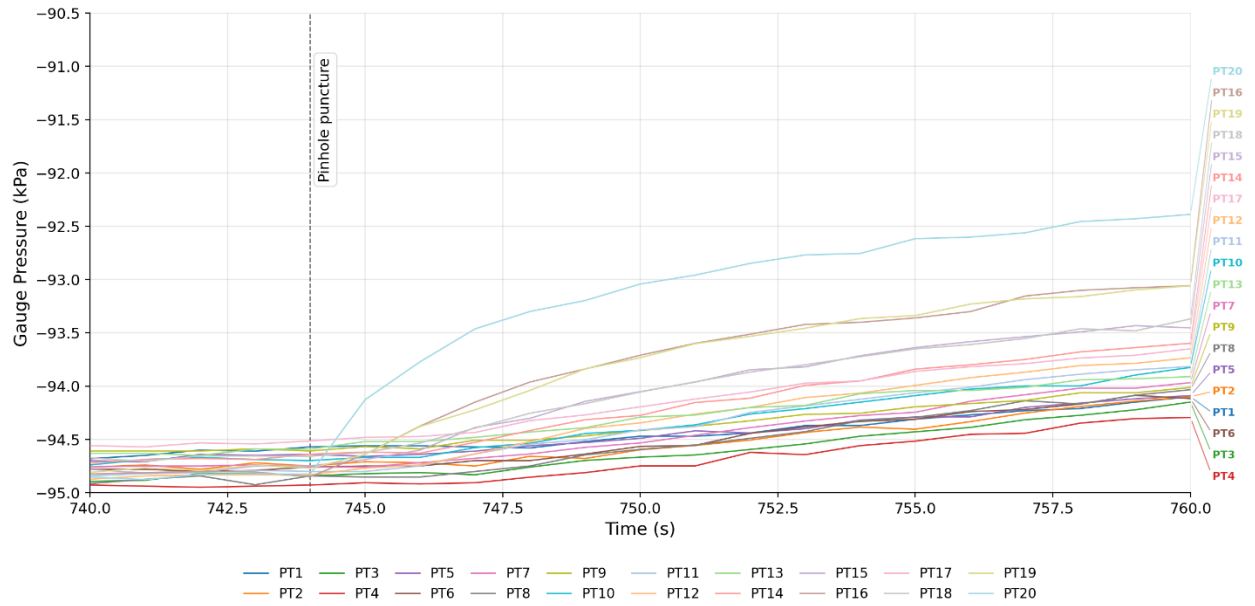


Figure 4.19: Pinhole puncture, Experiment #2

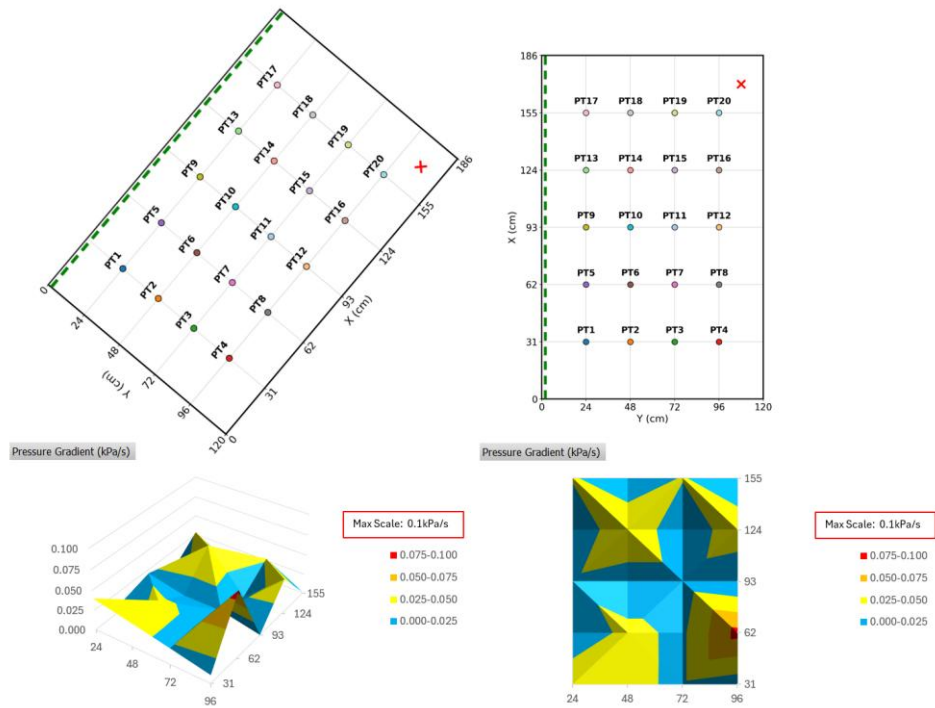


Figure 4.20: Contour map of dP/dt for $t=743-744s$ (pre-puncture baseline), Experiment #2

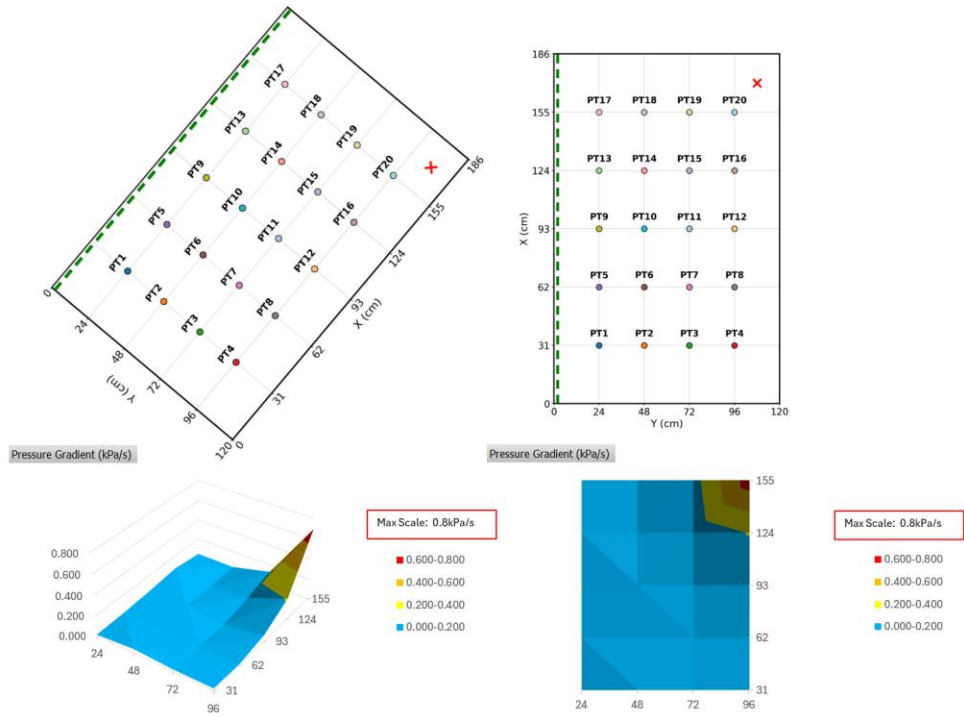


Figure 4.21: Contour map of dP/dt for $t=744-745s$ (peak transient leak), Experiment #2

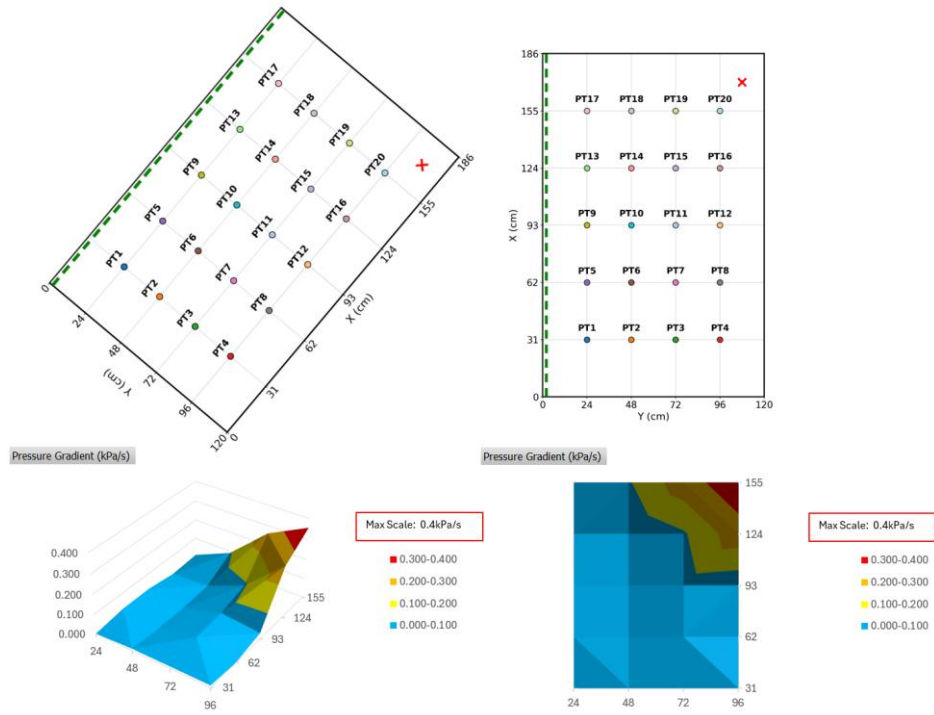


Figure 4.22: Contour map of dP/dt for $t=745-746s$ (first second of steady leak), Experiment #2

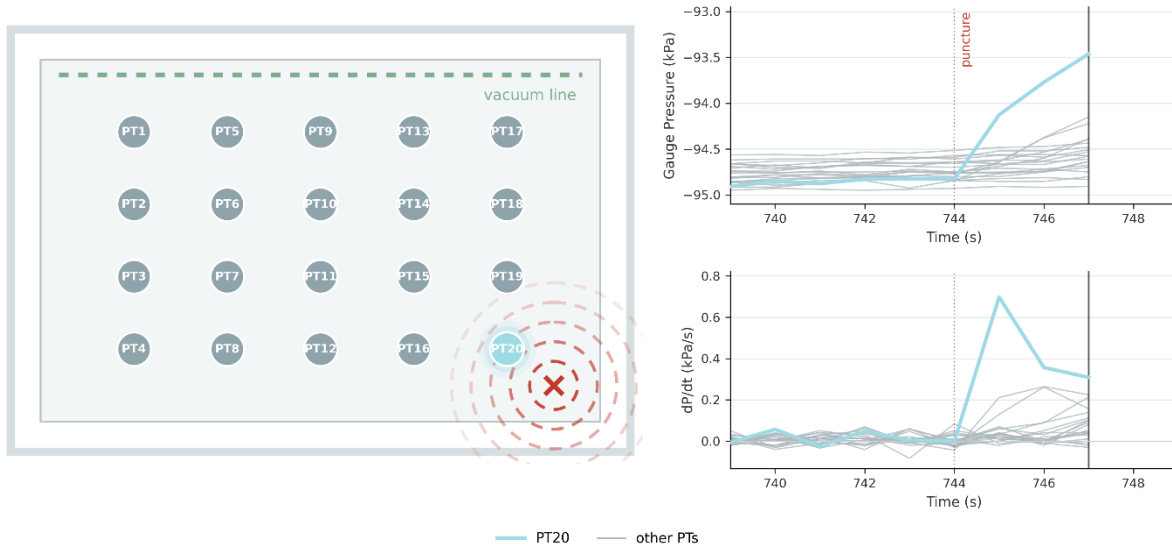


Figure 4.23: Localization window for Experiment #2 ($t=744$ to $747s$)

4.2.3 Experiment #3

In Experiment #3 a pinhole was punched at location X_3 near the upper-right corner of the fabric stack. This location is just outside the PT array and approximately 12cm below the vacuum line, Figure 4.24.

Figure 4.25 details key events of Experiment #3. The vacuum-drop test was conducted from $t = 65s$ to $365s$ and recorded a 4.04kPa rise in array-averaged gauge pressure, within acceptable industrial limits. Data acquisition stopped at $t = 5206s$; approach to atmosphere by approximately $t = 5900s$ was extrapolated from late-stage decay.

The vacuum pump was restarted at $t = 366s$ and shut off at $t = 720s$. The needle was inserted and extracted within one second at $t = 730s$, Figure 4.26. PT17, the transducer closest to X_3 , rose at 0.27kPa/s on puncture, roughly four times the next fastest rate. It peaked at 0.38kPa/s the following second and then the surrounding PTs responded. The transient phase spanned $t = 730s$ to $732s$, with steady-state leak phase beginning at $t = 733s$.

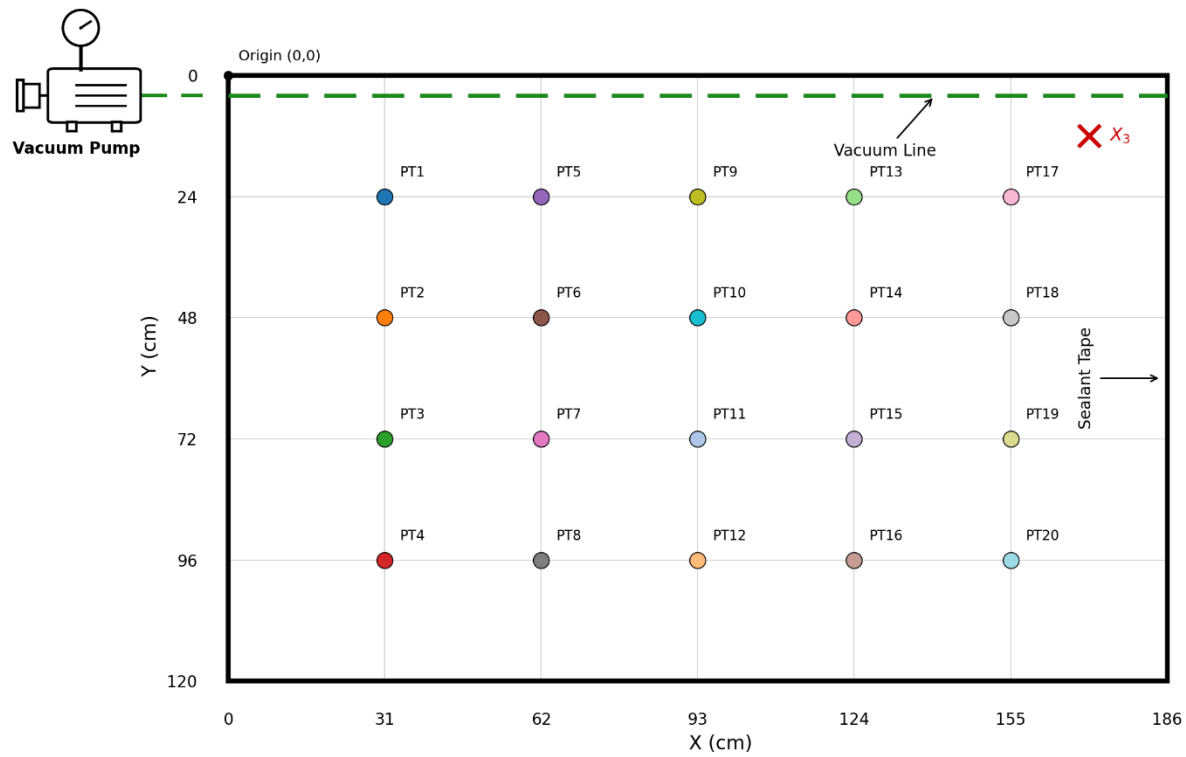


Figure 4.24: Pinhole location, Experiment #3

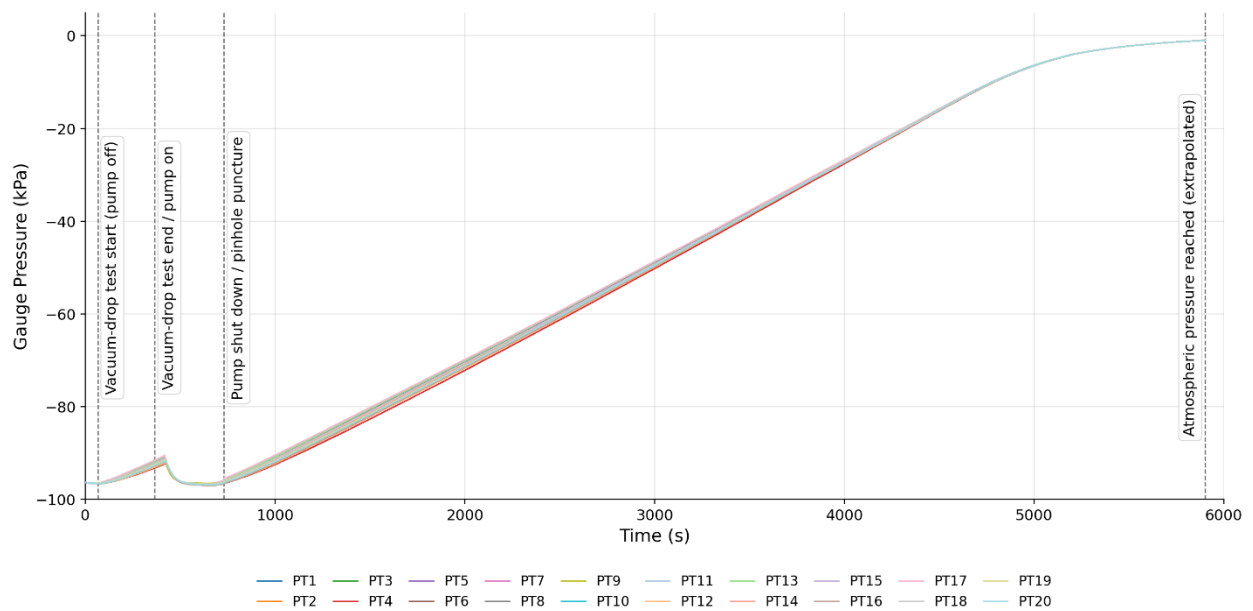


Figure 4.25: Key events, Experiment #3

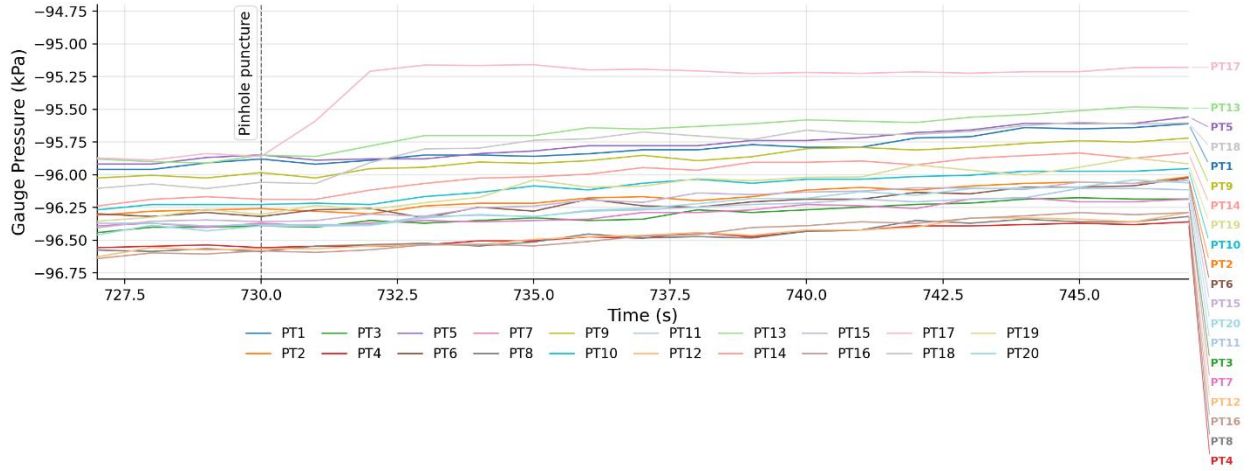


Figure 4.26: Pinhole puncture event, Experiment #3

Before puncture the dP/dt field is uniform and near zero across the array, Figure 4.27. One second after puncture the dP/dt field shows a single peak at PT17, nearest X_3 and confirming leak location, Figure 4.28. The leak dissipates as surrounding PTs equilibrate, Figure 4.29. Figure 4.30 presents Experiment #3, where PT17 peaked at 0.38kPa/s. Additional supporting figures are provided in Appendices B–E.

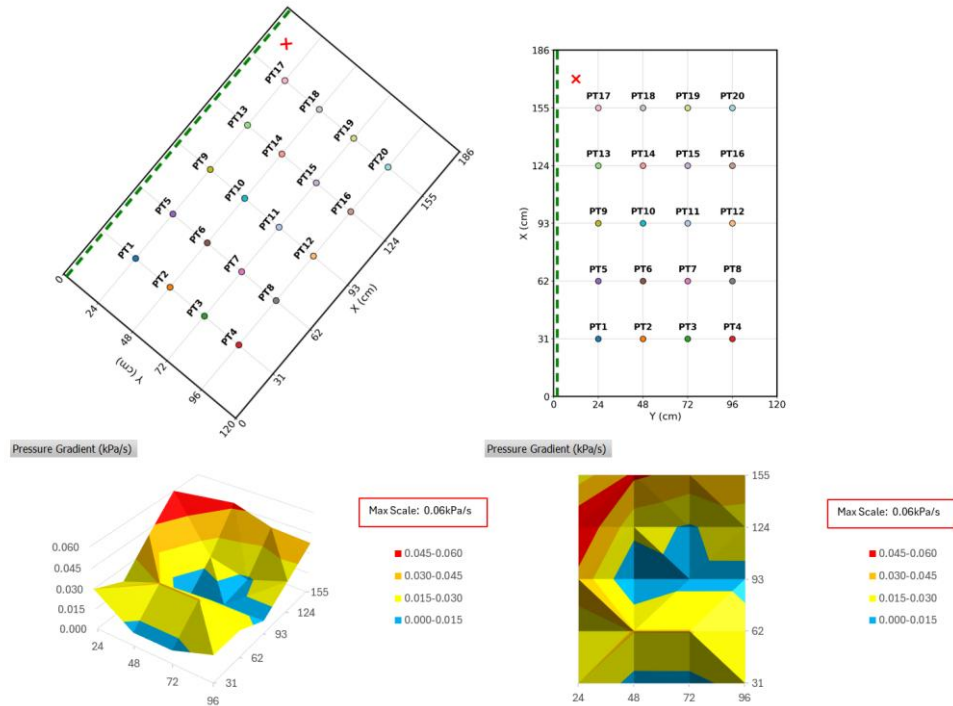


Figure 4.27: Contour map of dP/dt for $t=729-730s$ (pre-puncture baseline), Experiment #3

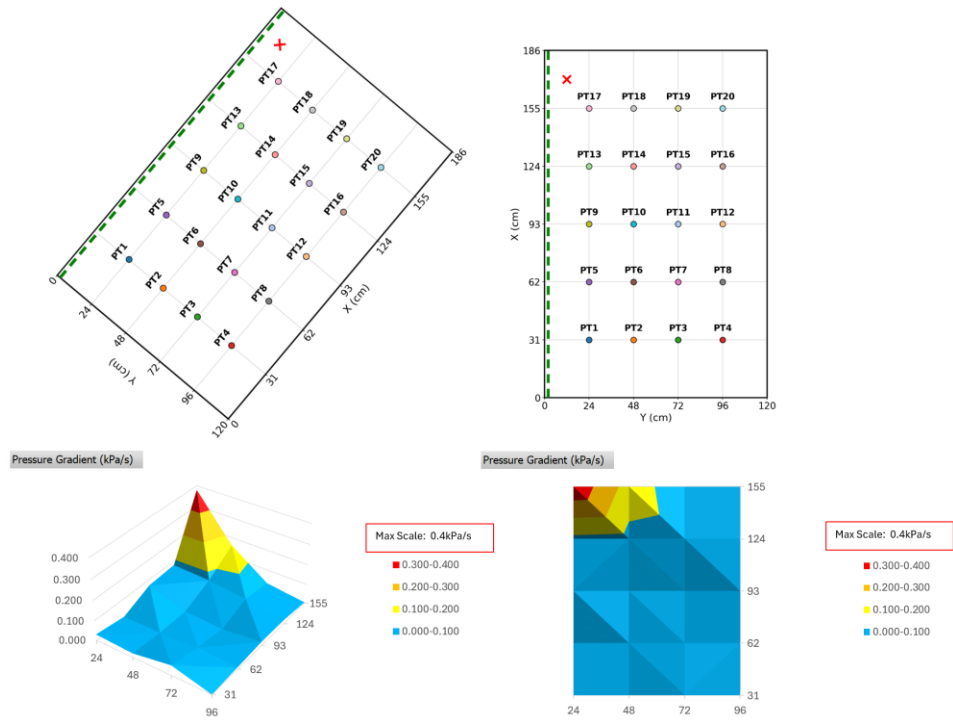


Figure 4.28: Contour map of dP/dt for $t=731-732s$ (peak transient leak), Experiment #3

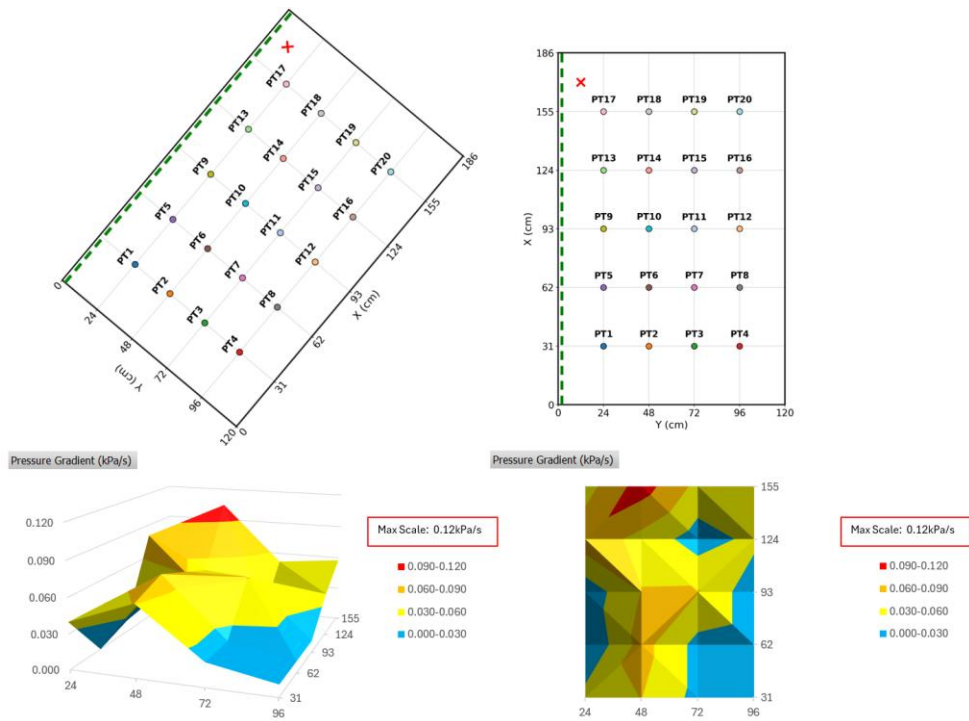


Figure 4.29: Contour map of dP/dt for $t=732-733s$ (first second of steady leak), Experiment #3

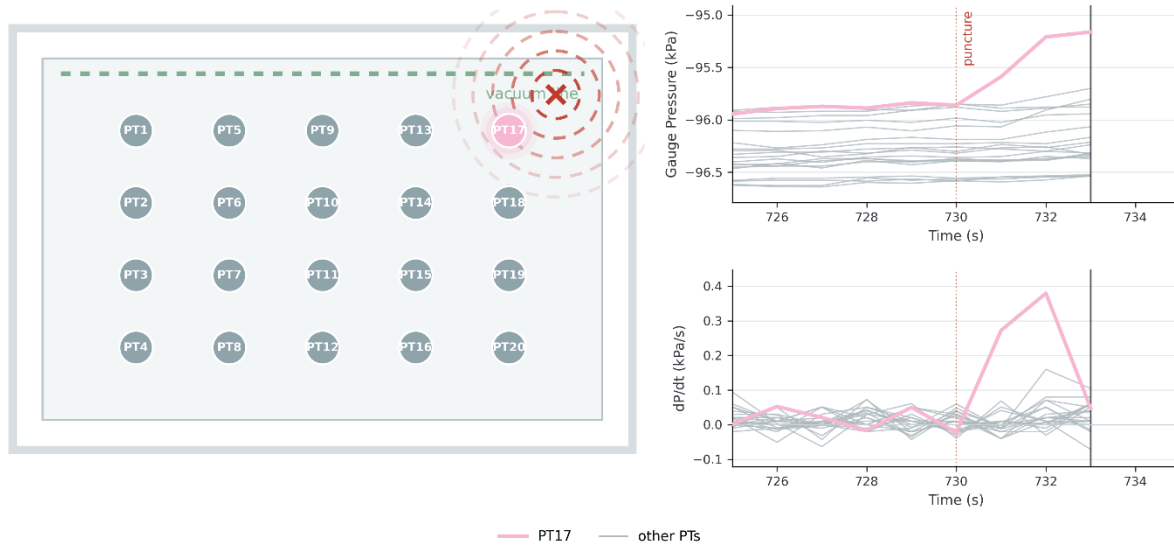


Figure 4.30: Localization window for Experiment #3 ($t=730$ to $733s$)

4.3 Experiments Using 0.14mm Diameter Needle

Results from Experiments #1 to #3 motivated a reduction in needle diameter from 0.25mm to 0.14mm. The 0.25mm punctures generated strong and unambiguous pressure-rate signatures, especially Experiment #1, which were useful for validating array response. A narrower diameter was therefore intended to produce a smaller less detectable leak, presenting a more demanding test of the localization method. The 0.14mm diameter needle was therefore used for Experiments #4 to #14 to generate smaller induced leaks more representative of leaks which industry needs to detect and localize.

4.3.1 Experiment #4

In Experiment #4 two pinholes were punched in sequence at the geometric centre of the fabric stack, using a 0.14mm diameter needle. The two punctures were approximately 1cm apart, Figure 4.31.

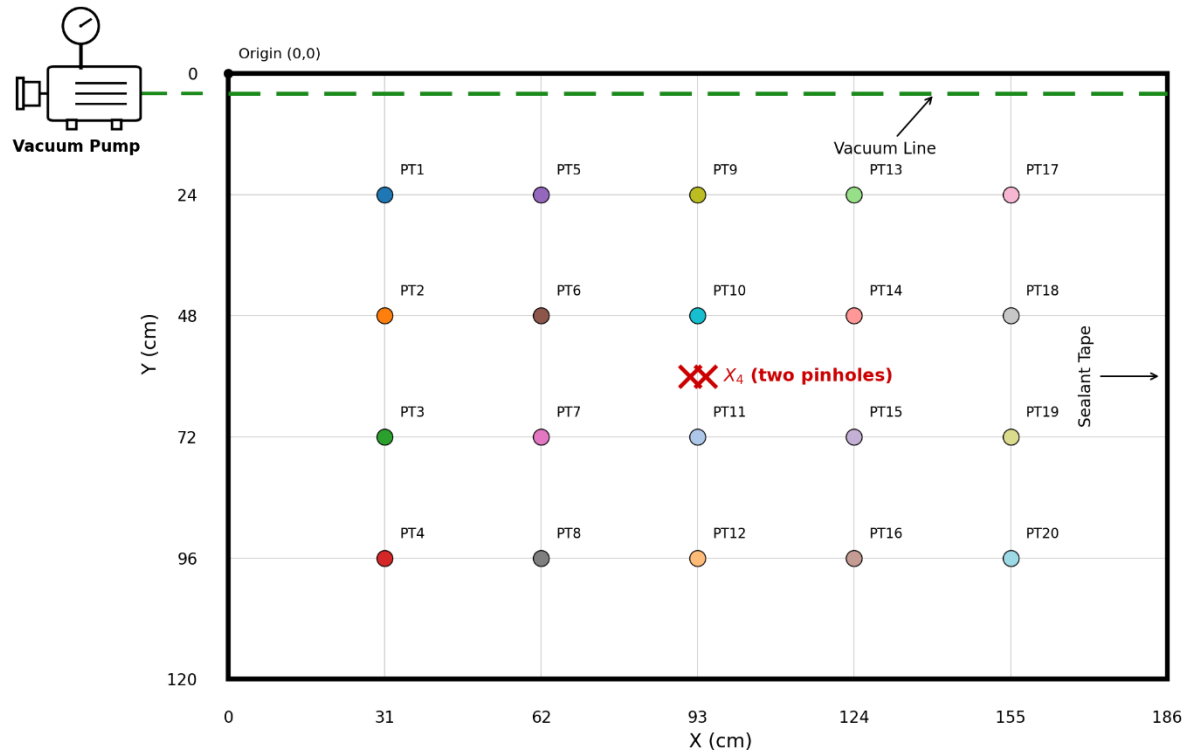


Figure 4.31: Pinhole locations, Experiment #4

Figure 4.32 shows key events in Experiment #4. The vacuum-drop test, conducted from $t = 131$ s to 431 s, recorded a 3.41 kPa rise, within acceptable industrial limits. The vacuum pump was restarted at $t = 555$ s and shut off at $t = 735$ s to set the pre-puncture baseline. The first and second pinholes were punched at $t = 784$ s and $t = 905$ s, respectively. The induced leaks drove gauge pressures across all sensors to atmospheric pressure by approximately $t = 5089$ s.

The first pinhole was punched at $t = 784$ s, Figure 4.33. PT11 and PT10, the PTs closest to X_4 , separated immediately from the rest of the array and peaked at 0.40 kPa/s and 0.38 kPa/s in the following second, ranking first and second across the twenty PTs; the next fastest, PT15 and PT6, trailed at about half that rate. The transient phase spanned $t = 784$ s to 786 s, with the steady-state leak phase beginning at $t = 787$ s.

The gauge pressures responded slowly suggesting that the first pinhole may not have fully penetrated the vacuum film. Therefore, a second pinhole was punched at $t = 905$ s, approximately 1 cm from the first, Figure 4.34. PT11 and PT10 again led, peaking at 0.82 kPa/s and 0.79 kPa/s in

the following second. The transient phase spanned $t = 905\text{s}$ to 907s , with the steady-state leak phase beginning at $t = 908\text{s}$.

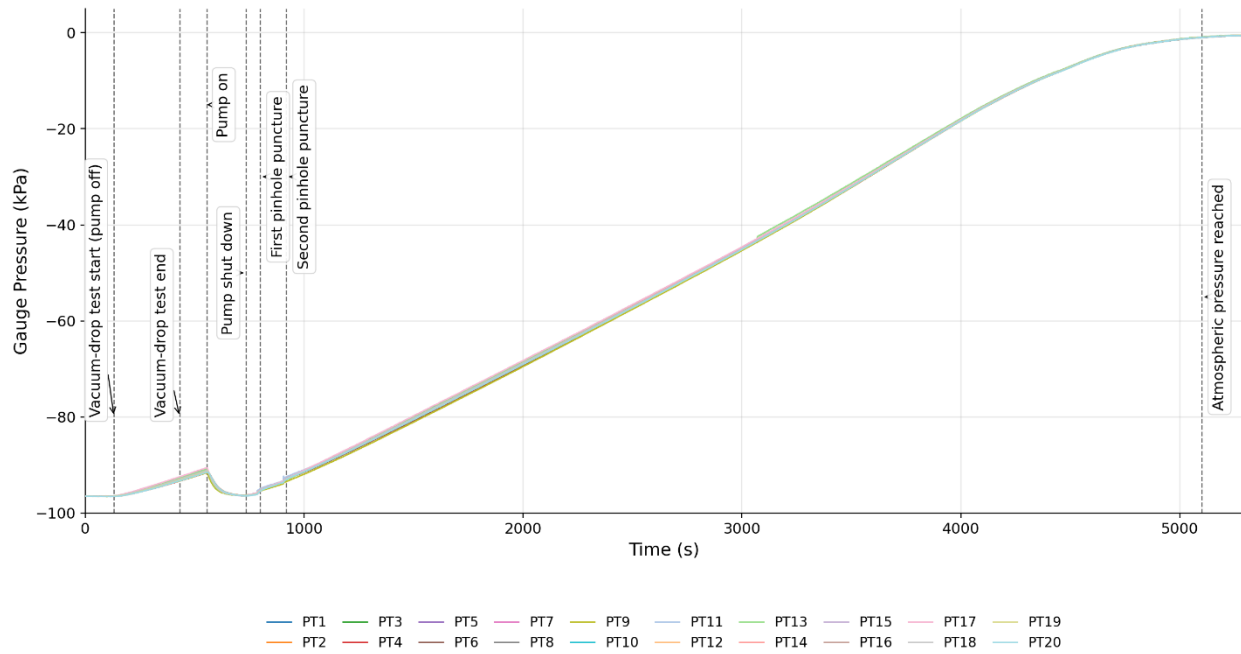


Figure 4.32: Key events, Experiment #4

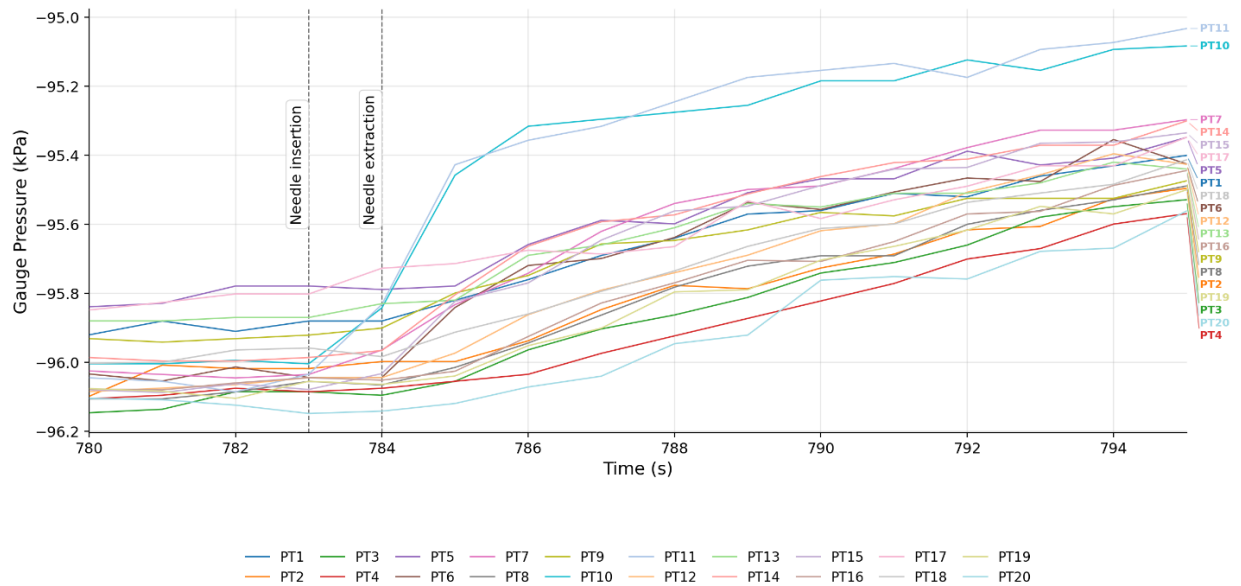


Figure 4.33: First pinhole puncture event, Experiment #4

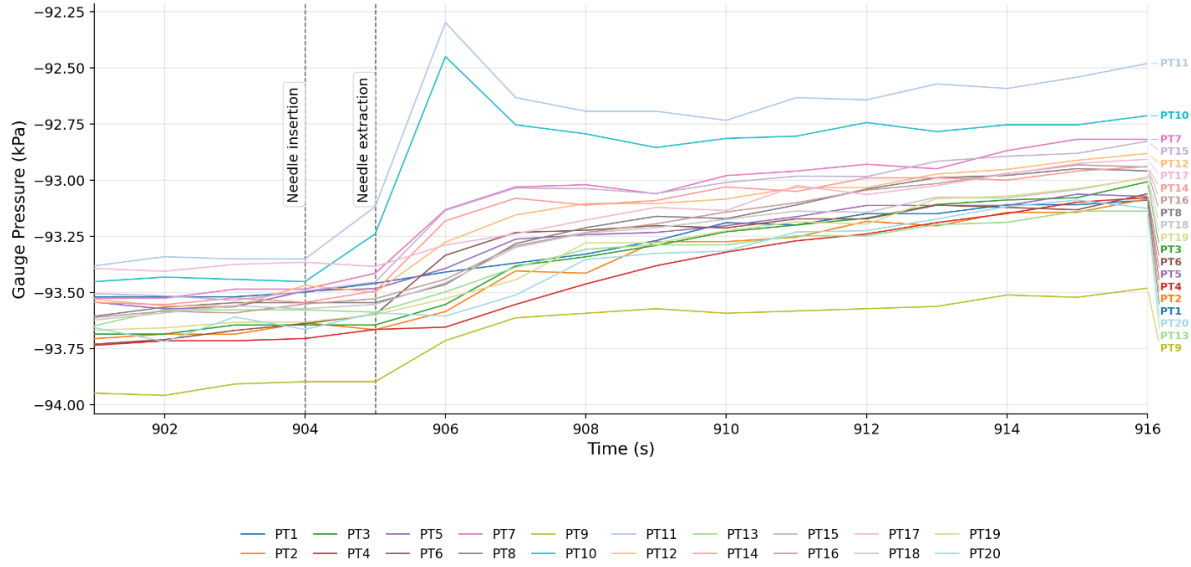


Figure 4.34: Second pinhole puncture event, Experiment #4

Before the first puncture the dP/dt field is uniform and near zero across the array, Figure 4.35, the reference against which puncture effects are read.

In the second following extraction the field shows a single peak at PT10 and PT11 at the centre, nearest X_4 , with a secondary ring of surrounding PTs, Figure 4.36. The peak then dissipates as the central region equilibrates, Figure 4.37. Figure 4.38 shows the localization window of the first of two punctures performed in Experiment #4.

The second puncture shows the same signature, Figure 4.39 to Figure 4.41: uniform before puncture, pronounced peak again centred on PT10 and PT11 in the second following extraction, then dissipation as signal spreads outward. Figure 4.42 shows the complete three-second window for Experiment #4. Additional supporting figures are provided in Appendices B–E.

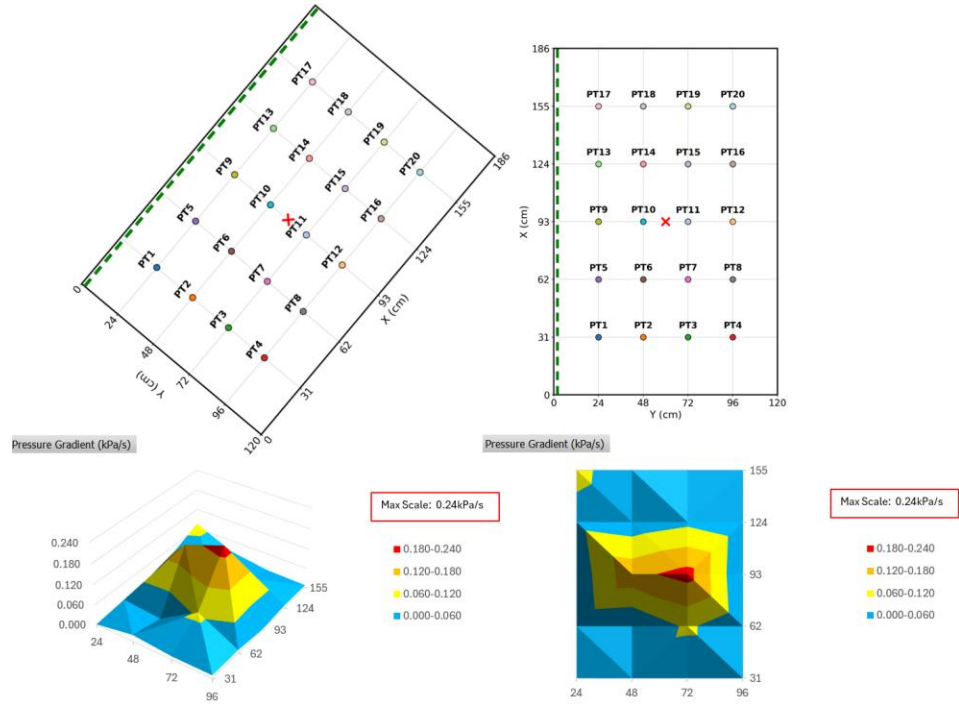


Figure 4.35: Contour map of dP/dt for $t = 783-784s$ (pre-puncture baseline), Experiment #4 first puncture

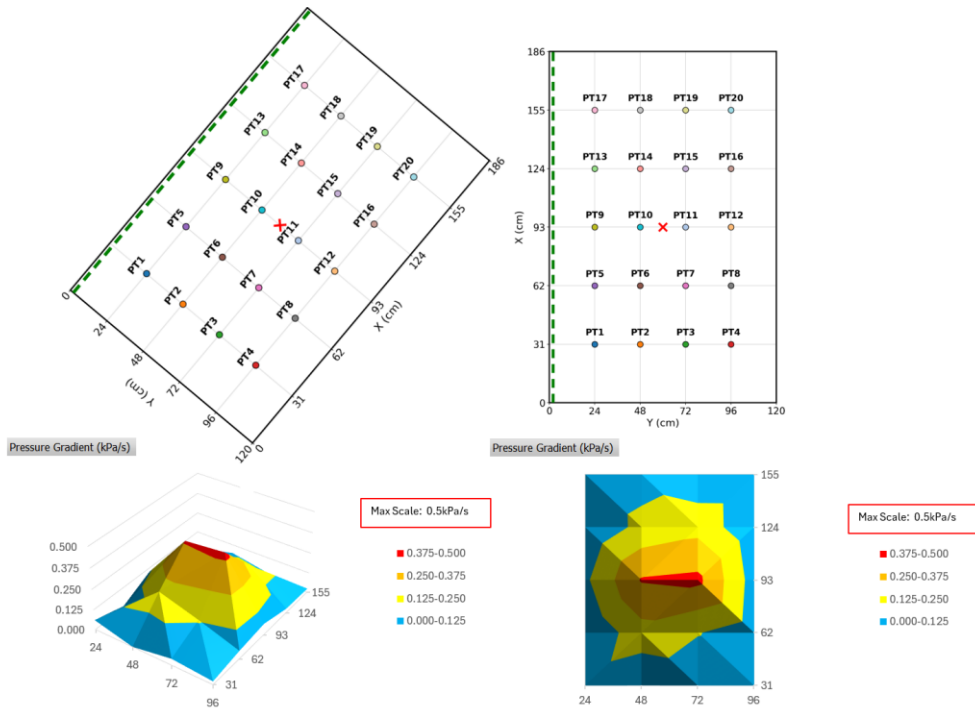


Figure 4.36: Contour map of dP/dt for $t = 784-785s$ (peak transient leak), Experiment #4 first puncture

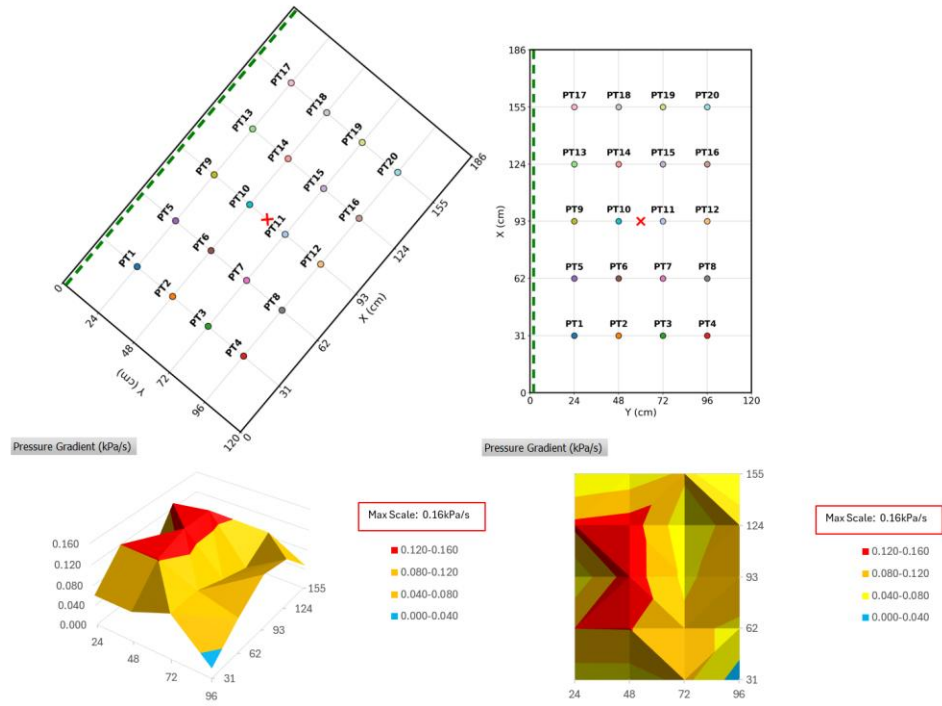


Figure 4.37: Contour map of dP/dt for $t = 785-786$ s (first second of steady leak), Experiment #4 first puncture

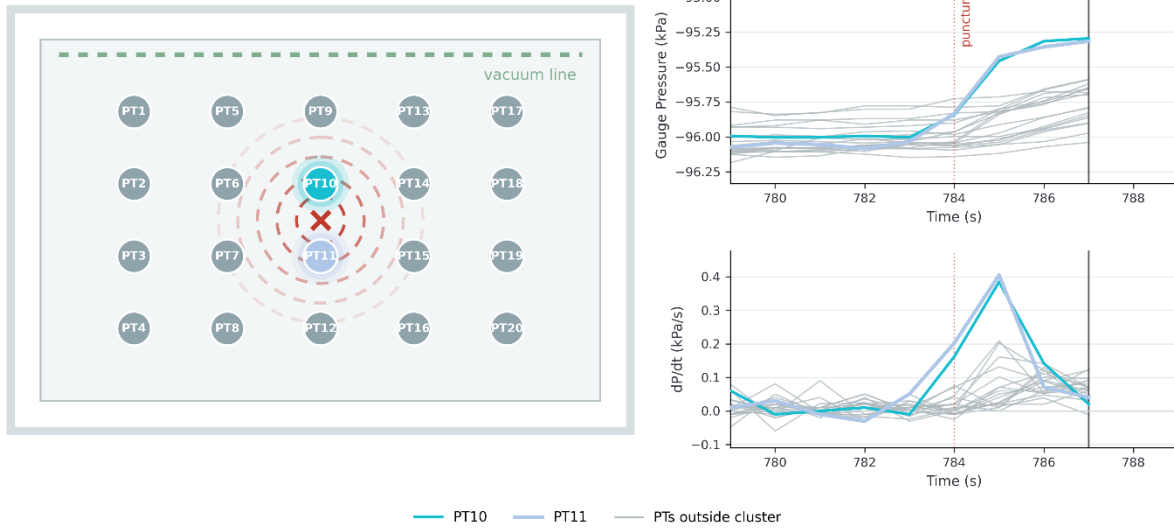


Figure 4.38: Localization window for the first puncture of Experiment #4 ($t = 784$ to 787 s)

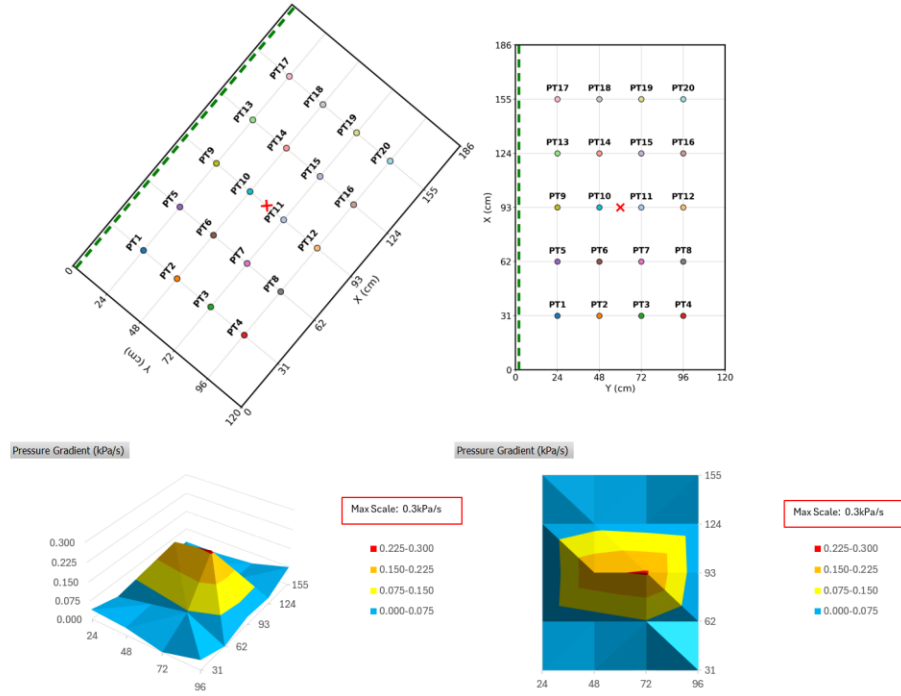


Figure 4.39: Contour map of dP/dt for $t = 904-905s$ (pre-puncture baseline), Experiment #4 second puncture

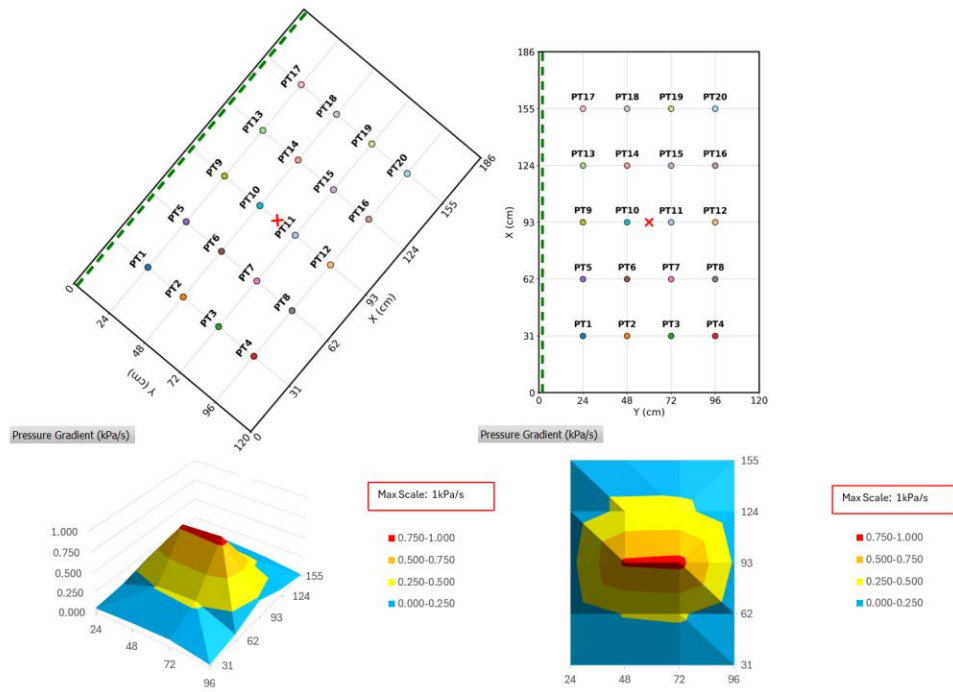


Figure 4.40: Contour map of dP/dt for $t = 905-906s$ (peak transient leak), Experiment #4 second puncture

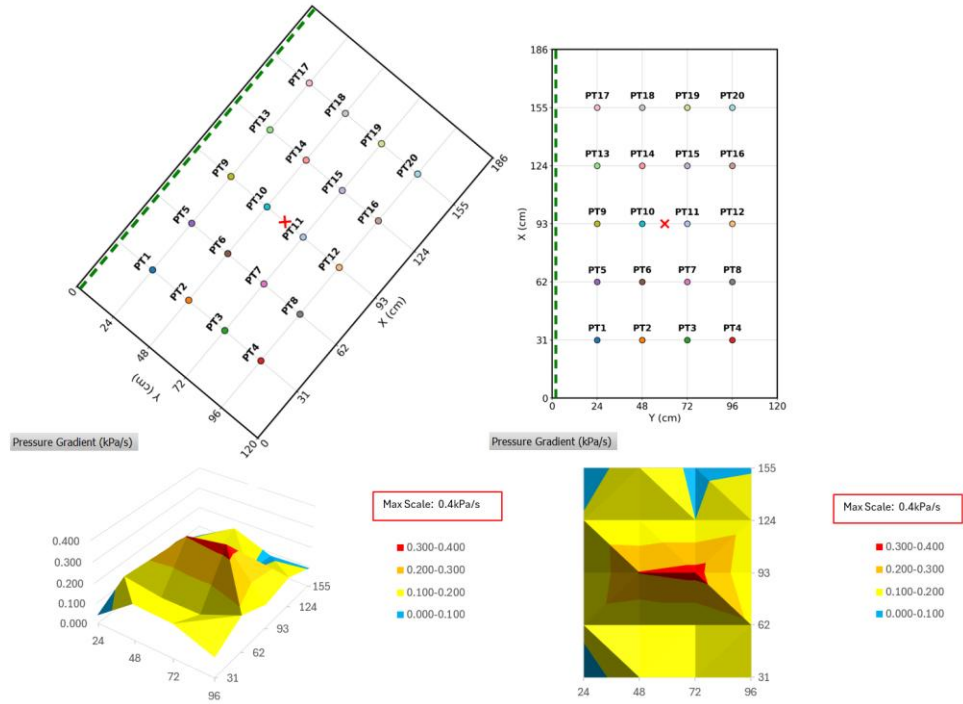


Figure 4.41: Contour map of dP/dt for $t = 906-907s$ (first second of steady leak), Experiment #4 second puncture

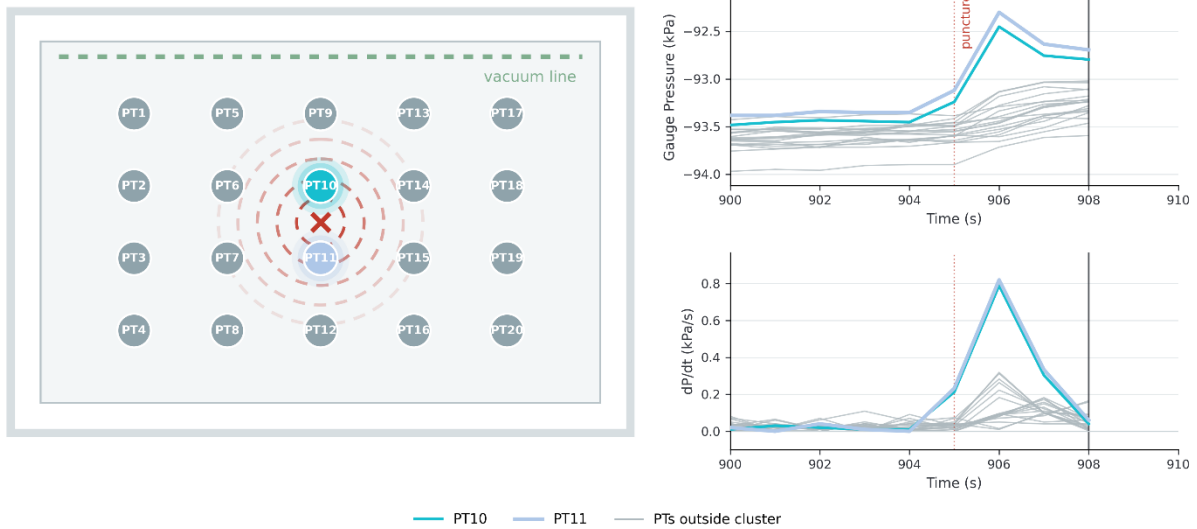


Figure 4.42: Localization window for the second puncture of Experiment #4 ($t=905$ to $908s$)

4.3.2 Experiment #5

In Experiment #5 a single pinhole was punched at location X_5 at the geometric centre of the fabric stack using a 0.14mm diameter needle, Figure 4.43.

Figure 4.44 details key events of Experiment #5. The vacuum-drop test was conducted from $t = 184\text{s}$ to 484s and recorded a 4.52kPa rise in array-averaged gauge pressure, within acceptable industrial limits. The induced pinhole leak drove gauge pressures across all PTs to atmospheric pressure by approximately $t = 4540\text{s}$.

The vacuum pump was restarted at $t = 485\text{s}$ and shut off at $t = 795\text{s}$. The pinhole was punctured at $t = 838\text{s}$, Figure 4.45. PT11 and PT10, the PTs closest to X_5 , rose at 0.77kPa/s and 0.50kPa/s respectively, roughly three times the next fastest rate. Both remained the highest as the surrounding PTs responded. The transient phase spanned $t = 838\text{s}$ to 840s , with steady-state leak phase beginning at $t = 841\text{s}$.

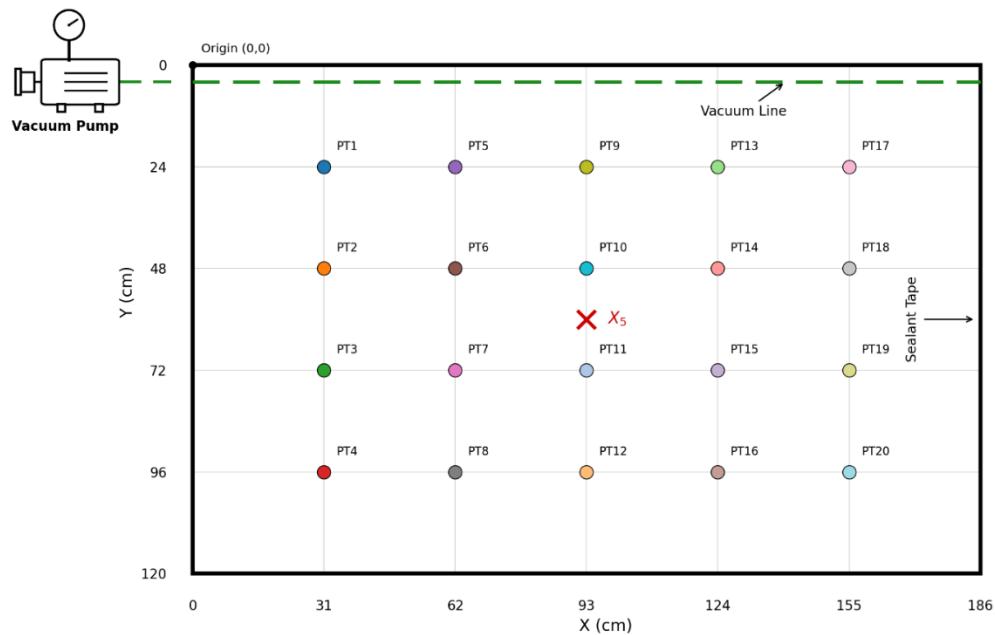


Figure 4.43: Pinhole location, Experiment #5

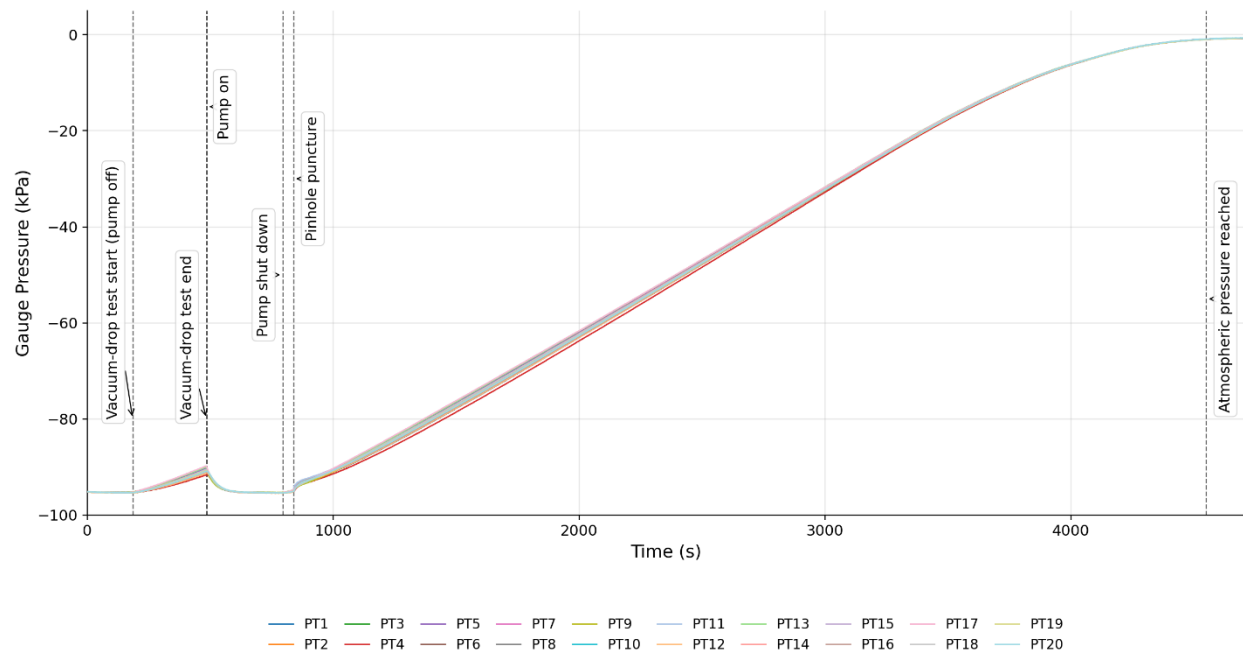


Figure 4.44: Key events, Experiment #5

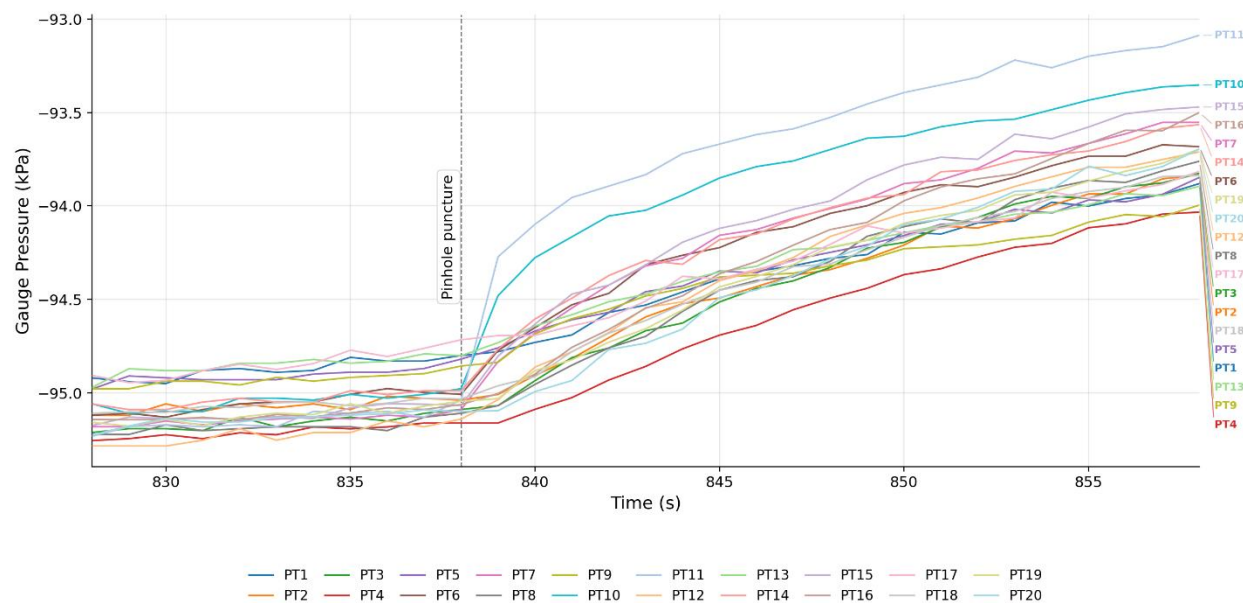


Figure 4.45: Pinhole puncture event, Experiment #5

Before puncture the dP/dt field is uniform and near zero across the array, Figure 4.46. At the moment of puncture the dP/dt field shows a peak centred on PT11 and PT10, nearest X_s and confirming leak location, Figure 4.47. The leak dissipates as central PTs equilibrate, Figure 4.48. The centre repeat in Figure 4.49 reproduced the previous result, with PT11 again leading. Additional supporting figures are provided in Appendices B–E.

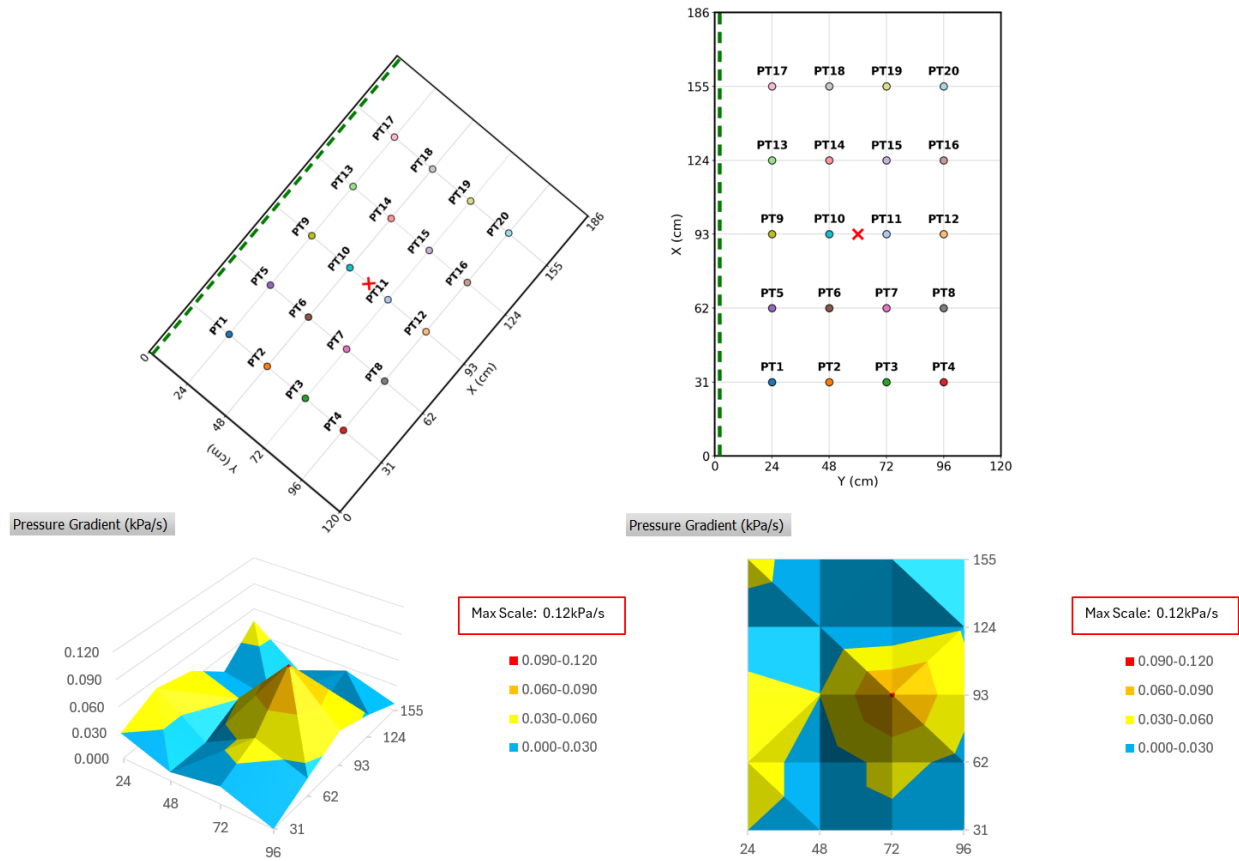


Figure 4.46: Contour map of dP/dt for $t = 837-838s$ (pre-puncture baseline), Experiment #5

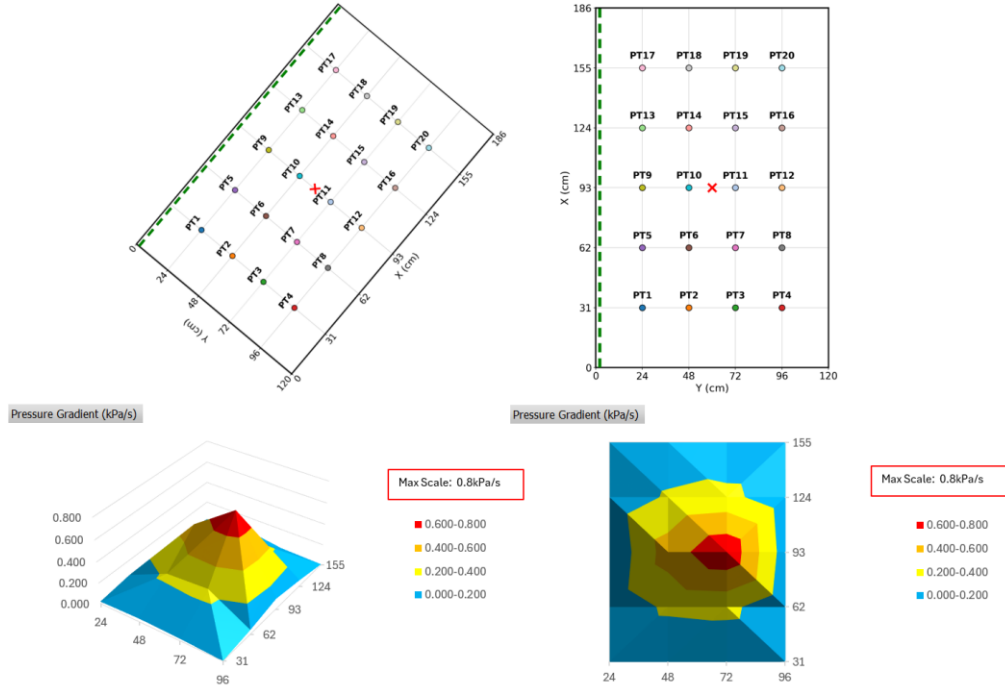


Figure 4.47: Contour map of dP/dt for $t = 838-839s$ (peak transient leak), Experiment #5

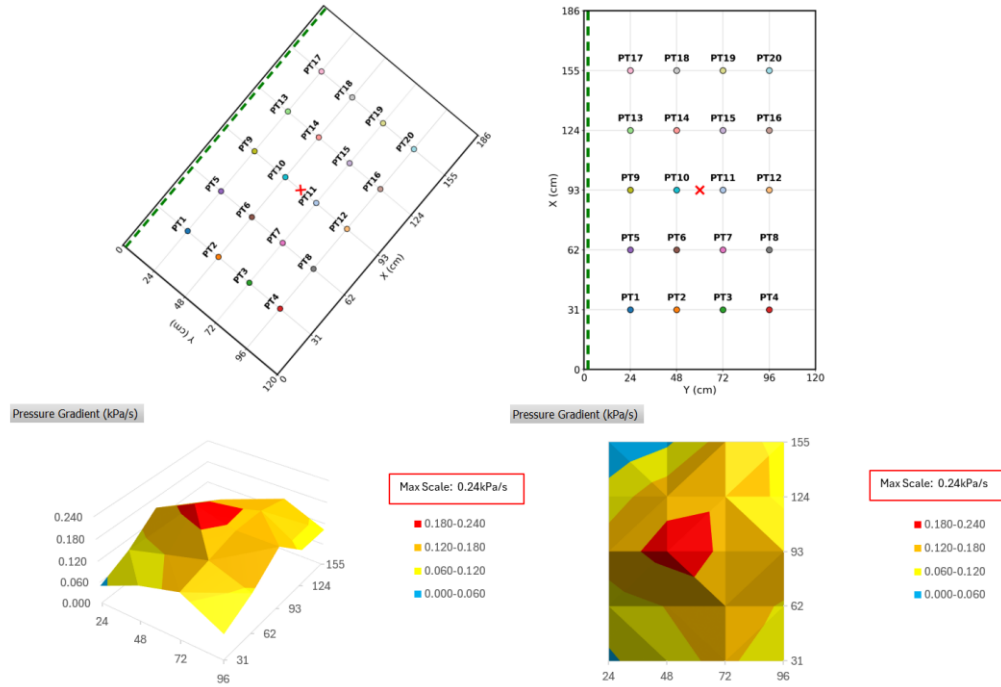


Figure 4.48: Contour map of dP/dt for $t = 839-840s$ (first second of steady leak), Experiment #5

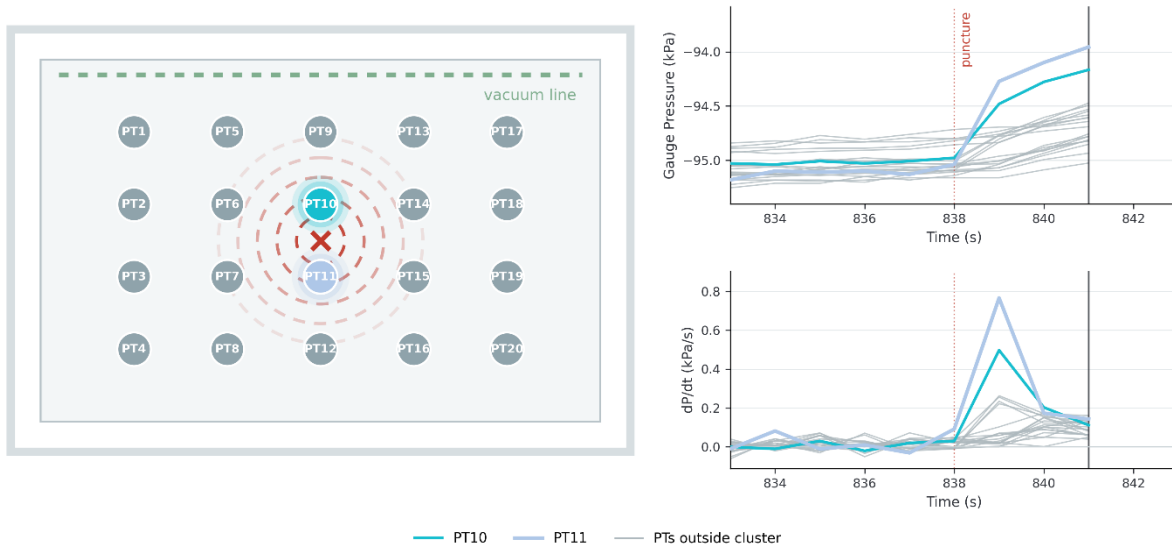


Figure 4.49: Localization window for Experiment #5 ($t=838$ to 841 s)

4.3.3 Experiment #6

In Experiment #6 a pinhole was punched at location X_6 near the upper-right corner of the fabric stack using a 0.14mm diameter needle. This location is just outside the PT array and approximately 12cm below the vacuum line, Figure 4.50.

Figure 4.51 details key events of Experiment #6. The vacuum-drop test was conducted from $t = 131$ s to 431 s and recorded a 4.67kPa rise in array-averaged gauge pressure. Data acquisition stopped at $t = 3827$ s; approach to atmosphere by approximately $t = 4340$ s was extrapolated from late-stage decay.

The vacuum pump was restarted at $t = 432$ s and shut off at $t = 670$ s. The pinhole was punched at $t = 726$ s, Figure 4.52. PT17, the transducer closest to X_6 , rose at 0.79kPa/s, more than seven times the next-fastest rate. It remained the highest as the surrounding PTs responded. The transient phase spanned $t = 726$ s to 729 s, with steady-state leak phase beginning at $t = 730$ s.

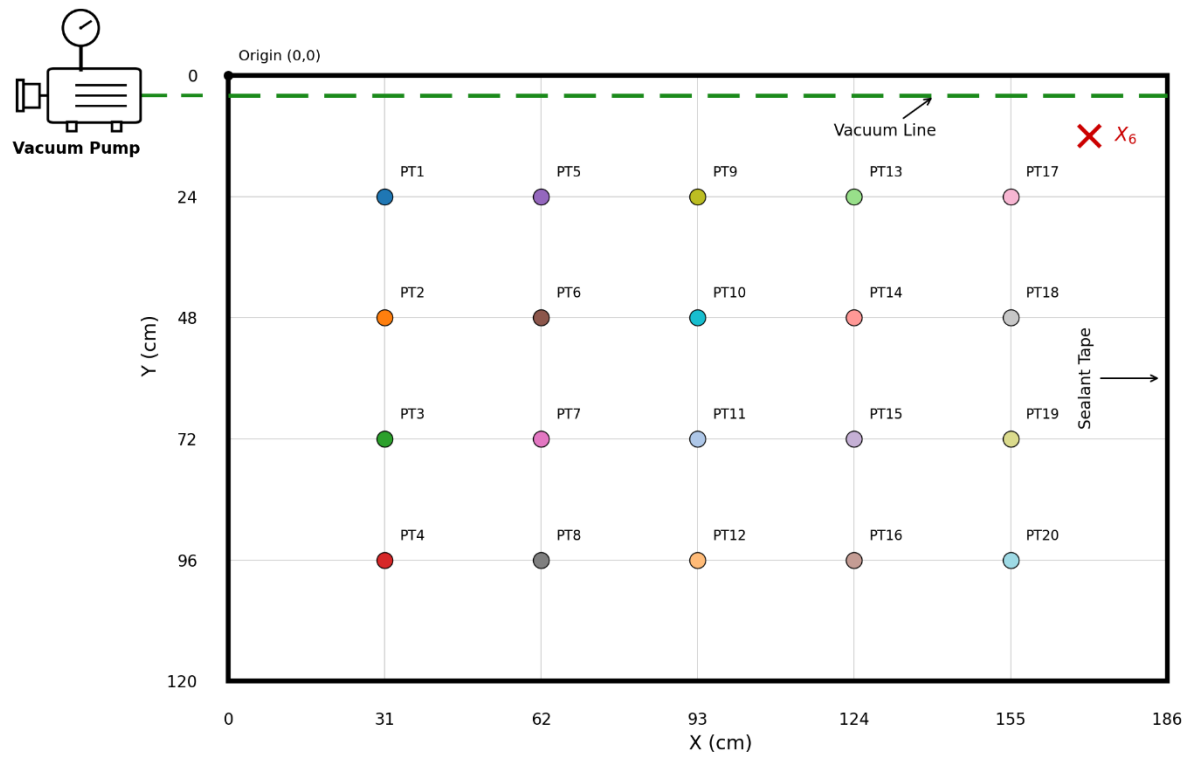


Figure 4.50: Pinhole location, Experiment #6

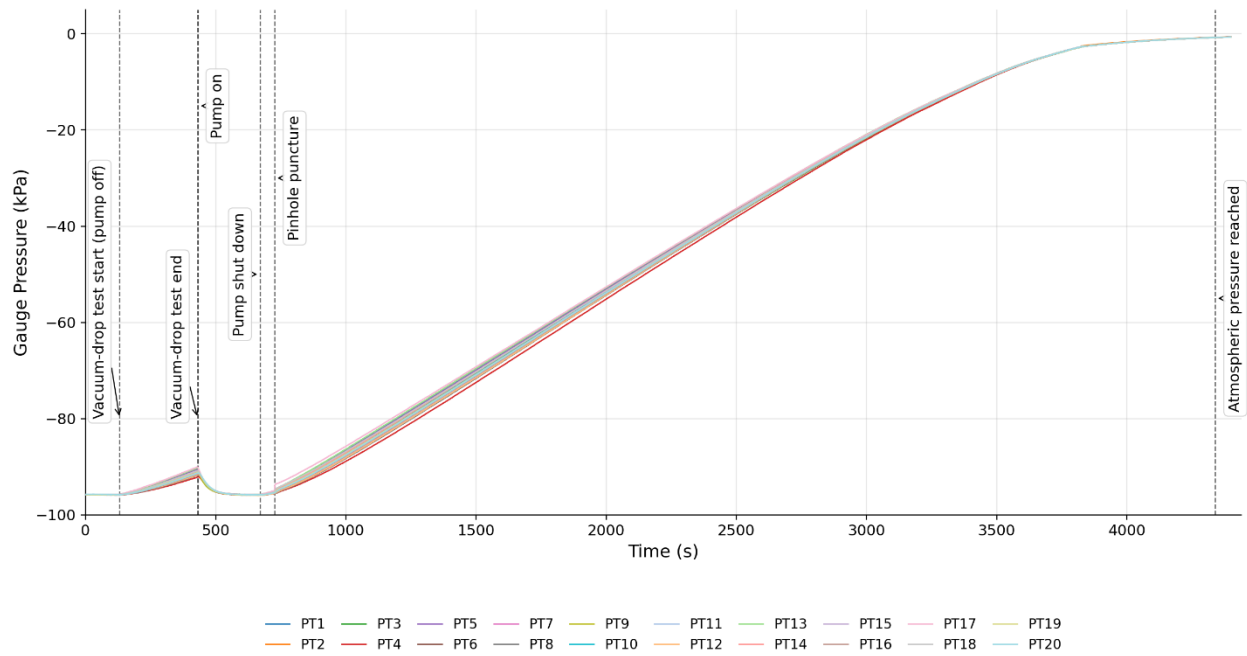


Figure 4.51: Key events, Experiment #6

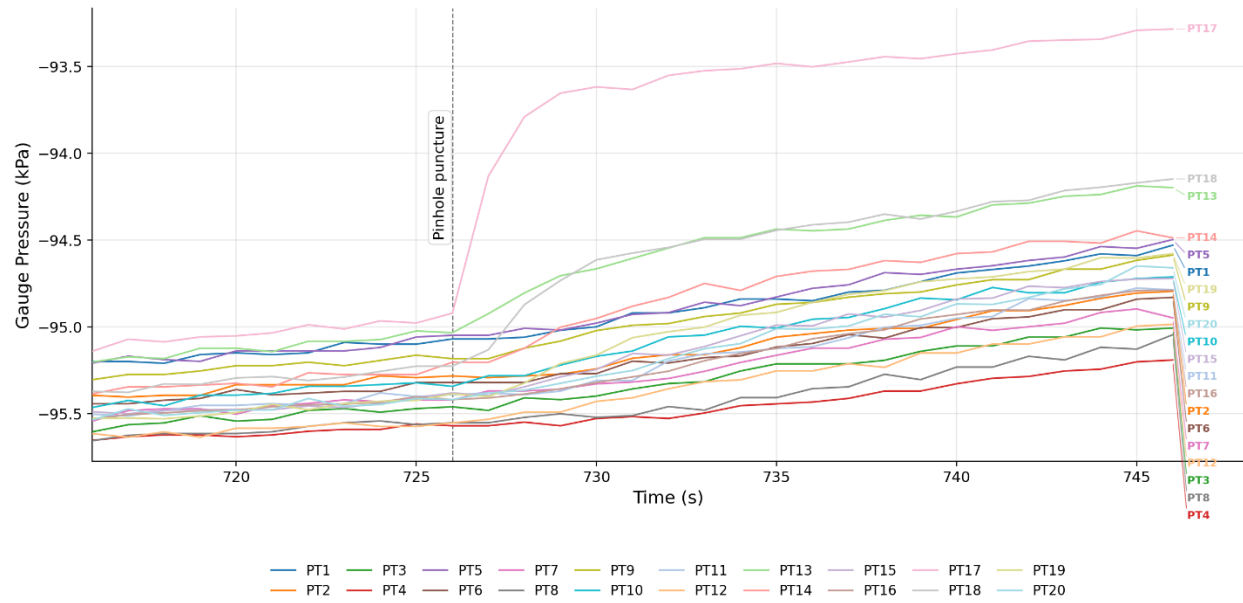


Figure 4.52: Pinhole puncture event, Experiment #6

Before puncture the dP/dt field is uniform and near zero across the array, Figure 4.53. At the moment of puncture the dP/dt field shows a single peak at PT17, nearest X_6 and confirming leak location, Figure 4.54. The leak dissipates as surrounding PTs equilibrate, Figure 4.55. Figure 4.56 shows Experiment #6, where the 0.14mm needle at the same corner as Experiment #3. Additional supporting figures are provided in Appendices B–E.

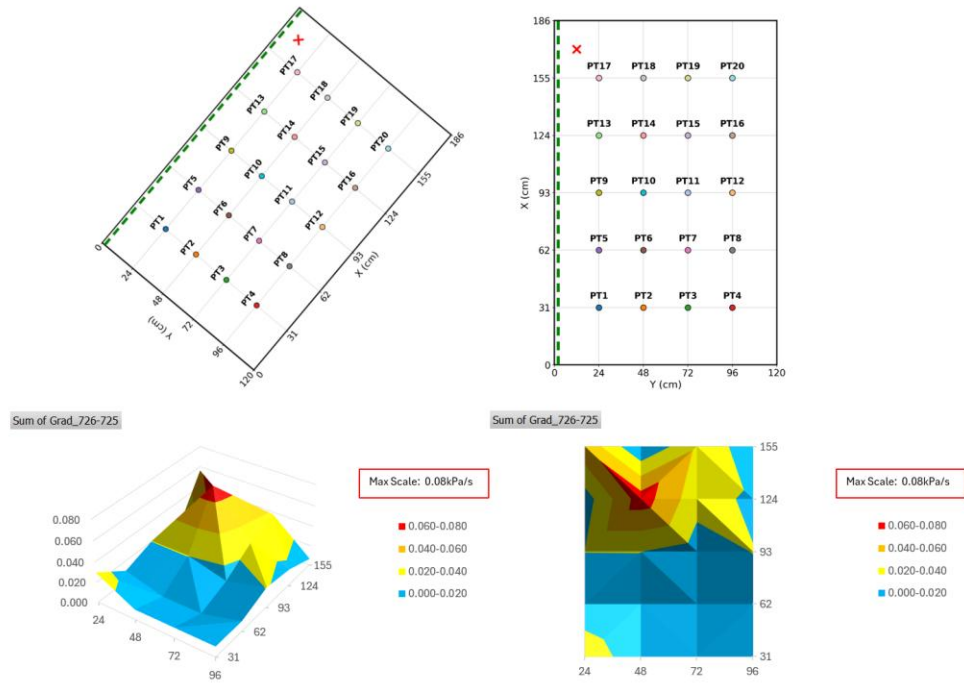


Figure 4.53: Contour map of dP/dt for $t = 725-726s$ (pre-puncture baseline), Experiment #6

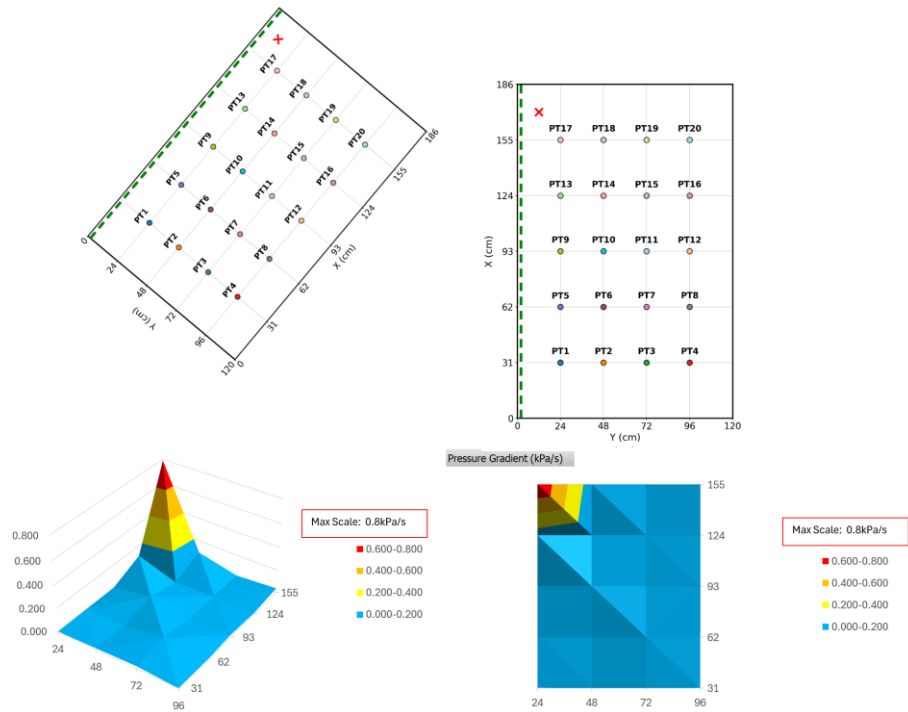


Figure 4.54: Contour map of dP/dt for $t = 726-727s$ (peak transient leak), Experiment #6

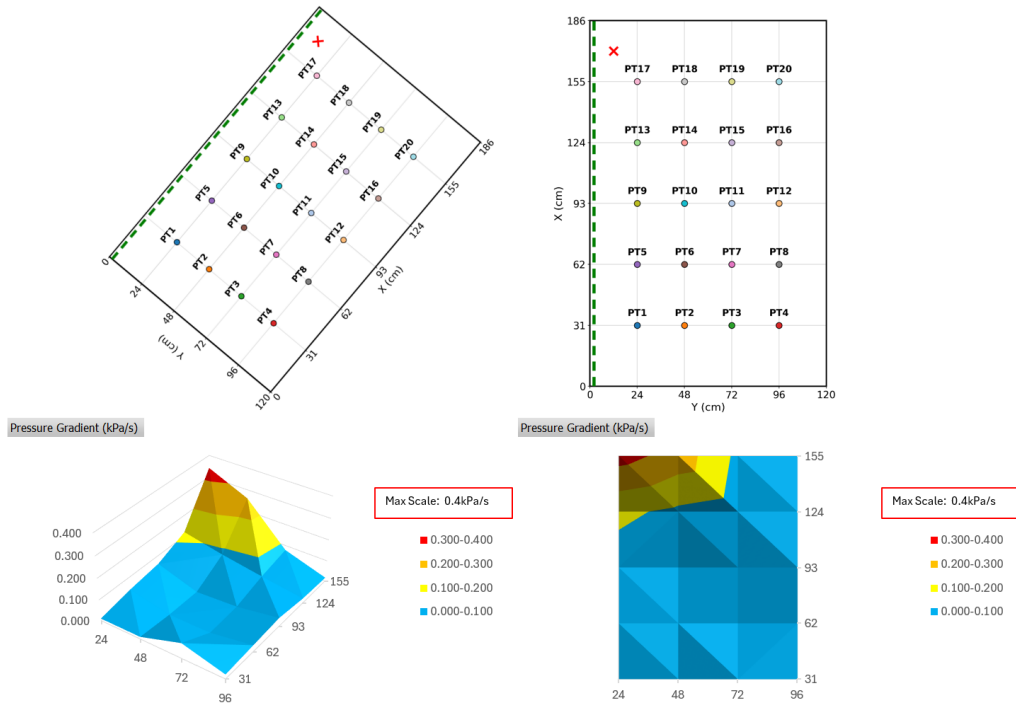


Figure 4.55: Contour map of dP/dt for $t = 727-728s$ (first second of steady leak), Experiment #6

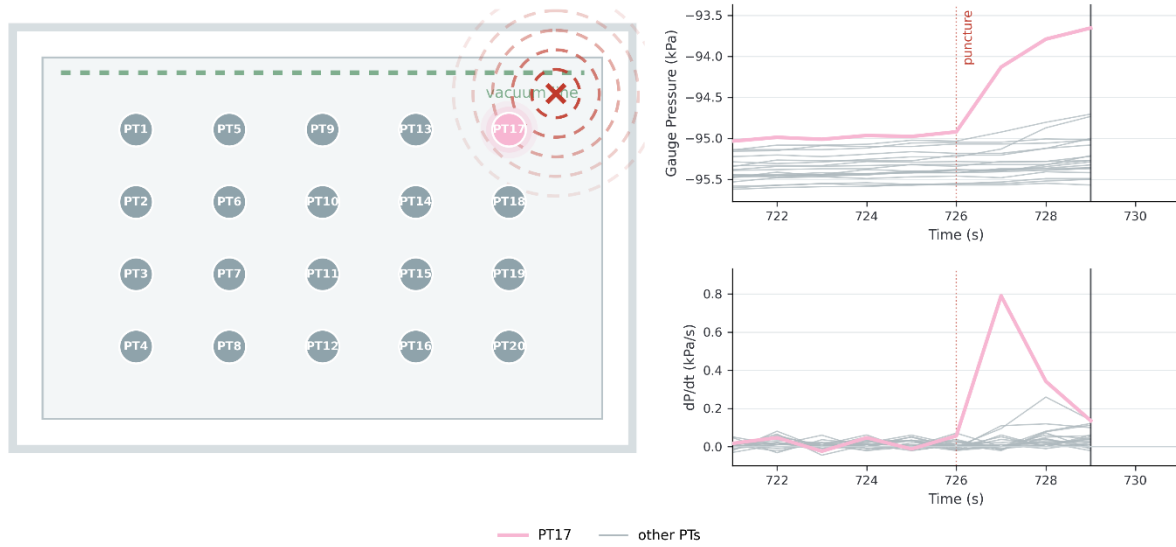


Figure 4.56: Localization window for Experiment #6 ($t=726$ to $729s$)

4.3.4 Experiment #7

In Experiment #7 a pinhole was punched at location X_7 near the bottom-centre of the fabric stack at the edge farthest from the vacuum line, using a 0.14mm diameter needle, Figure 4.57.

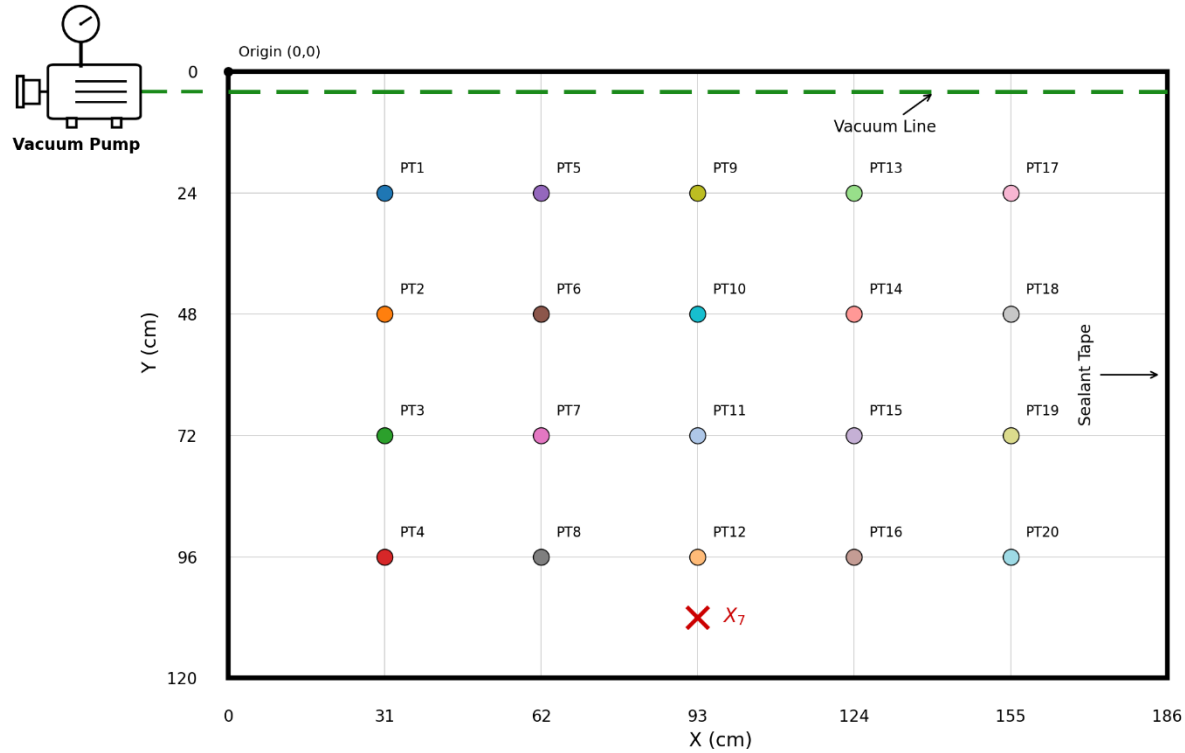


Figure 4.57: Pinhole location, Experiment #7

Figure 4.58 details key events of Experiment #7. The vacuum-drop test was conducted from $t = 85\text{s}$ to 385s and recorded a 3.27kPa rise in array-averaged gauge pressure.

The vacuum pump was restarted at $t = 390\text{s}$ and shut off at $t = 550\text{s}$. The pinhole was punched at $t = 603\text{s}$, Figure 4.59. PT12, the PT closest to X_7 , responded on puncture and peaked at 0.86kPa/s the following second, narrowly ahead of the next-fastest. The transient phase spanned $t = 603\text{s}$ to 607s , with steady-state leak phase beginning at $t = 608\text{s}$.

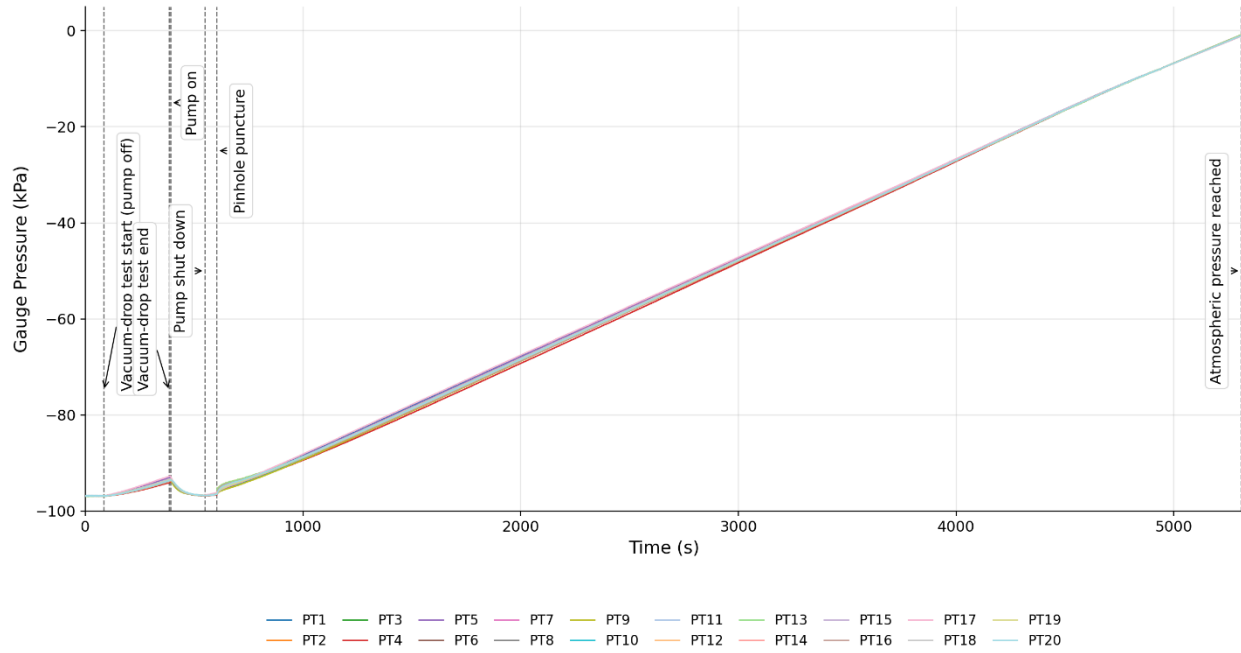


Figure 4.58: Key events, Experiment #7

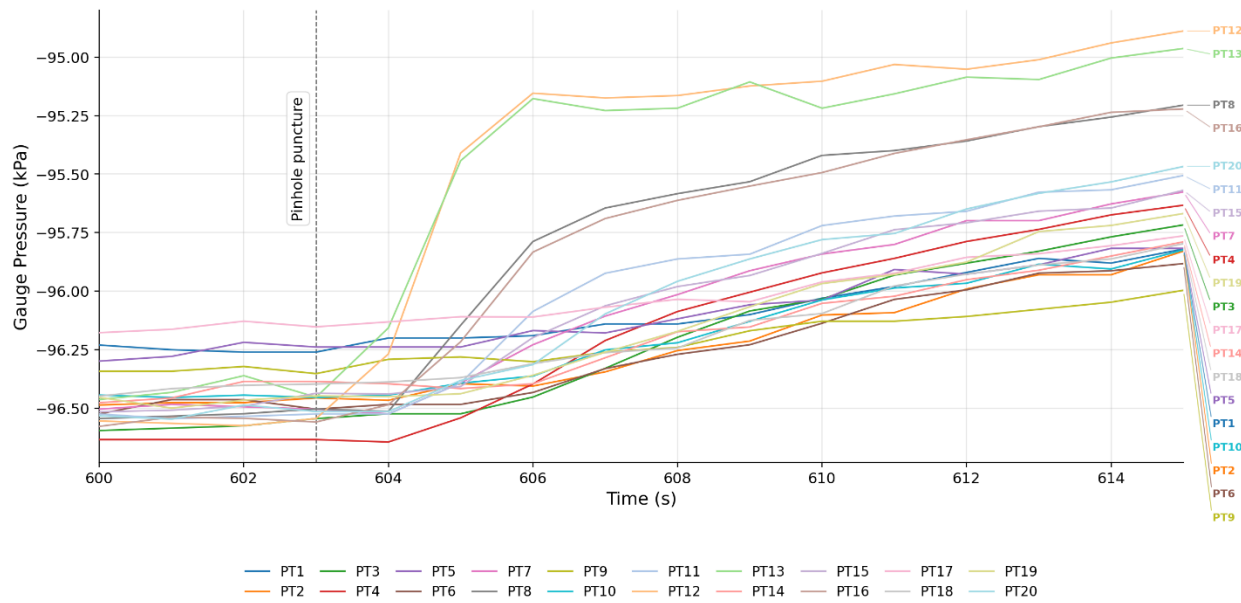


Figure 4.59: Pinhole puncture event, Experiment #7

Before puncture the dP/dt field is near zero across the array with a small peak at PT13, Figure 4.60. One second after puncture the dP/dt field shows a peak at PT12 and PT13, Figure 4.61. The

dominant response at PT12 is consistent with known pinhole location. The simultaneous elevated response at PT13 indicates a secondary dP/dt gradient feature that is not spatially adjacent to the pinhole. This may reflect interaction with the vacuum-line region, an existing system leak, preferential air movement through a low-resistance pathway, or a measurement artifact. This anomalous response is discussed further in Chapter 5. The leak dissipates as surrounding PTs equilibrate, Figure 4.62. Figure 4.63 shows the complete three-second window for Experiment #7. Additional supporting figures are provided in Appendices B–E.

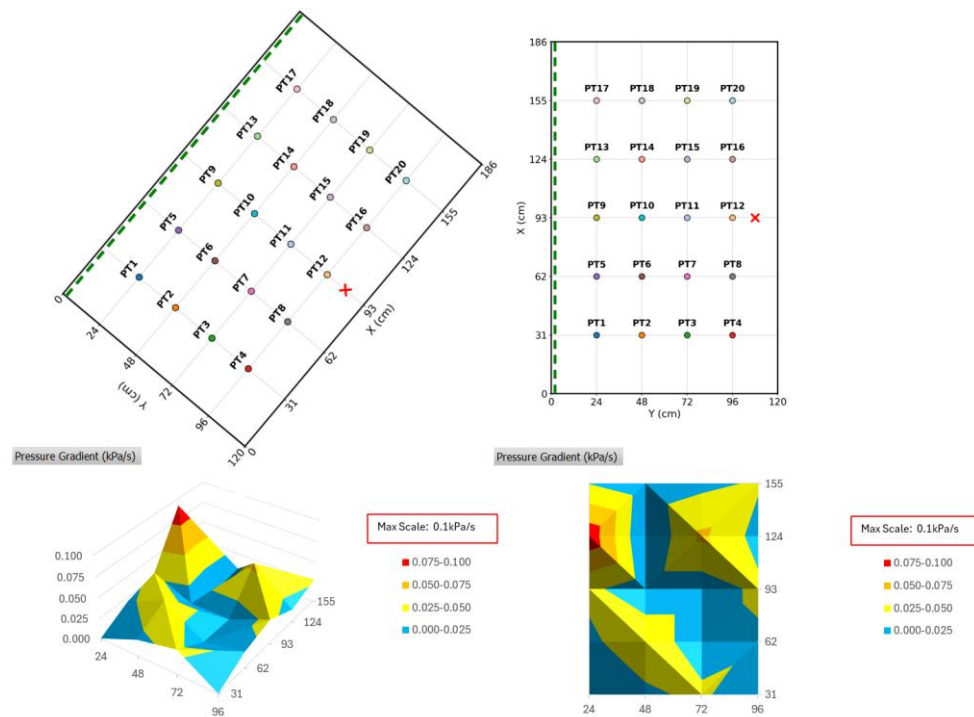


Figure 4.60: Contour map of dP/dt for $t = 602-603s$ (pre-puncture baseline), Experiment #7

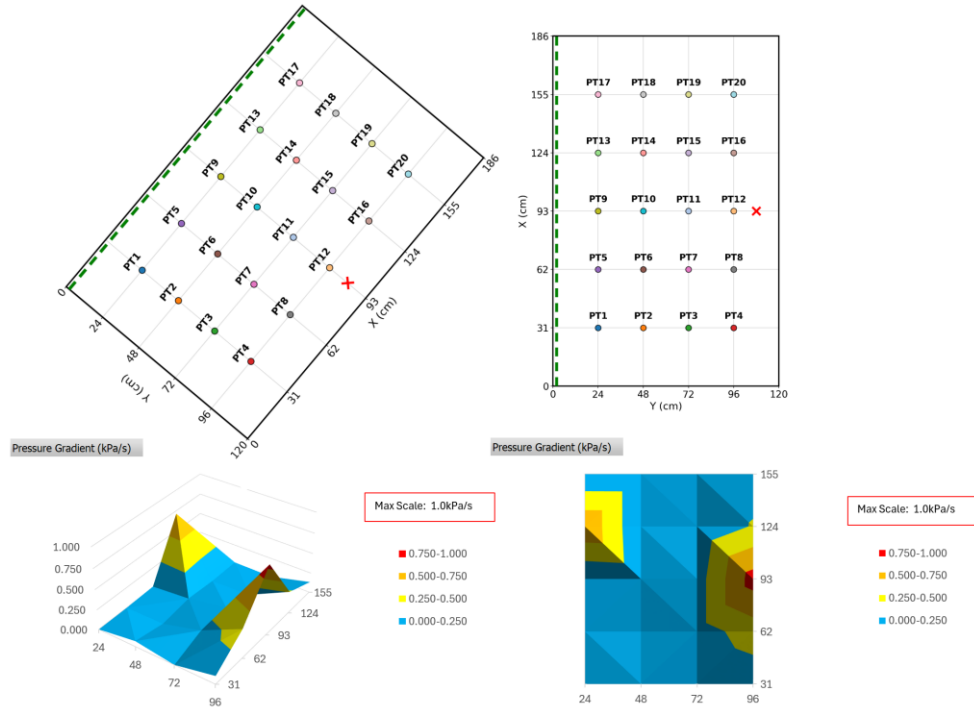


Figure 4.61: Contour map of dP/dt for $t = 604-605s$ (peak transient leak), Experiment #7

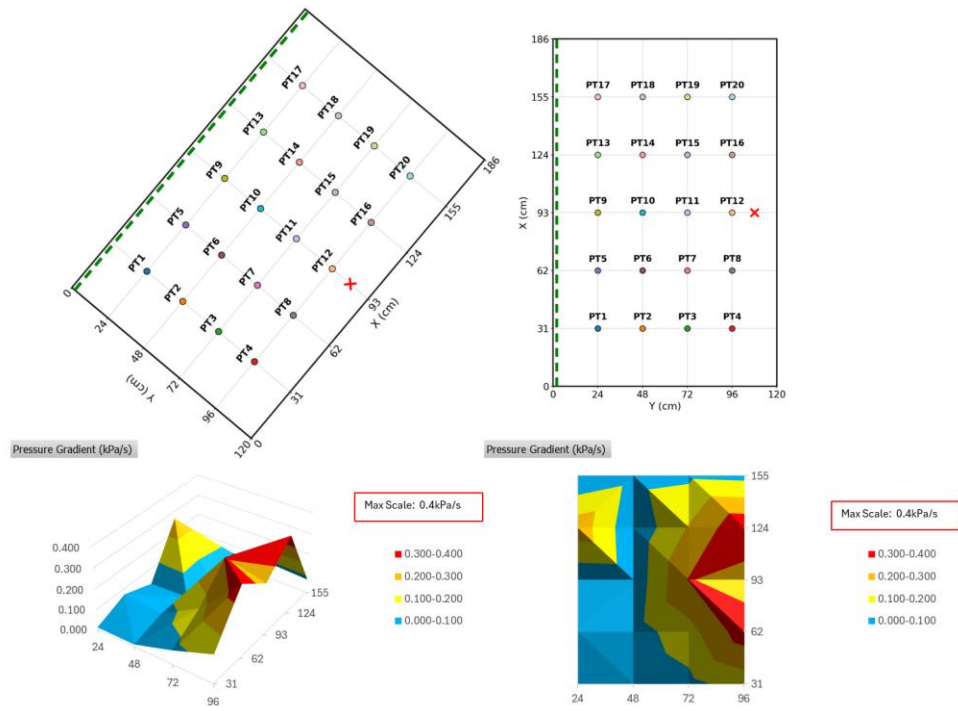


Figure 4.62: Contour map of dP/dt for $t = 605-606s$ (first second of steady leak), Experiment #7

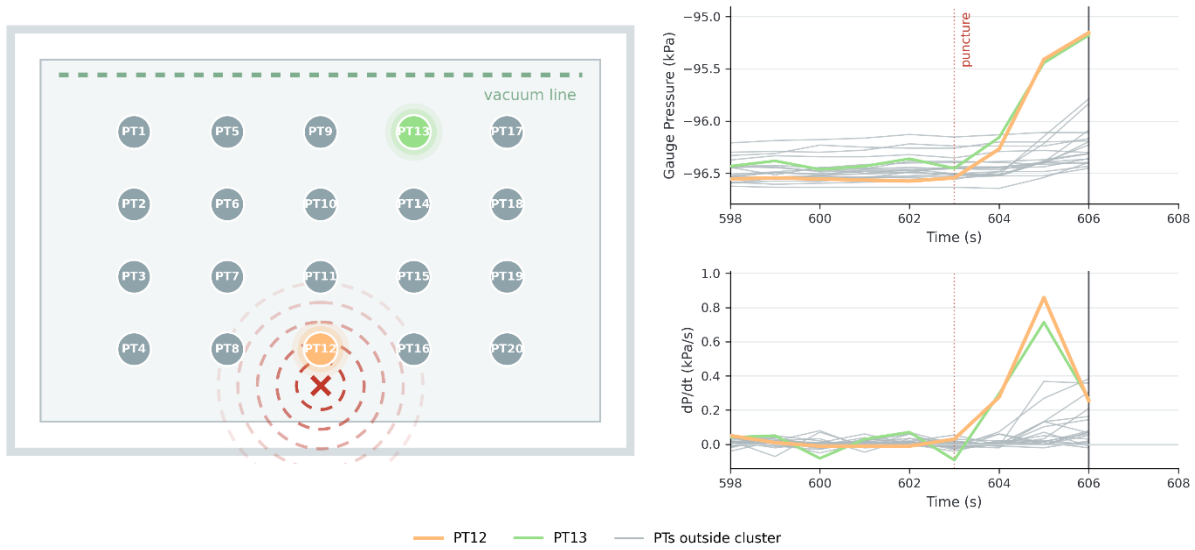


Figure 4.63: Localization window for Experiment #7 ($t=603$ to $606s$)

4.3.5 Experiment #8

In Experiment #8 a pinhole was punched at location X_8 near the top-left corner of the fabric stack using a 0.14mm diameter needle. This location is just outside the PT array and approximately 12cm below the vacuum line, Figure 4.64.

Figure 4.65 details key events of Experiment #8. The vacuum-drop test was conducted from $t = 448s$ to $748s$ and recorded a 3.92kPa rise in array-averaged gauge pressure.

The vacuum pump was restarted at $t = 753s$ and shut off at $t = 926s$ to set the pre-puncture baseline. The pinhole was punched at $t = 981s$, Figure 4.66. PT1, the transducer closest to X_8 , rose at 0.13kPa/s on puncture and peaked at 0.47kPa/s the following second. This peak was roughly four times the next fastest rate. The transient phase spanned $t = 981s$ to $985s$, with steady-state leak phase beginning at $t = 986s$.

Before puncture the dP/dt field is uniform and near zero across the array, Figure 4.67. One second after puncture the dP/dt field shows a peak at PT1, nearest X_8 and confirming leak location, Figure 4.68. The leak dissipates as surrounding PTs equilibrate, Figure 4.69. Figure 4.70 shows the complete three-second window for Experiment #8. Additional supporting figures are provided in Appendices B–E.

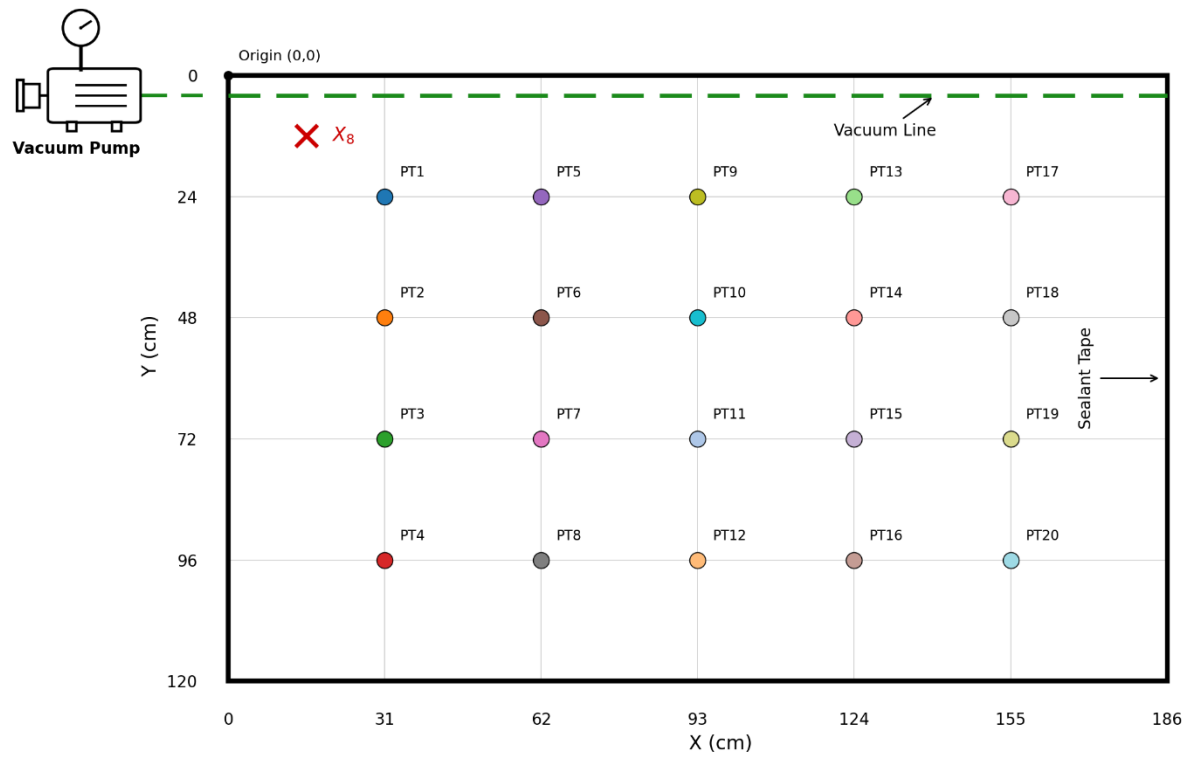


Figure 4.64: Pinhole location, Experiment #8

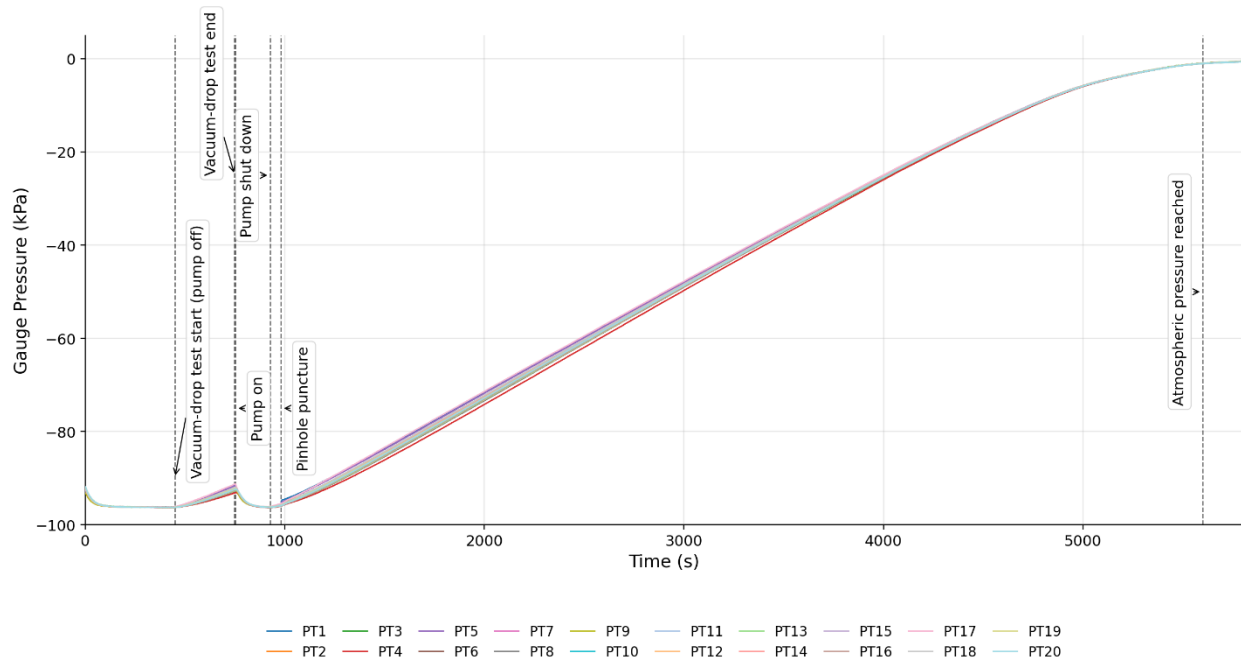


Figure 4.65: Key events, Experiment #8

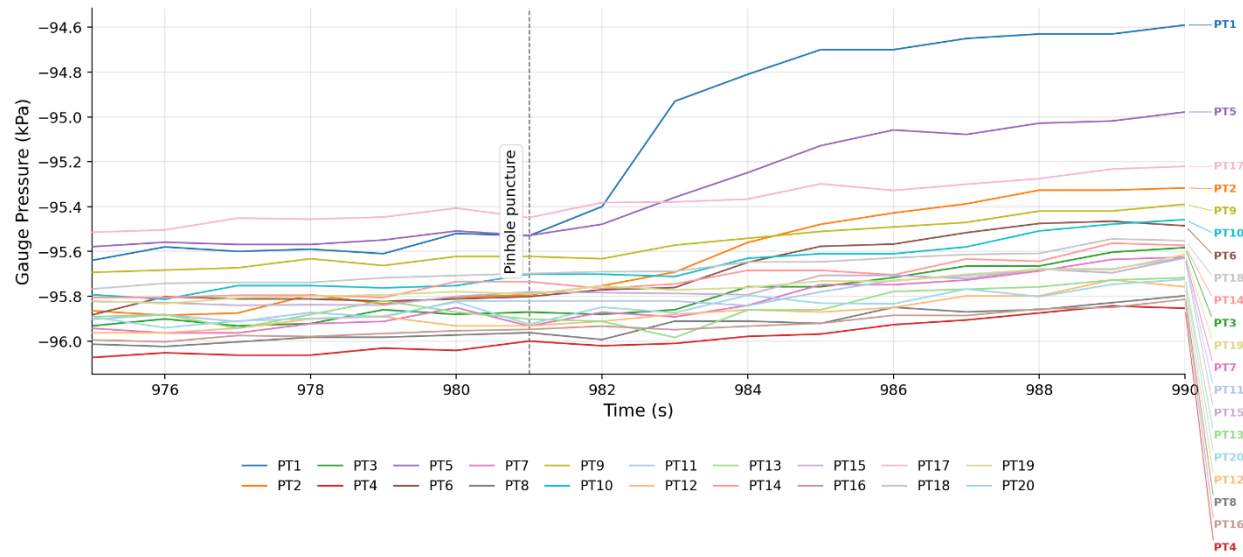


Figure 4.66: Pinhole puncture event, Experiment #8

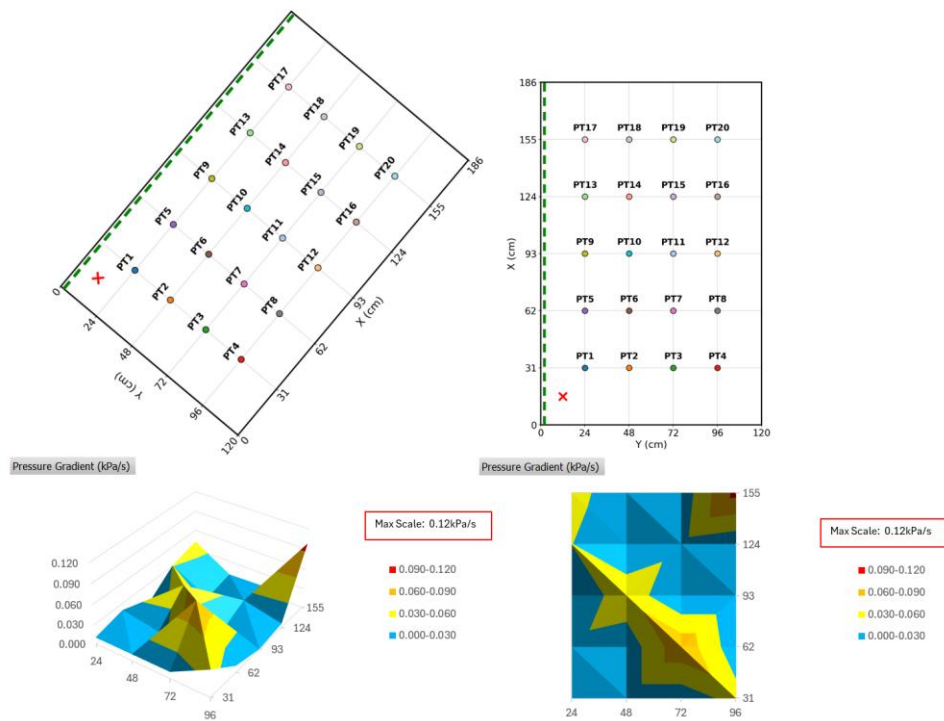


Figure 4.67: Contour map of dP/dt for $t = 980-981s$ (pre-puncture baseline), Experiment #8

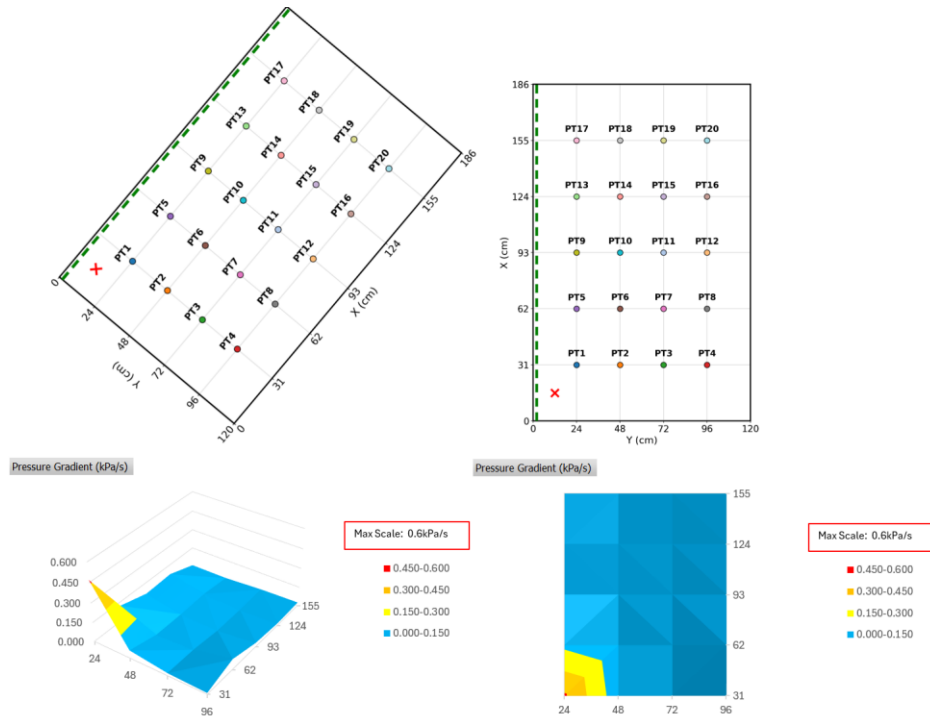


Figure 4.68: Contour map of dP/dt for $t = 982-983s$ (peak transient leak), Experiment #8

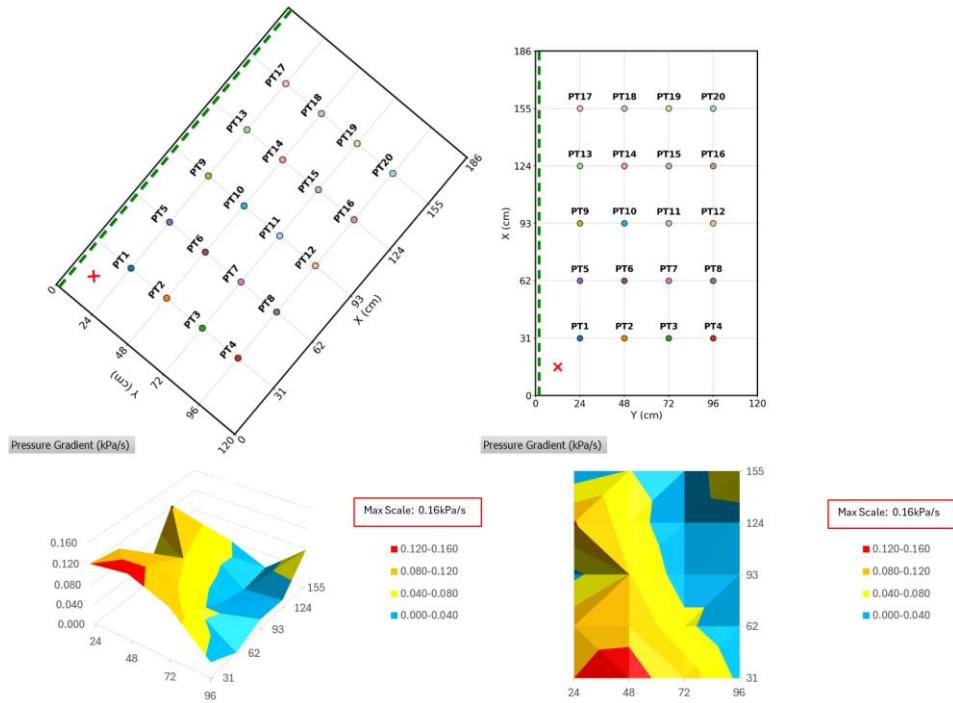


Figure 4.69: Contour map of dP/dt for $t = 983-984s$ (first second of steady leak), Experiment #8

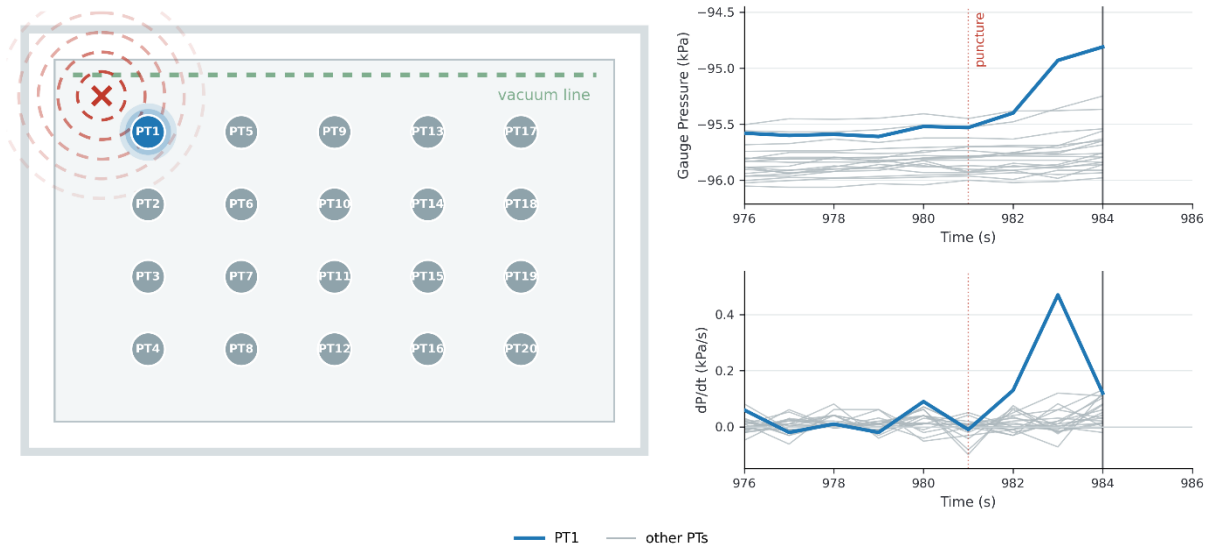


Figure 4.70: Localization window for Experiment #8 ($t=981$ to $984s$)

4.3.6 Experiment #9

In Experiment #9 a pinhole was punched at location X_9 near the top-centre of the fabric stack using a 0.14mm diameter needle. This location lies just outside the PT array, 12cm below the vacuum line and directly above PT9, Figure 4.71.

Figure 4.72 details key events of Experiment #9. The vacuum-drop test was conducted from $t = 227s$ to $527s$ and recorded a 4.65kPa rise in array-averaged gauge pressure.

The vacuum pump was restarted at $t = 528s$ and shut off at $t = 850s$ to set the pre-puncture baseline. The pinhole was punched at $t = 932s$, Figure 4.73. PT9, the transducer closest to X_9 , rose at 0.31kPa/s on puncture and peaked at 0.67kPa/s the following second, more than twice the next-fastest rate. The transient phase spanned $t = 932s$ to $935s$, with steady-state leak phase beginning at $t = 936s$.

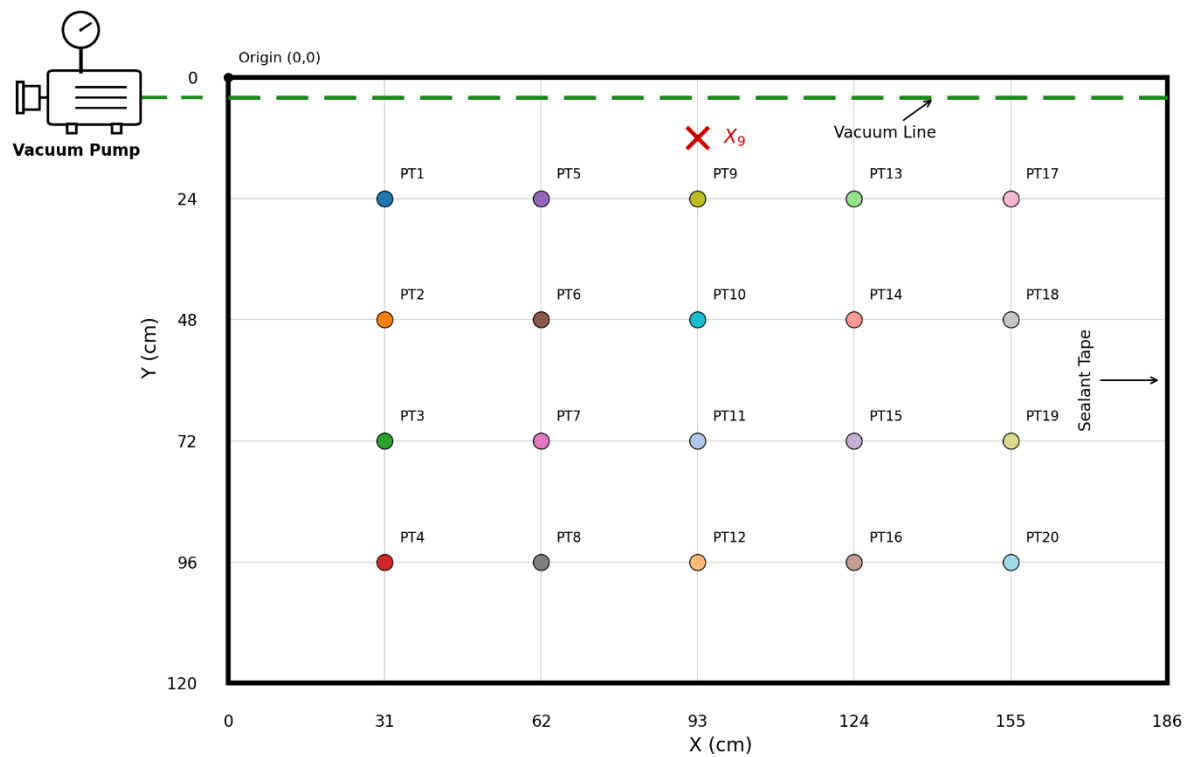


Figure 4.71: Pinhole location, Experiment #9

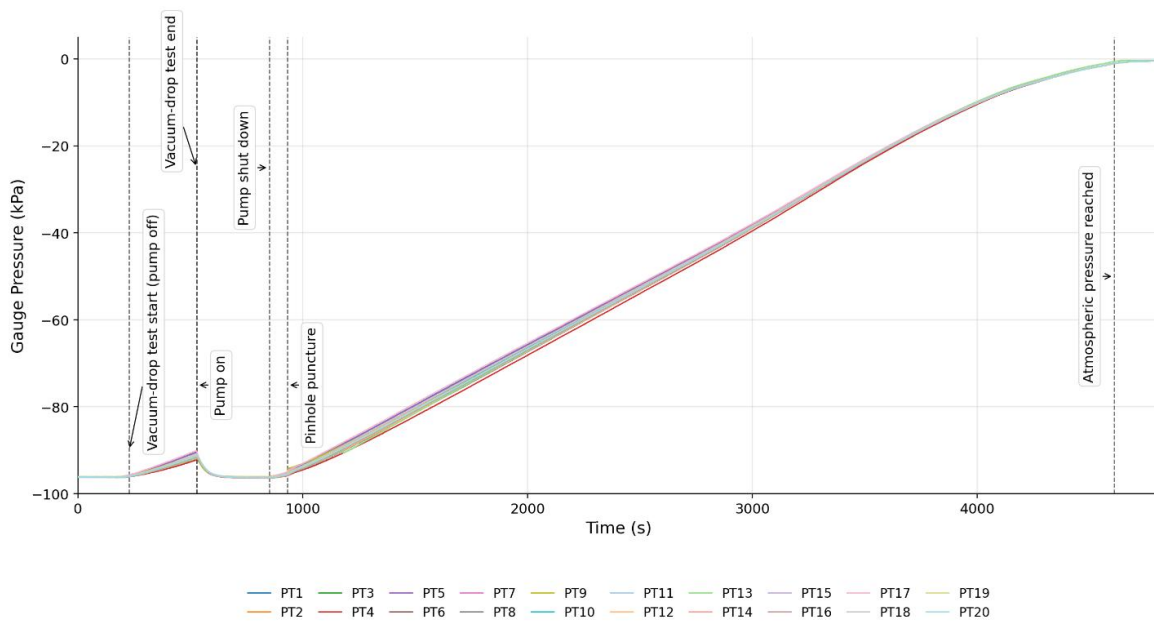


Figure 4.72: Key events, Experiment #9

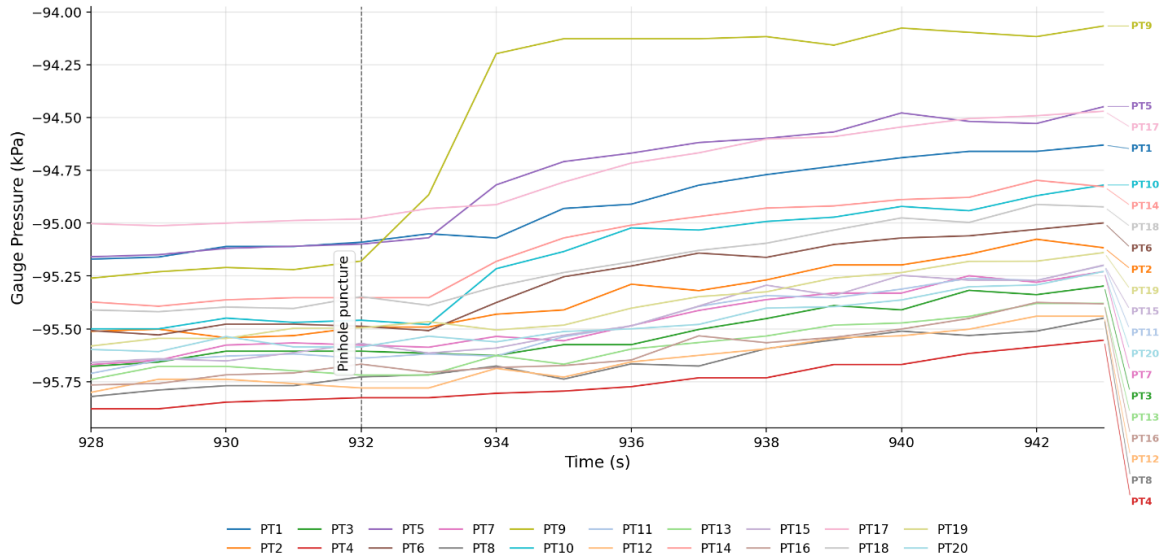


Figure 4.73: Pinhole puncture event, Experiment #9

Before puncture the dP/dt field is uniform and near zero across the array, Figure 4.74. One second after puncture the dP/dt field shows a peak at PT9, nearest X_9 and confirming leak location, Figure 4.75. The leak dissipates as surrounding PTs equilibrate, Figure 4.76. Figure 4.77 shows the complete three-second window for Experiment #9. Additional supporting figures are provided in Appendices B–E.

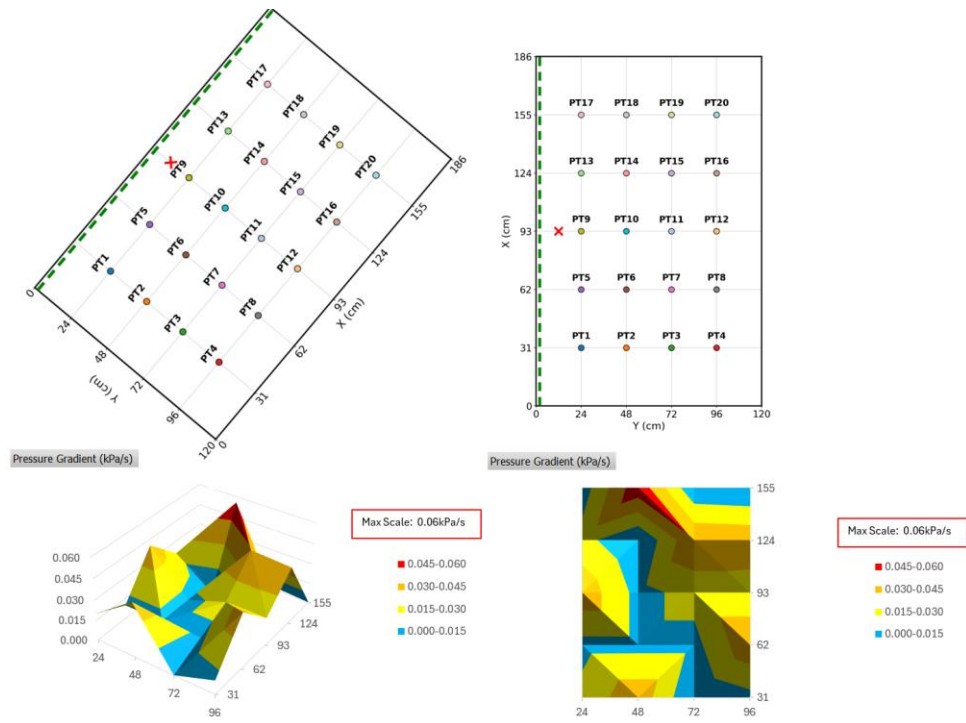


Figure 4.74: Contour map of dP/dt for $t = 931-932s$ (pre-puncture baseline), Experiment #9

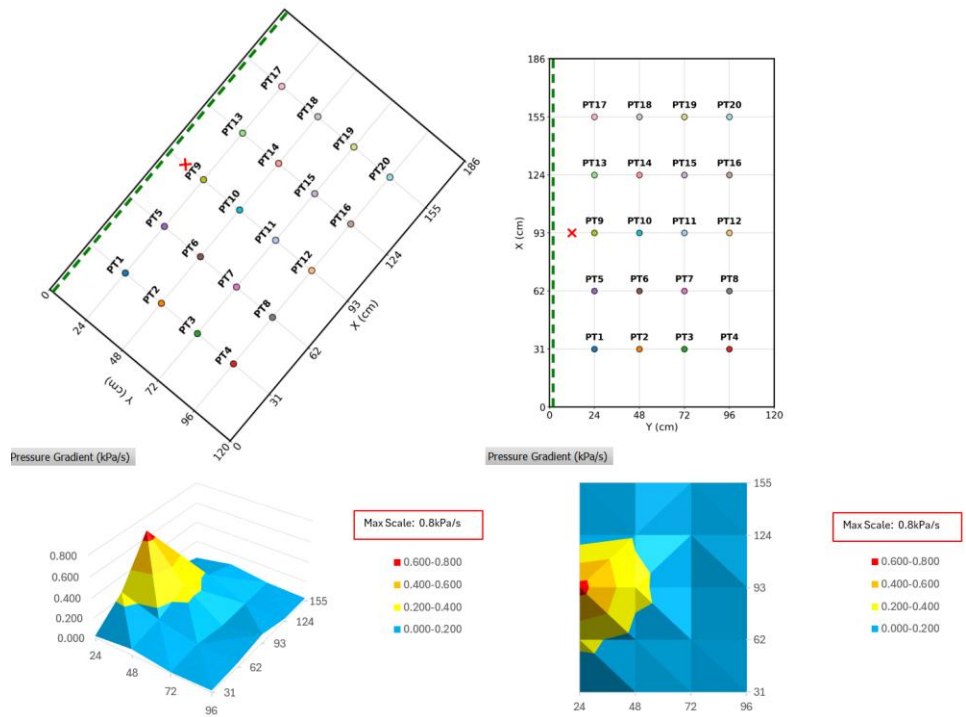


Figure 4.75: Contour map of dP/dt for $t = 933-934s$ (peak transient leak), Experiment #9

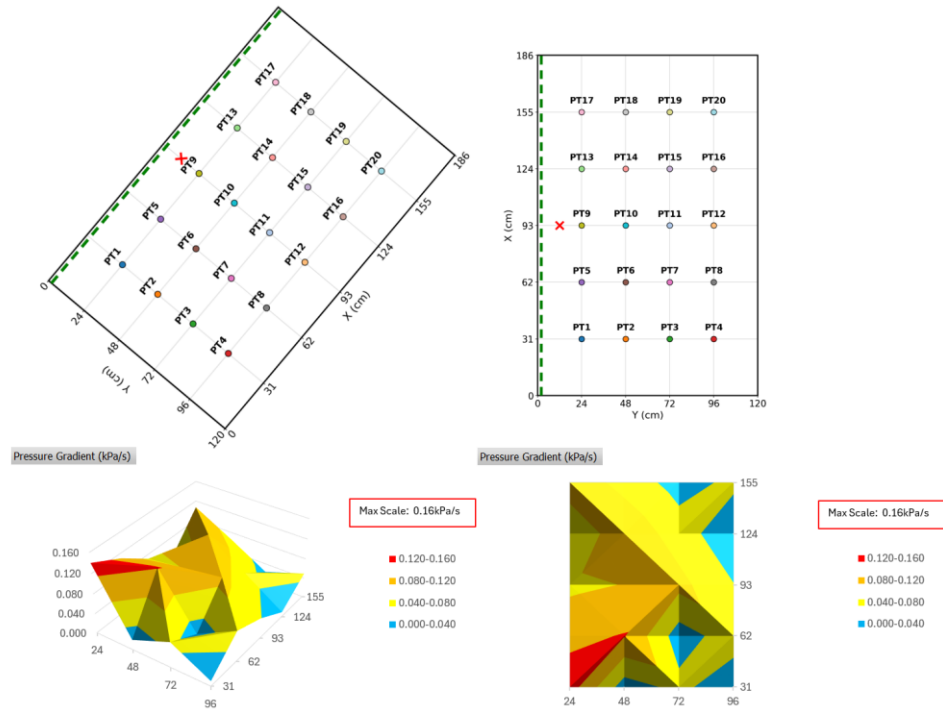


Figure 4.76: Contour map of dP/dt for $t = 934-935s$ (first second of steady leak), Experiment #9

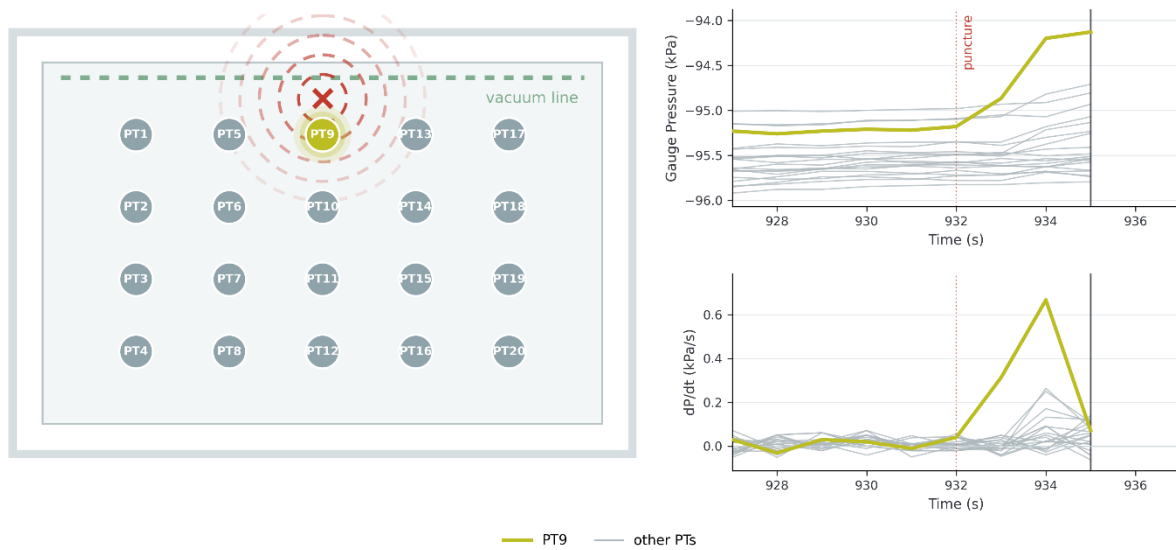


Figure 4.77: Localization window for Experiment #9 ($t=932$ to $935s$)

4.3.7 Experiment #10

In Experiment #10 a pinhole was punched at location X_{10} near the mid-left of the fabric stack using a 0.14mm diameter needle. This location lies at the geometric centre of the square formed by PT2, PT3, PT6, and PT7, each 19.6cm distant so no single transducer is closest, Figure 4.78.

Figure 4.79 details key events of Experiment #10. The vacuum-drop test was conducted from $t = 38$ s to 338s and recorded a 2.66kPa rise. The vacuum pump was restarted at $t = 339$ s and shut off at $t = 460$ s. The pinhole was punched at $t = 503$ s, Figure 4.80. The four PTs equidistant from X_{10} , PT2, PT3, PT6, and PT7 rose together on puncture to a cluster mean of 0.13kPa/s, more than three times the fastest transducer outside the cluster. The following second, the left side of the cluster accelerated with PT2 reaching 0.20kPa/s before the four PTs reconverged. The transient phase spanned $t = 503$ s to 506s, with steady-state leak phase beginning at $t = 507$ s.

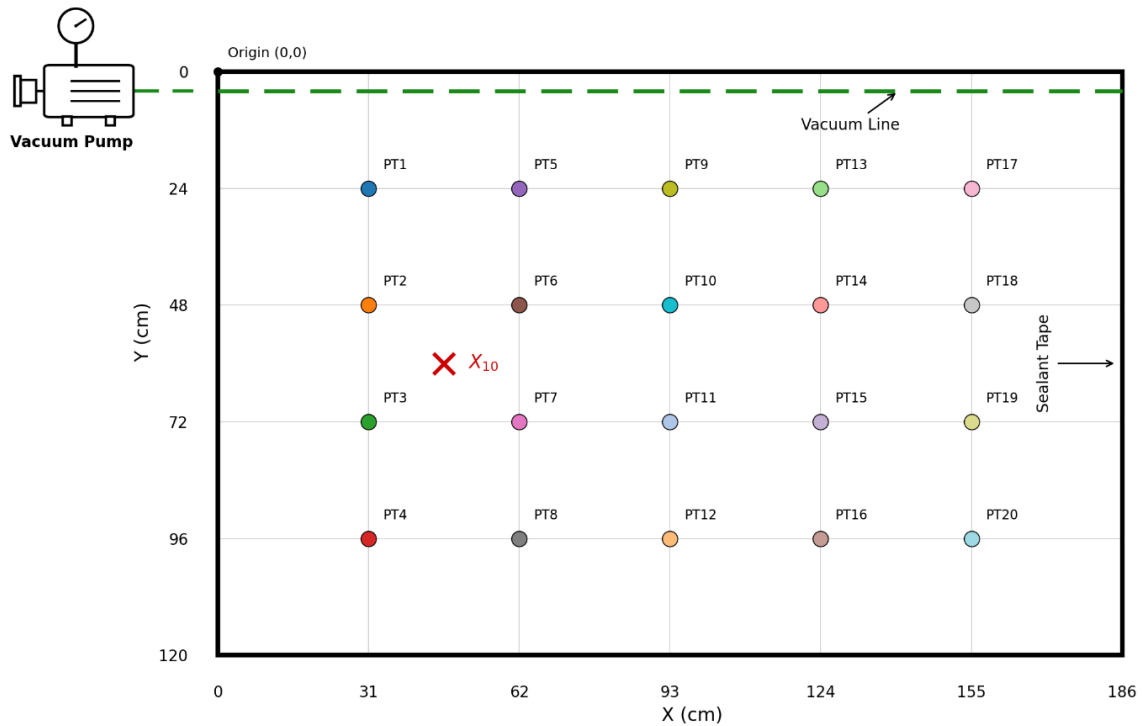


Figure 4.78: Pinhole location, Experiment #10

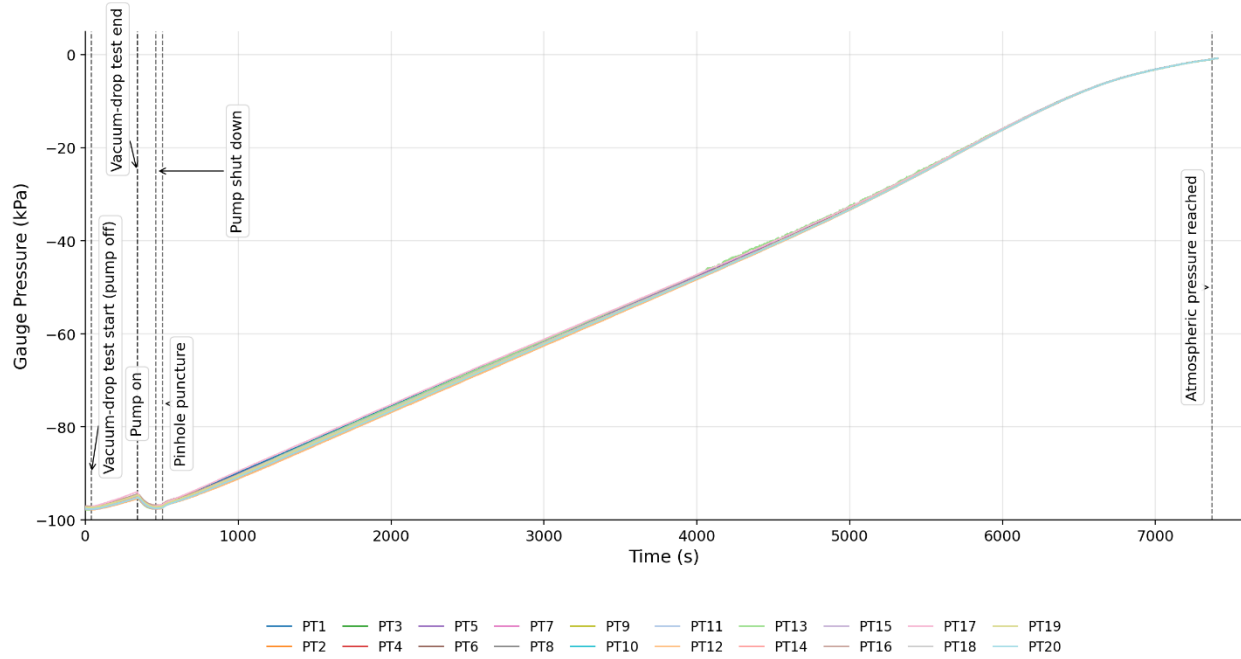


Figure 4.79: Key events, Experiment #10

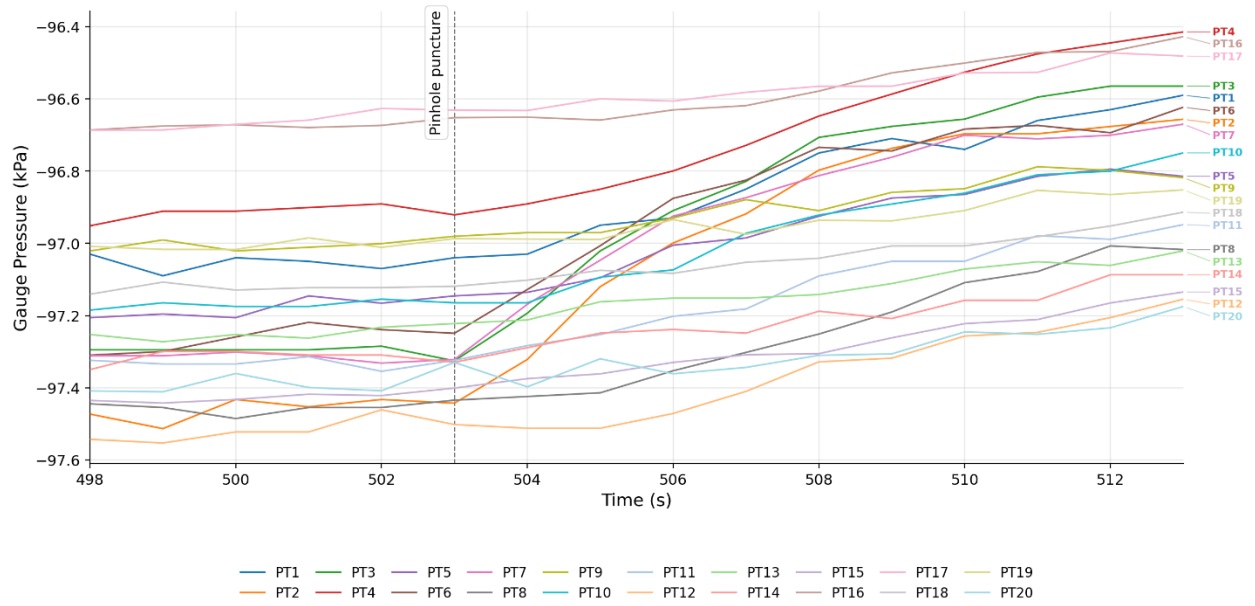


Figure 4.80: Pinhole puncture event, Experiment #10

Before puncture the dP/dt field was uniform and near zero across the array, Figure 4.81. In the first second after puncture the four cluster PTs responded symmetrically about X_{10} , confirming

leak location, Figure 4.82. Response peaked in the following second as the left side of the cluster accelerated with PT2 reaching 0.20kPa/s, Figure 4.83. The cluster then reconverged to a uniform signature as the leak settled, Figure 4.84. Here the leak was roughly equidistant from four surrounding PTs. The response at each was reduced by the larger pinhole-to-PT distance, yielding a smaller per-PT rise and a less distinct post-puncture dP/dt field than at single-PT locations. This point and the brief shift in leading PT within the cluster are discussed further in Chapter 5. Figure 4.85 shows the complete three-second window for Experiment #10. Additional supporting figures are provided in Appendices B–E.

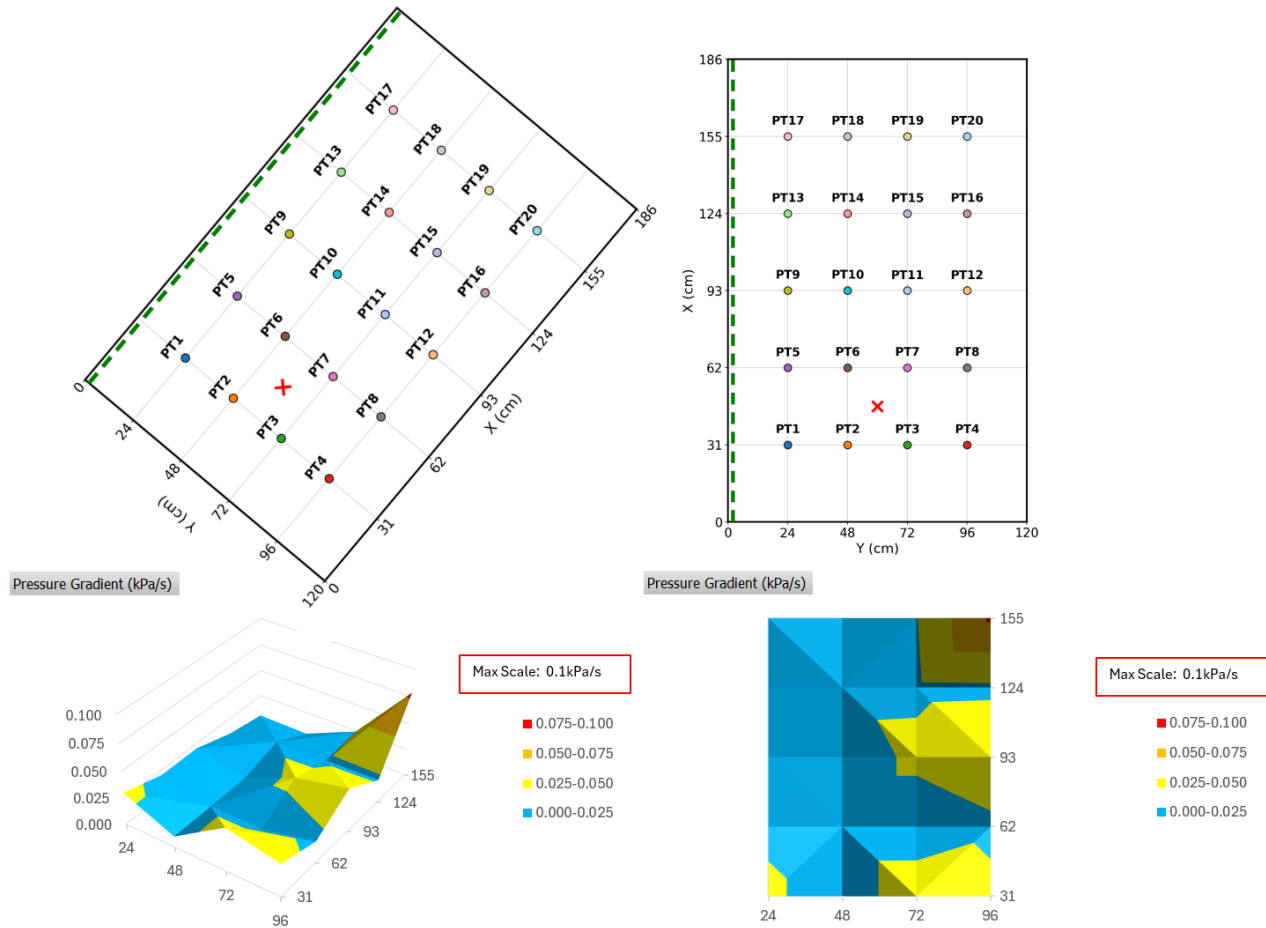


Figure 4.81: Contour map of dP/dt for $t = 502-503s$ (pre-puncture baseline), Experiment #10

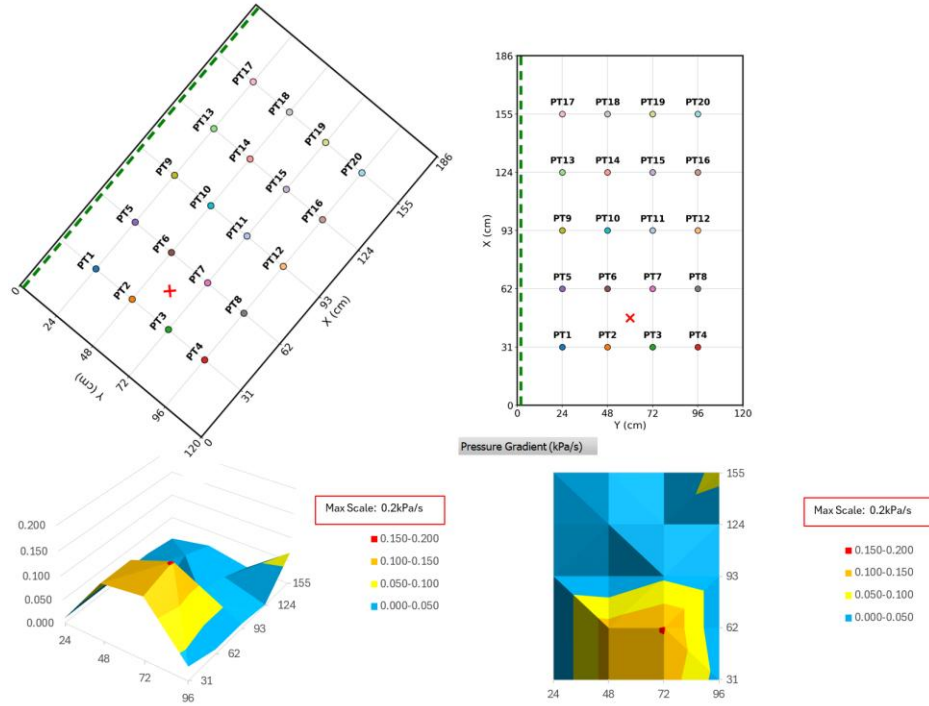


Figure 4.82: Contour map of dP/dt for $t = 503-504s$ (first second after puncture), Experiment #10

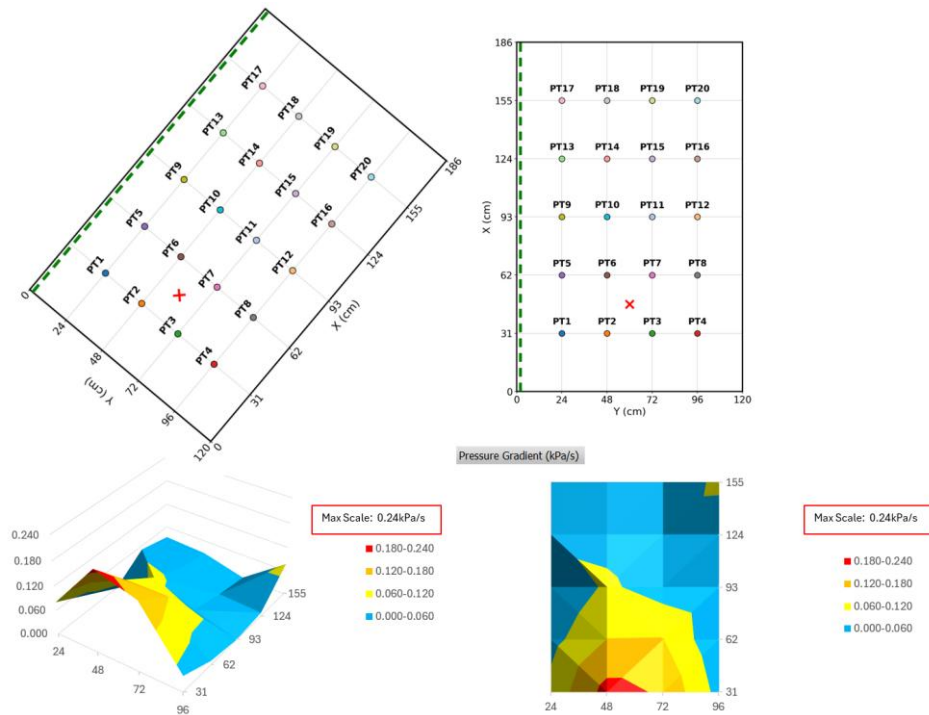


Figure 4.83: Contour map of dP/dt for $t = 504-505s$ (peak transient), Experiment #10

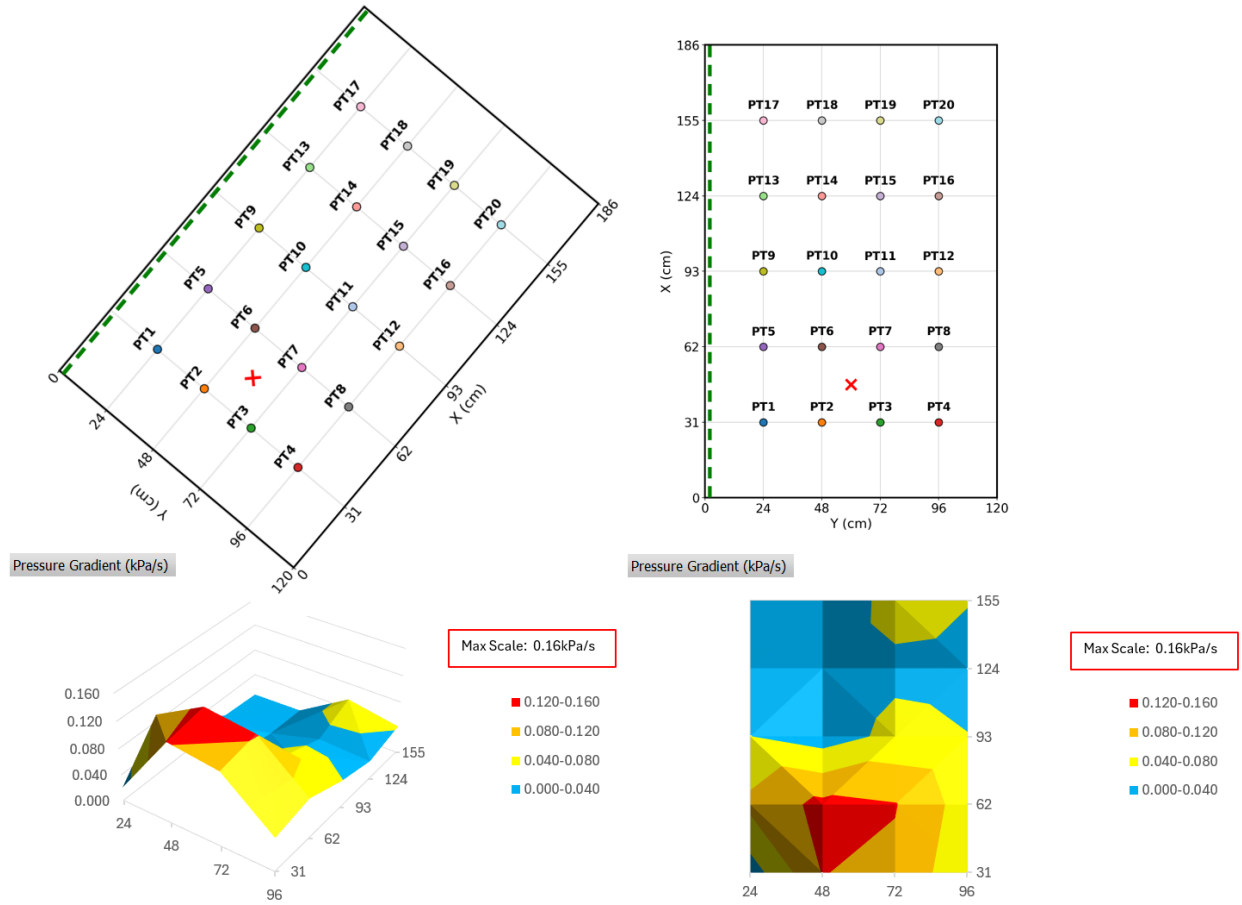


Figure 4.84: Contour map of dP/dt for $t = 505-506$ s (first second of steady leak), Experiment #10

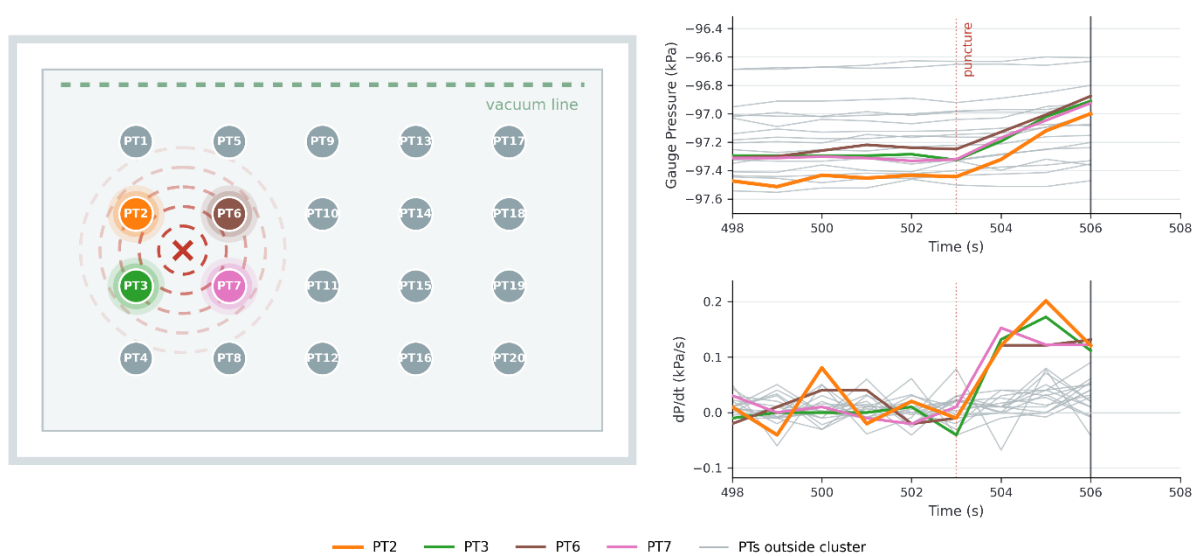


Figure 4.85: Localization window for Experiment #10 ($t = 503$ to 506 s)

4.3.8 Experiment #11

In Experiment #11 a pinhole was punched at location X_{11} at the centre of the fabric stack using a 0.14mm diameter needle. This location lies midway between PT10 and PT11, each 12cm distant, Figure 4.86.

Figure 4.87 details key events of Experiment #11. The vacuum-drop test was conducted from $t = 15\text{s}$ to 315s and recorded a 2.70kPa rise in array-averaged gauge pressure.

The vacuum pump was restarted at $t = 316\text{s}$ and shut off at $t = 903\text{s}$. The pinhole was punched at $t = 955\text{s}$, Figure 4.88. PT10 and PT11, the PTs closest to X_{11} , rose together on puncture, with PT11 peaking at 0.31kPa/s and PT10 at 0.28kPa/s. Both were more than four times the next-fastest rate. The transient phase spanned $t = 955\text{s}$ to 957s , with steady-state leak phase beginning at $t = 958\text{s}$.

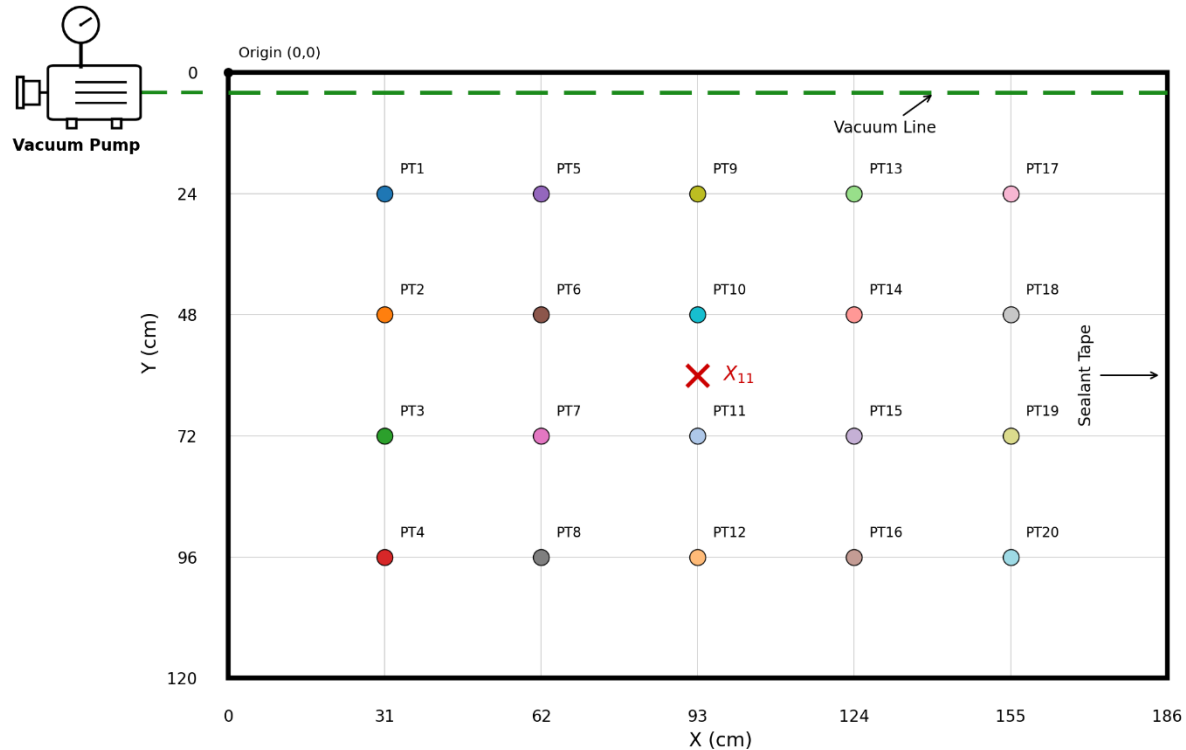


Figure 4.86: Pinhole location, Experiment #11

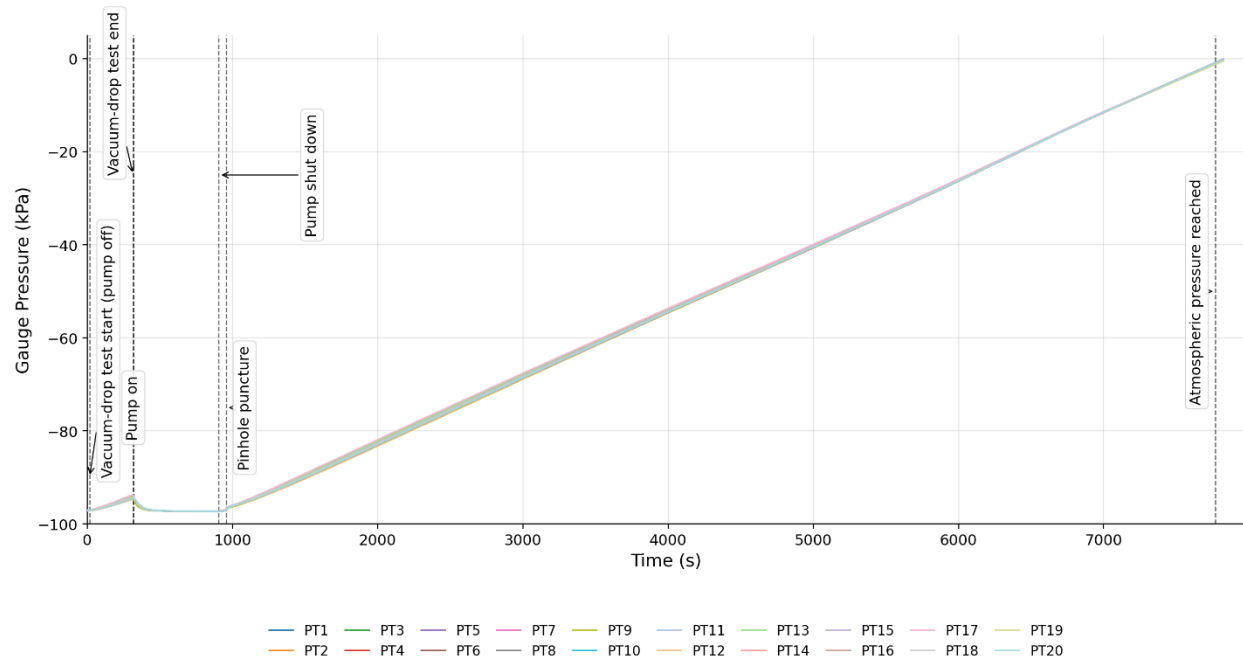


Figure 4.87: Key events, Experiment #11

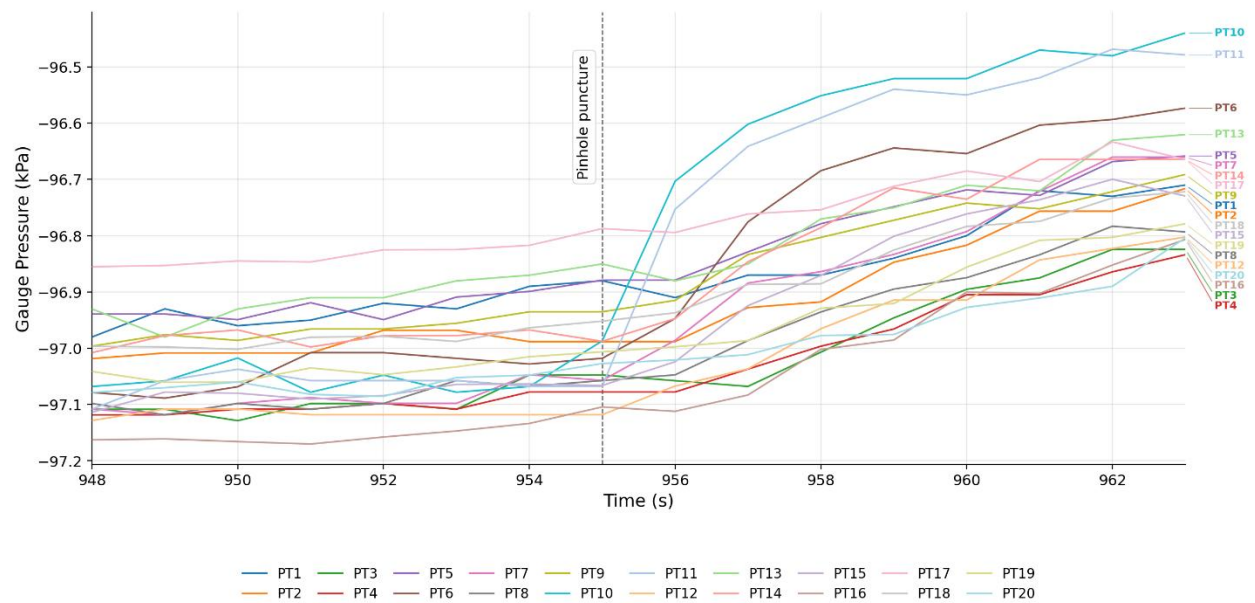


Figure 4.88: Pinhole puncture event, Experiment #11

Before puncture the dP/dt field is uniform and near zero across the array, Figure 4.89. At the moment of puncture the dP/dt field shows a peak at PT10 and PT11, nearest X_{11} and confirming

leak location, Figure 4.90. The leak dissipated as surrounding PTs equilibrated, Figure 4.91. Figure 4.92 shows the complete three-second window for Experiment #11. This experiment featured one of the highest vacuum levels of the campaign, and its row-averaged baseline departed from the usual ordering by distance from the vacuum line (Figure D.10). This behaviour is discussed further in Chapter 5. Additional supporting figures are provided in Appendices B–E.

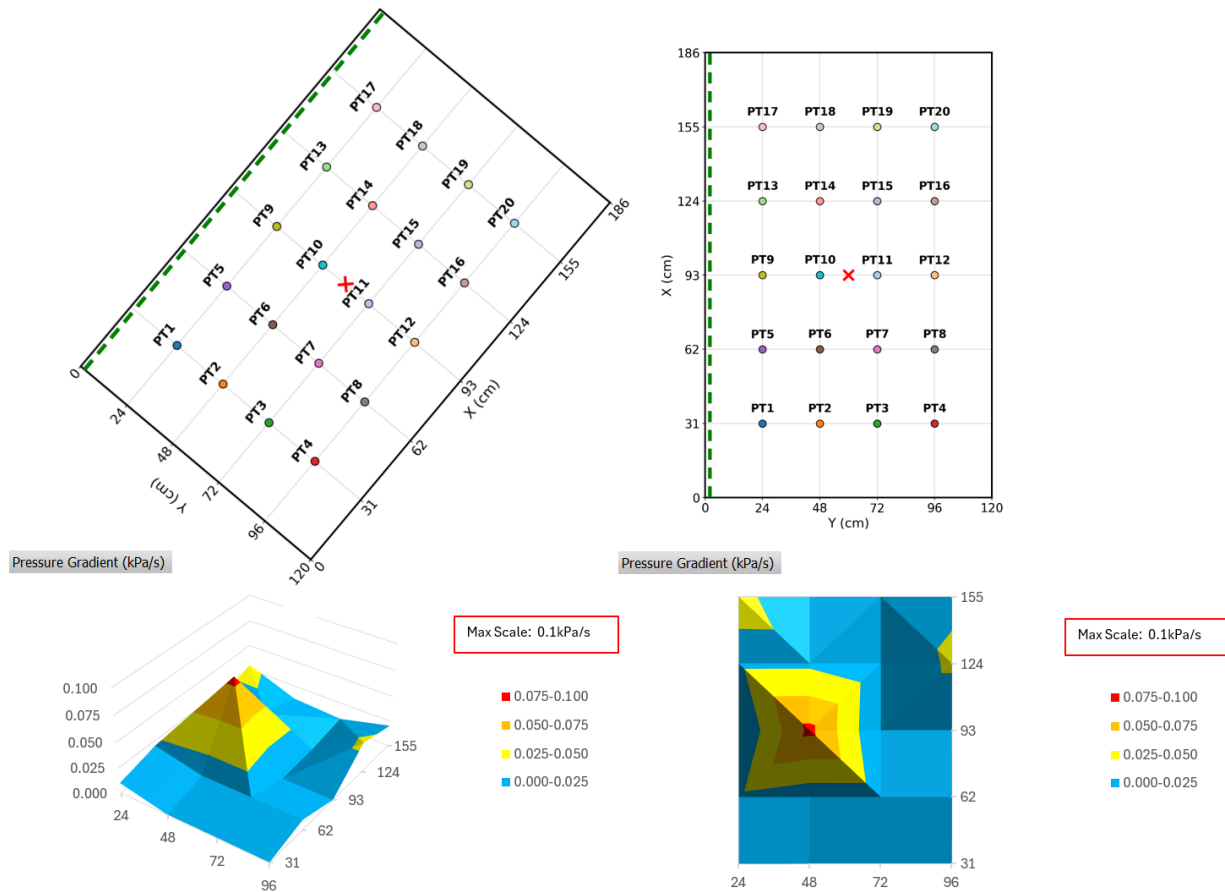


Figure 4.89: Contour map of dP/dt for $t = 954-955s$ (pre-puncture baseline), Experiment #11

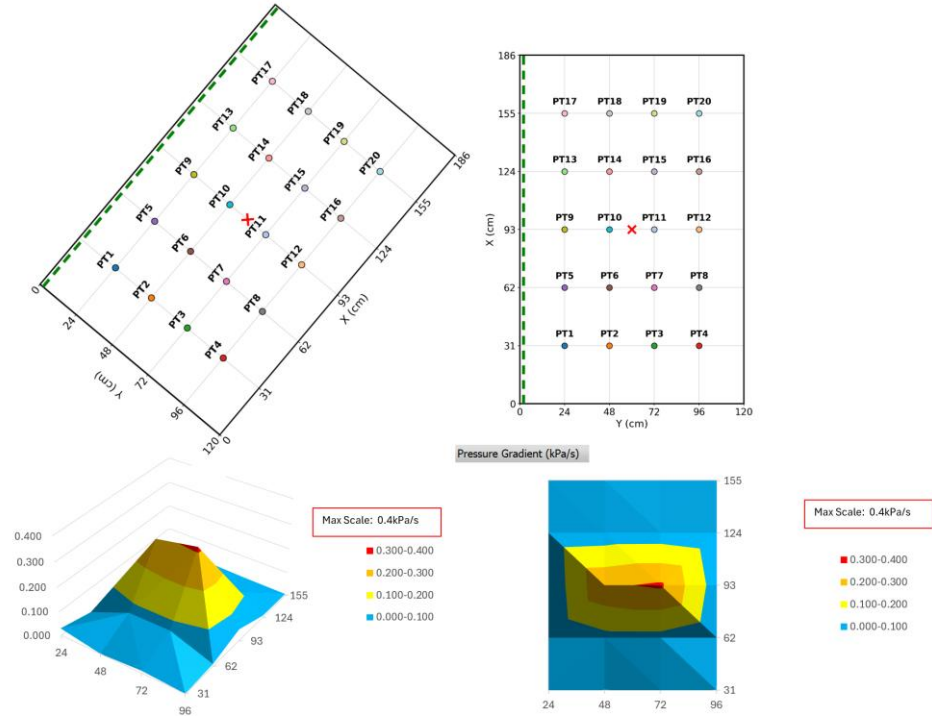


Figure 4.90: Contour map of dP/dt for $t = 955-956s$ (peak transient leak), Experiment #11

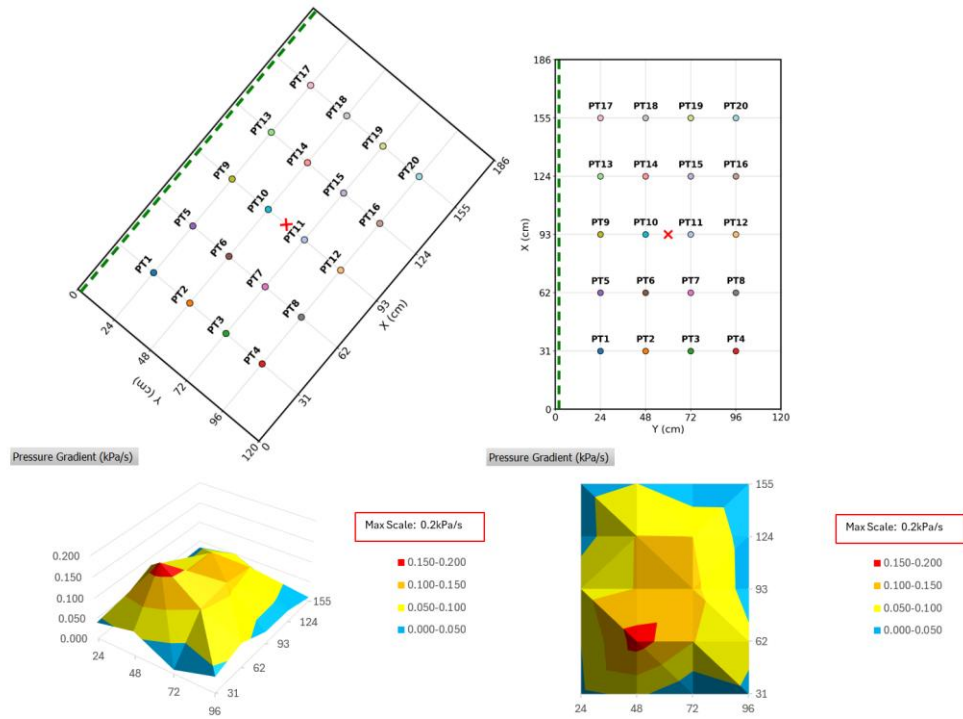


Figure 4.91: Contour map of dP/dt for $t = 956-957s$ (first second of steady leak), Experiment #11

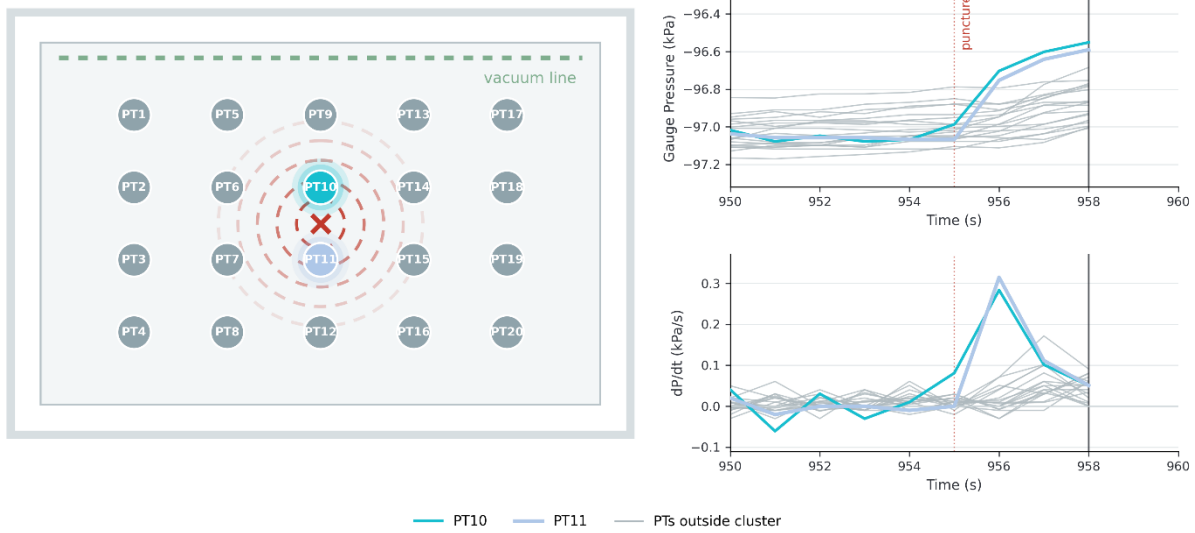


Figure 4.92: Localization window for Experiment #11 ($t=955$ to $958s$)

4.3.9 Experiment #12

In Experiment #12 a pinhole was punched at location X_{12} near the mid-right of the fabric stack using a 0.14mm diameter needle. This location lies at the geometric centre of the square formed by PT14, PT15, PT18, and PT19, each 19.6cm distant hence no single transducer is closest, Figure 4.93.

Figure 4.94 details key events of Experiment #12. The vacuum-drop test was conducted from $t = 81s$ to $381s$ and recorded a 2.82kPa rise. The vacuum pump was restarted at $t = 382s$ and shut off at $t = 608s$ to set the pre-puncture baseline. The pinhole was punched at $t = 666s$, Figure 4.95. The four PTs equidistant from X_{12} , PT14, PT15, PT18 and PT19 rose together one second after puncture to a cluster mean of 0.16kPa/s, more than three times the fastest transducer outside of the cluster. The transient phase spanned $t = 666s$ to $669s$, with steady-state leak phase beginning at $t = 670s$.

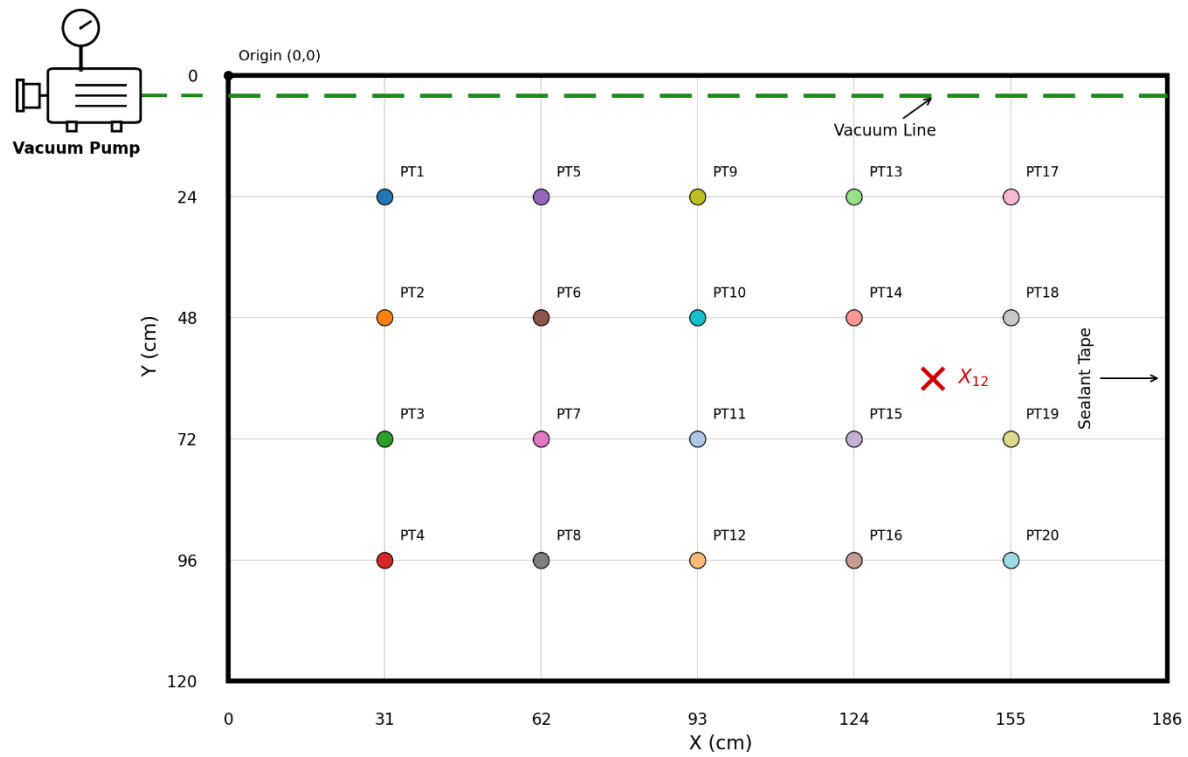


Figure 4.93: Pinhole location, Experiment #12

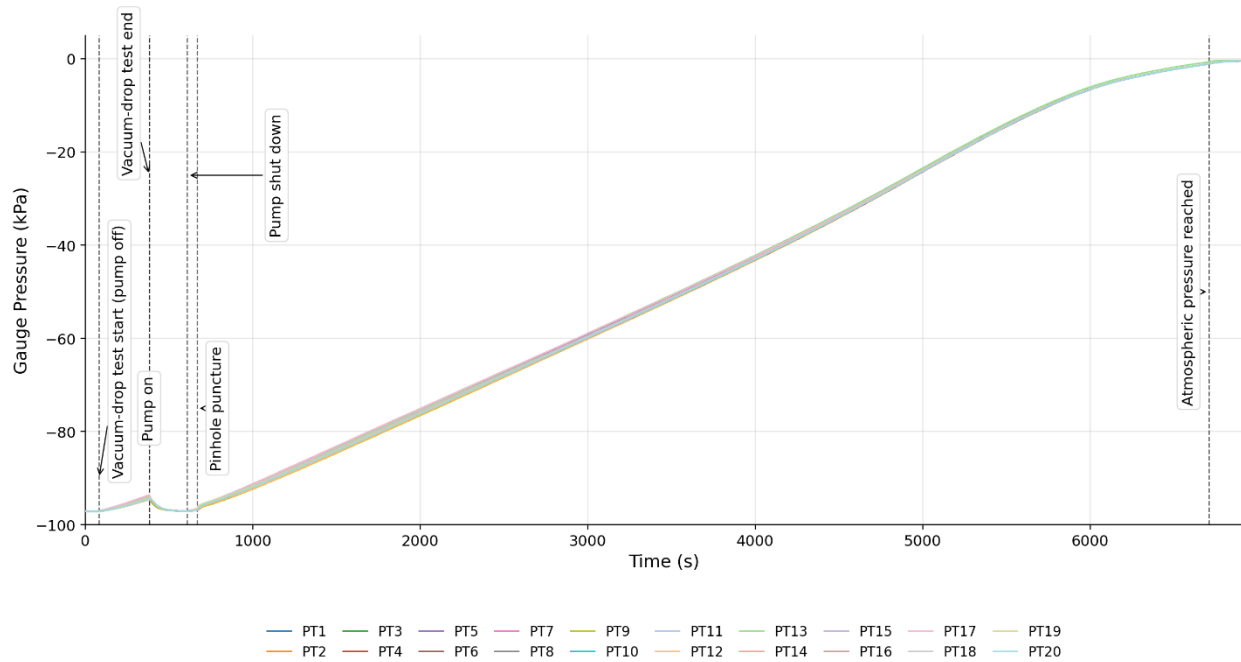


Figure 4.94: Key events, Experiment #12

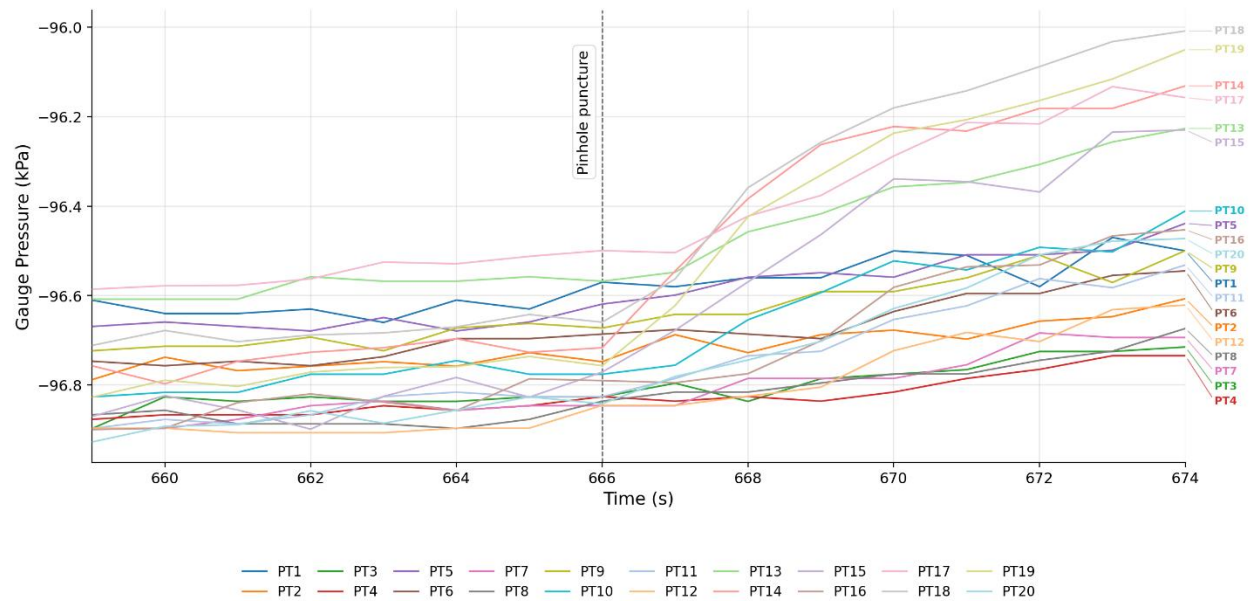


Figure 4.95: Pinhole puncture event, Experiment #12

Before puncture the dP/dt field is uniform and near zero across the array, Figure 4.96. One second after puncture the dP/dt field shows a cluster of elevated rates at PT14, PT15, PT18, and PT19 about X_{12} , confirming leak location, Figure 4.97. The cluster persists through a one-second time window, Figure 4.98, then dissipates as surrounding PTs equilibrate, Figure 4.99. As in Experiment #10, the leading PT within the cluster peaked at 0.20kPa/s (PT2 in Experiment #10 and PT18 in Experiment #12) and shifts briefly before the four PTs reconverge; this is discussed further in Chapter 5. Figure 4.100 shows the complete three-second window for Experiment #12. Additional supporting figures are provided in Appendices B–E.

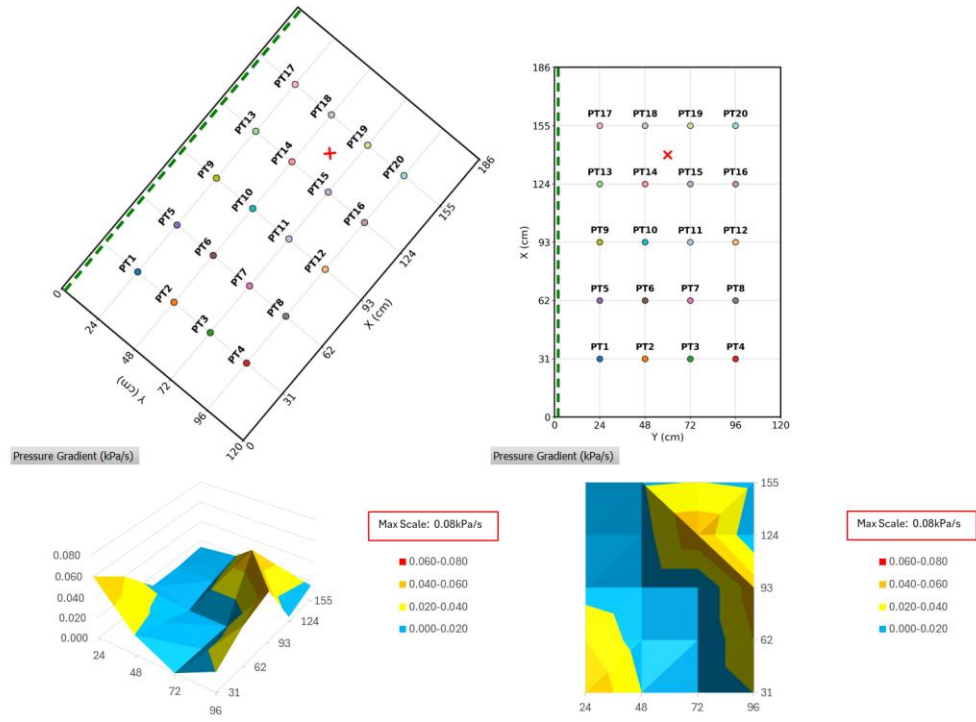


Figure 4.96: Contour map of dP/dt for $t = 665-666s$ (pre-puncture baseline), Experiment #12

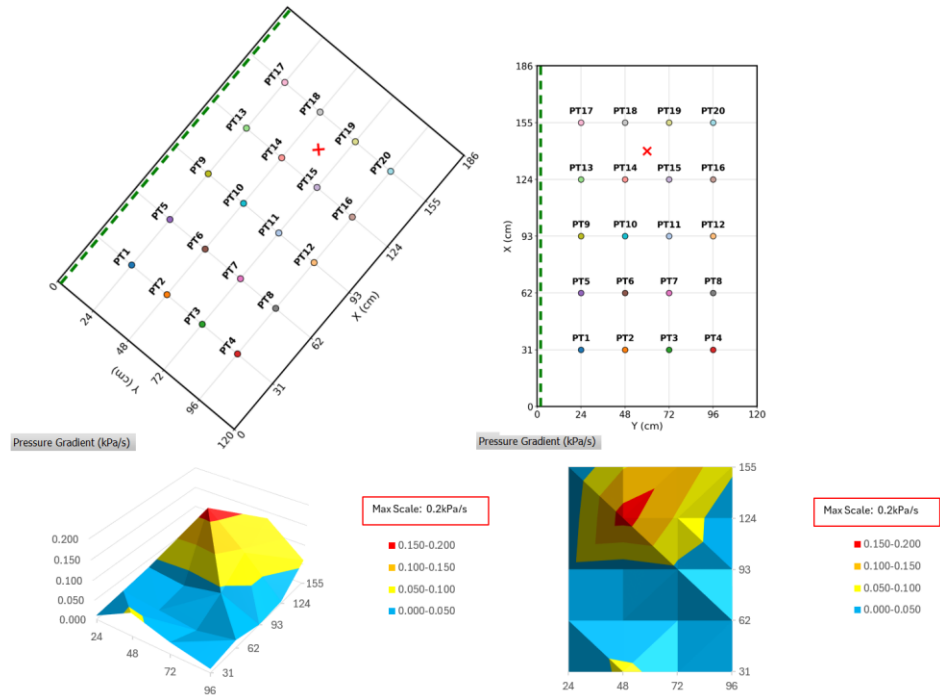


Figure 4.97: Contour map of dP/dt for $t = 666-667s$ (transient onset), Experiment #12

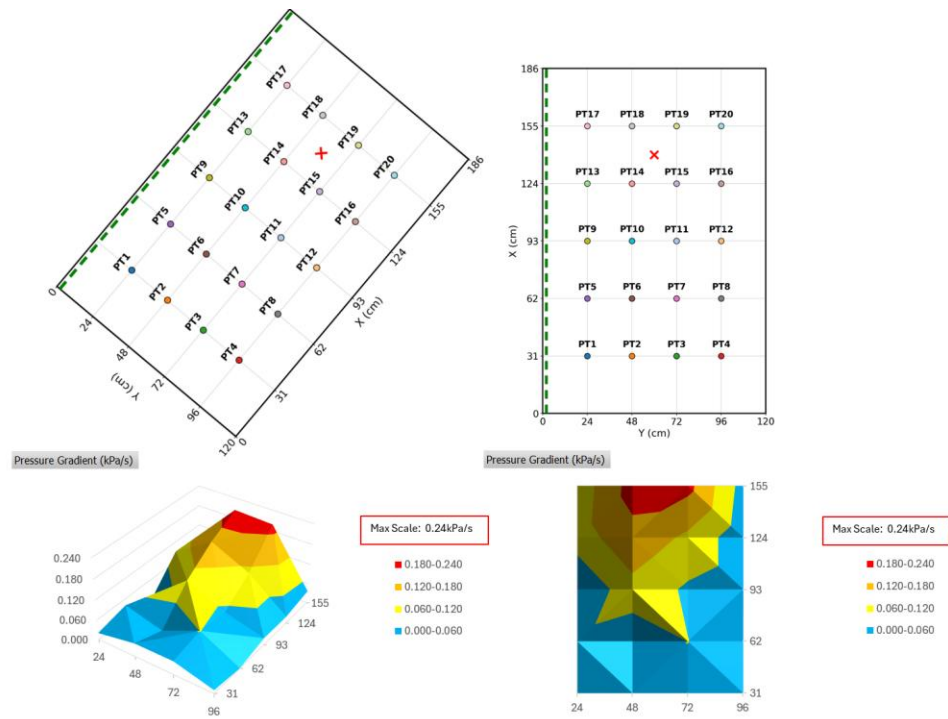


Figure 4.98: Contour map of dP/dt for $t = 667-668s$ (peak transient leak), Experiment #12

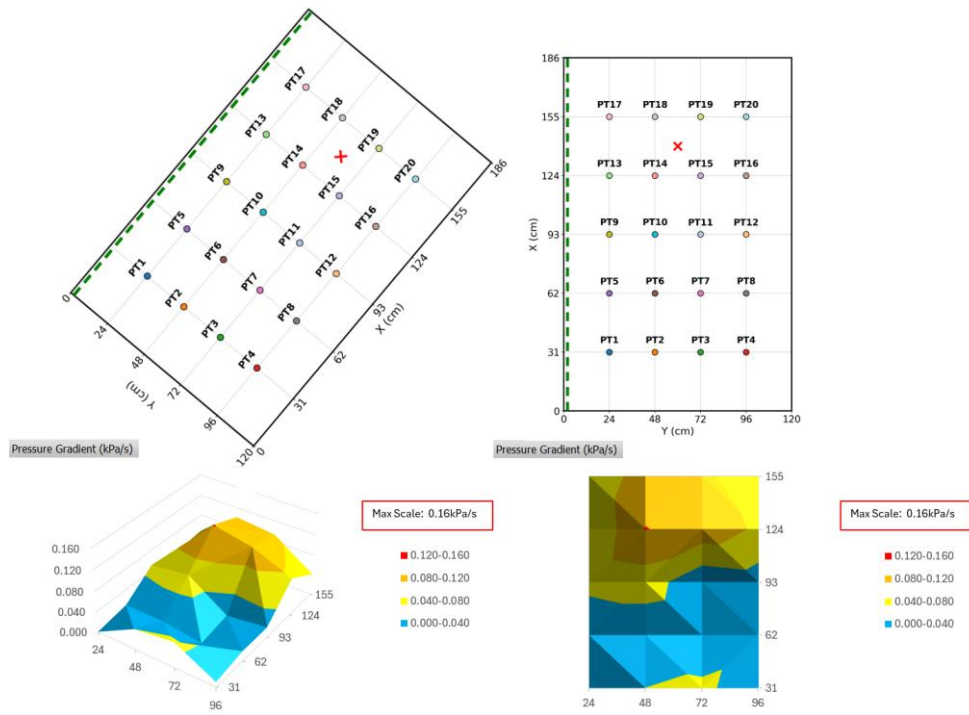


Figure 4.99: Contour map of dP/dt for $t = 668-669s$ (first second of steady leak), Experiment #12

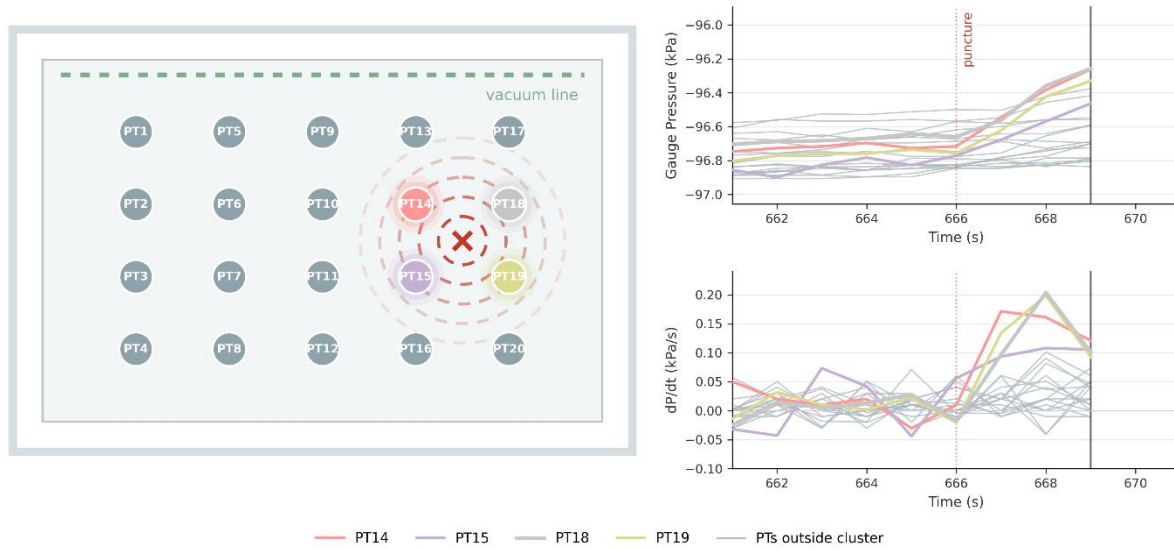


Figure 4.100: Localization window for Experiment #12 ($t=666$ to 669 s)

4.3.10 Experiment #13

In Experiment #13 a pinhole was punched at location X_{13} near the mid-left edge of the fabric stack using a 0.14mm diameter needle. This location lies just outside the array on the left edge, between PT2 and PT3, each 19.6cm distant, Figure 4.101.

Figure 4.102 details key events of Experiment #13. The vacuum-drop test was conducted from $t = 74$ s to 374 s and recorded a 2.78kPa rise in array-averaged gauge pressure.

The vacuum pump was restarted at $t = 375$ s and shut off at $t = 549$ s to set the pre-puncture baseline. The pinhole was punched at $t = 602$ s, Figure 4.103. PT2 and PT3, the PTs closest to X_{13} rose together on puncture, PT2 peaking at 0.22kPa/s and PT3 at 0.21kPa/s, more than three times the next-fastest rate. The transient phase spanned $t = 602$ s to 604 s, with steady-state leak phase beginning at $t = 605$ s.

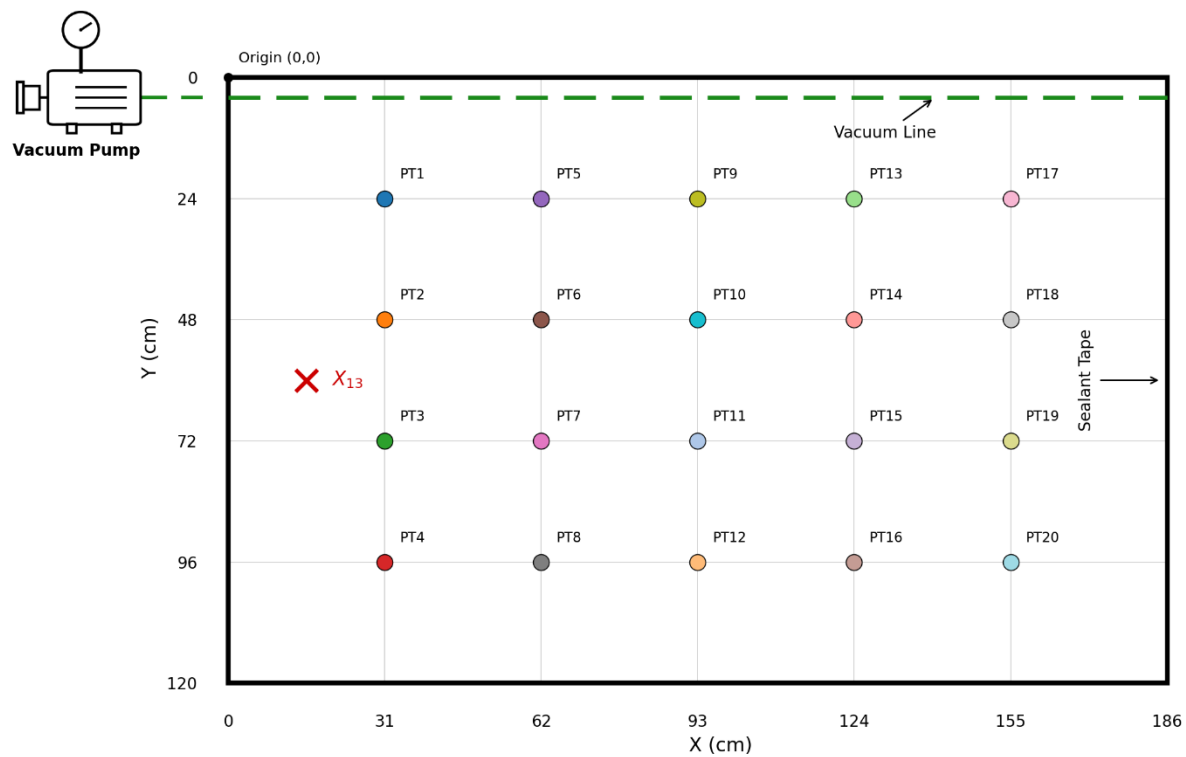


Figure 4.101: Pinhole location, Experiment #13

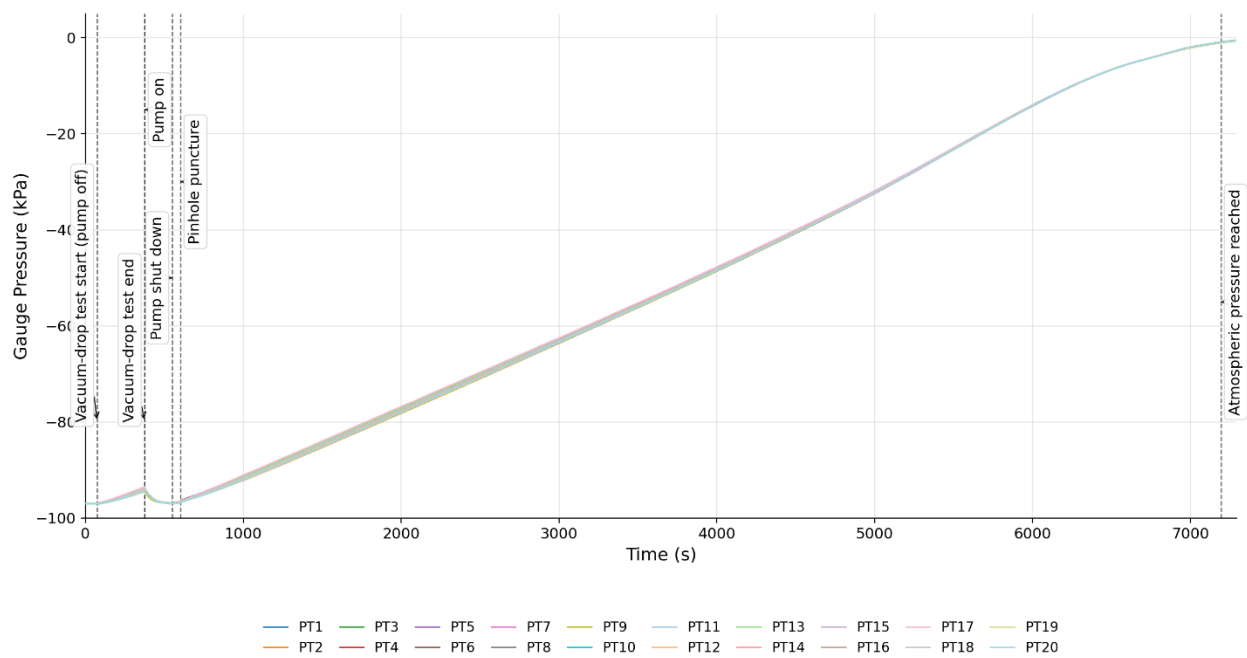


Figure 4.102: Key events, Experiment #13

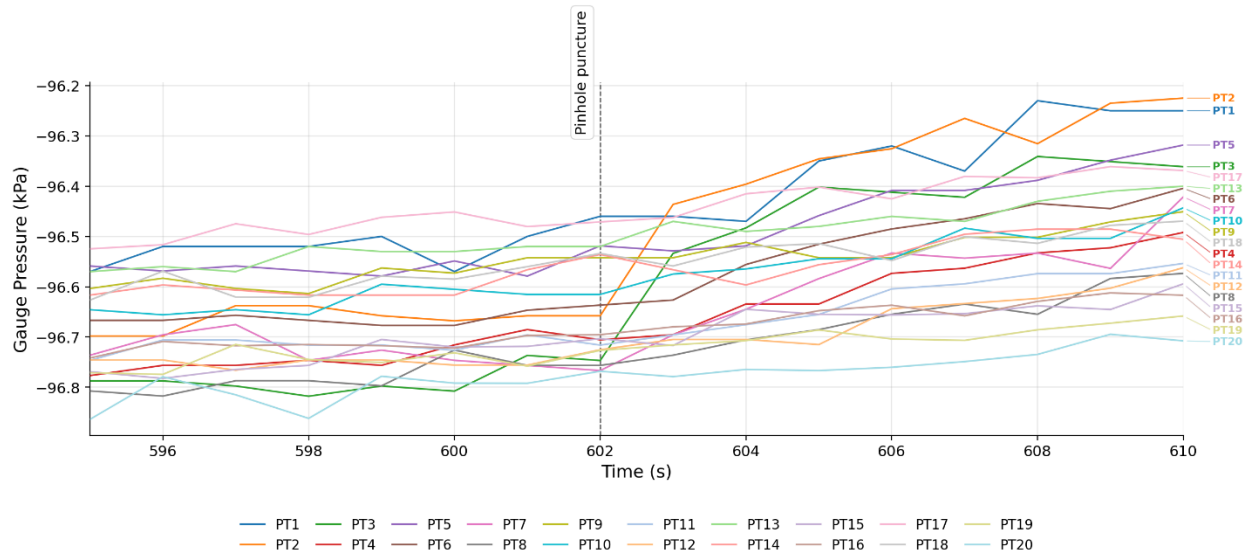


Figure 4.103: Pinhole puncture event, Experiment #13

Before puncture the dP/dt field is uniform and near zero across the array, Figure 4.104. At the moment of puncture the dP/dt field shows a peak at PT2 and PT3, nearest X_{13} and confirming leak location, Figure 4.105. The leak dissipates as surrounding PTs equilibrate, Figure 4.106. Figure 4.107 shows the complete three-second window for Experiment #13. Although this experiment was conducted at one of the highest vacuum levels of the campaign, the pinhole had only a modest effect on gauge pressure. This most likely reflects an insufficient puncture. This is discussed further in Chapter 5. Additional supporting figures are provided in Appendices B–E.

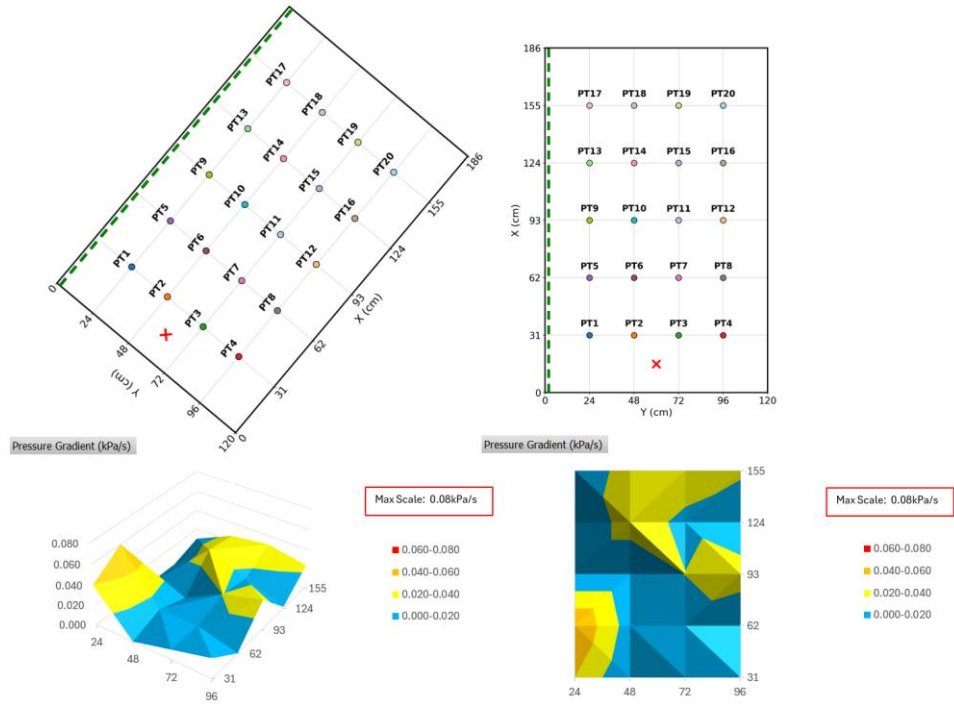


Figure 4.104: Contour map of dP/dt for $t = 601-602s$ (pre-puncture baseline), Experiment #13

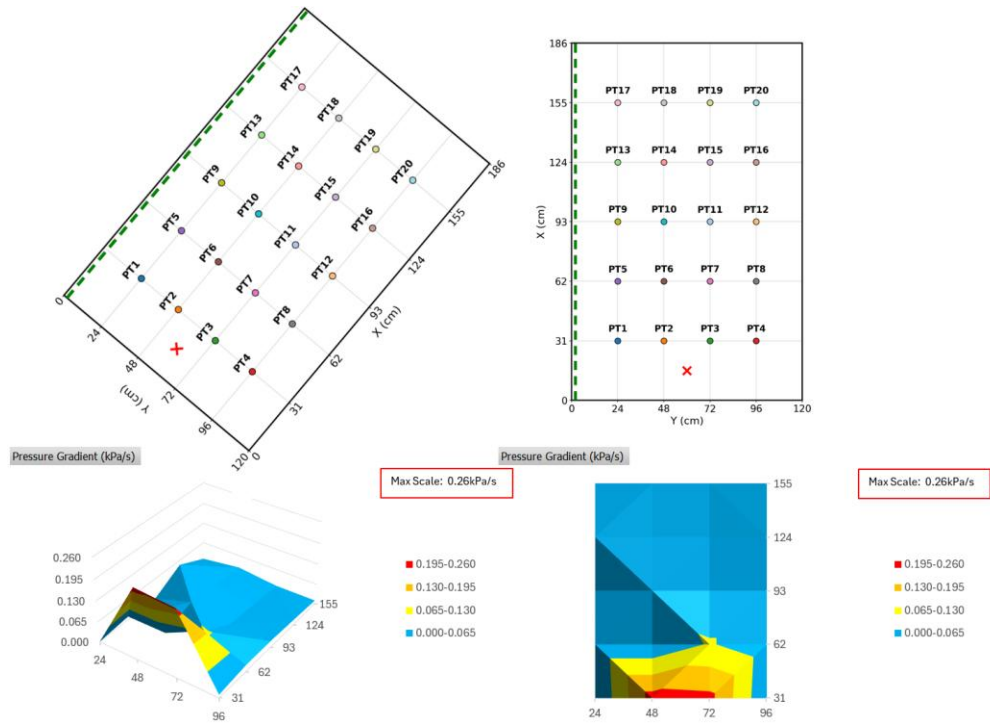


Figure 4.105: Contour map of dP/dt for $t = 602-603s$ (peak transient leak), Experiment #13

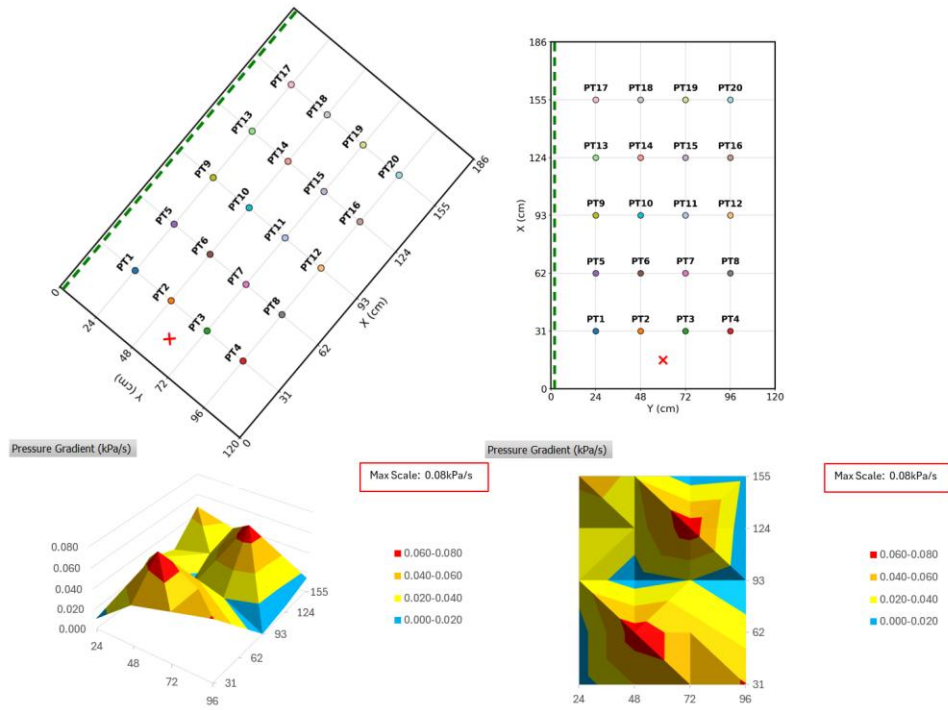


Figure 4.106: Contour map of dP/dt for $t = 603-604s$ (first second of steady leak), Experiment #13

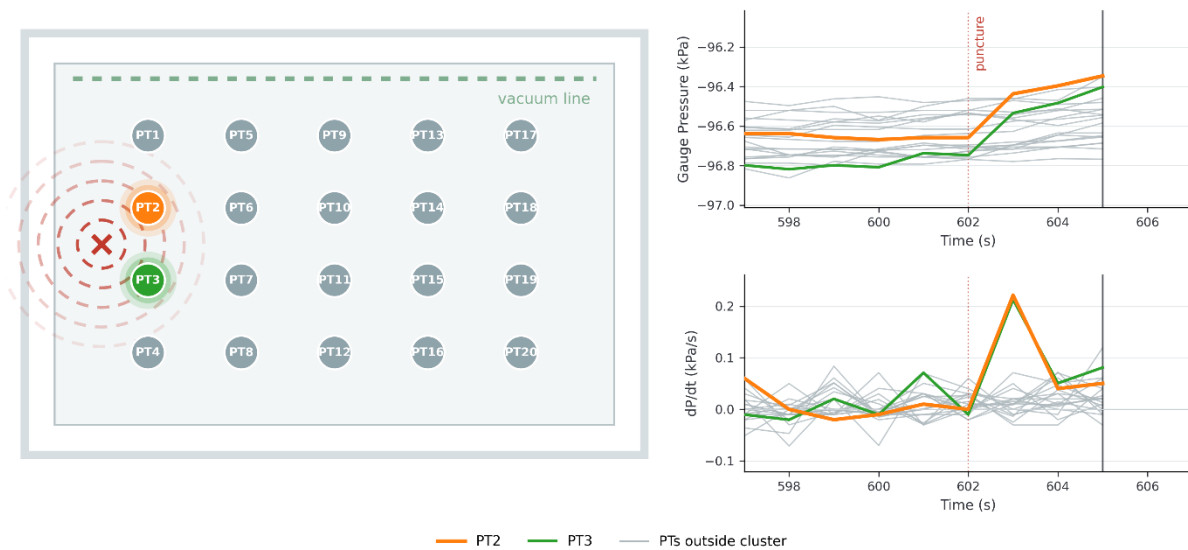


Figure 4.107: Localization window for Experiment #13 ($t=602$ to $605s$)

4.3.11 Experiment #14

In Experiment #14 a pinhole was punched at location X_{14} near the bottom mid-left of the fabric stack using a 0.14mm diameter needle. This location lies between PT4 and PT8, each 19.6cm distant, Figure 4.108.

Figure 4.109 details key events of Experiment #14. The vacuum-drop test was conducted from $t = 36s$ to $336s$ and recorded a 2.24kPa rise in array-averaged gauge pressure. The vacuum pump was restarted at $t = 337s$ and shut off at $t = 505s$ to set the pre-puncture baseline. The pinhole was punched at $t = 558s$, Figure 4.110. PT4 and PT8, the PTs closest to X_{14} , rose together one second after puncture, with PT4 peaking at 0.24kPa/s and PT8 at 0.22kPa/s. Both were more than three times the next fastest rate. The transient phase spanned $t = 558s$ to $561s$, with steady-state leak phase beginning at $t = 562s$.

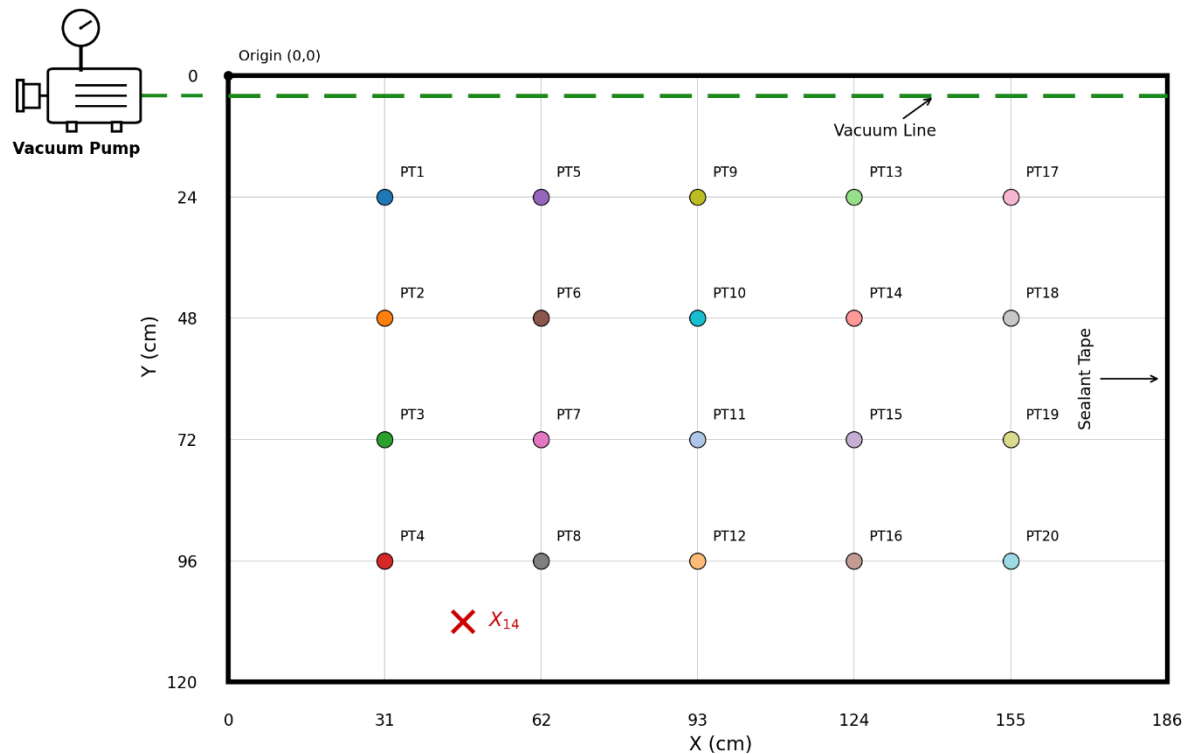


Figure 4.108: Pinhole location, Experiment #14

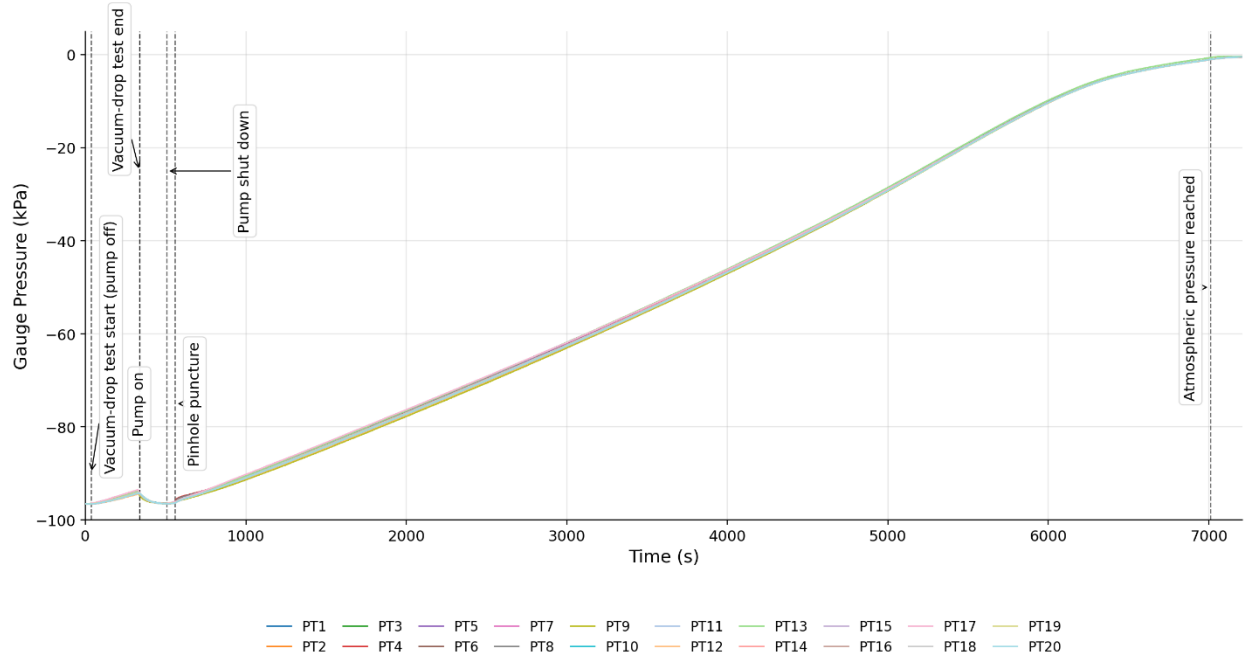


Figure 4.109: Key events, Experiment #14

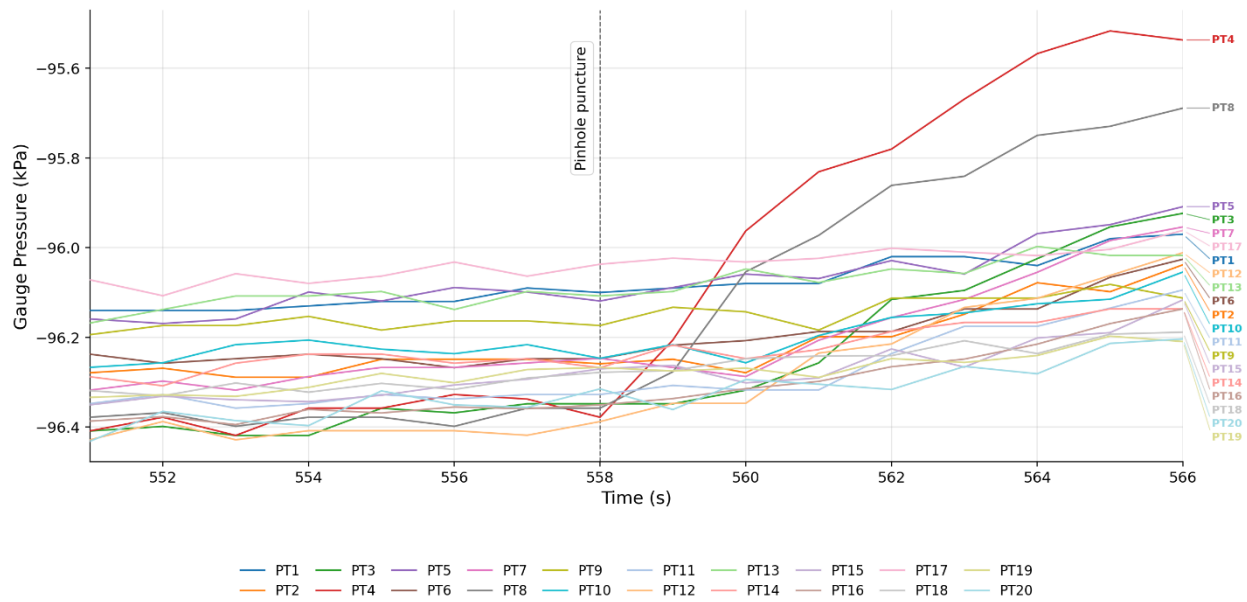


Figure 4.110: Pinhole puncture event, Experiment #14

Before puncture the dP/dt field is uniform and near zero across the array, Figure 4.111. One second after puncture the dP/dt field shows a peak at PT4 and PT8, nearest X_{14} and confirming

leak location, Figure 4.112. The leak dissipates as surrounding PTs equilibrate, Figure 4.113. Figure 4.114 shows the complete three-second window for Experiment #14. Additional supporting figures are provided in Appendices B–E.

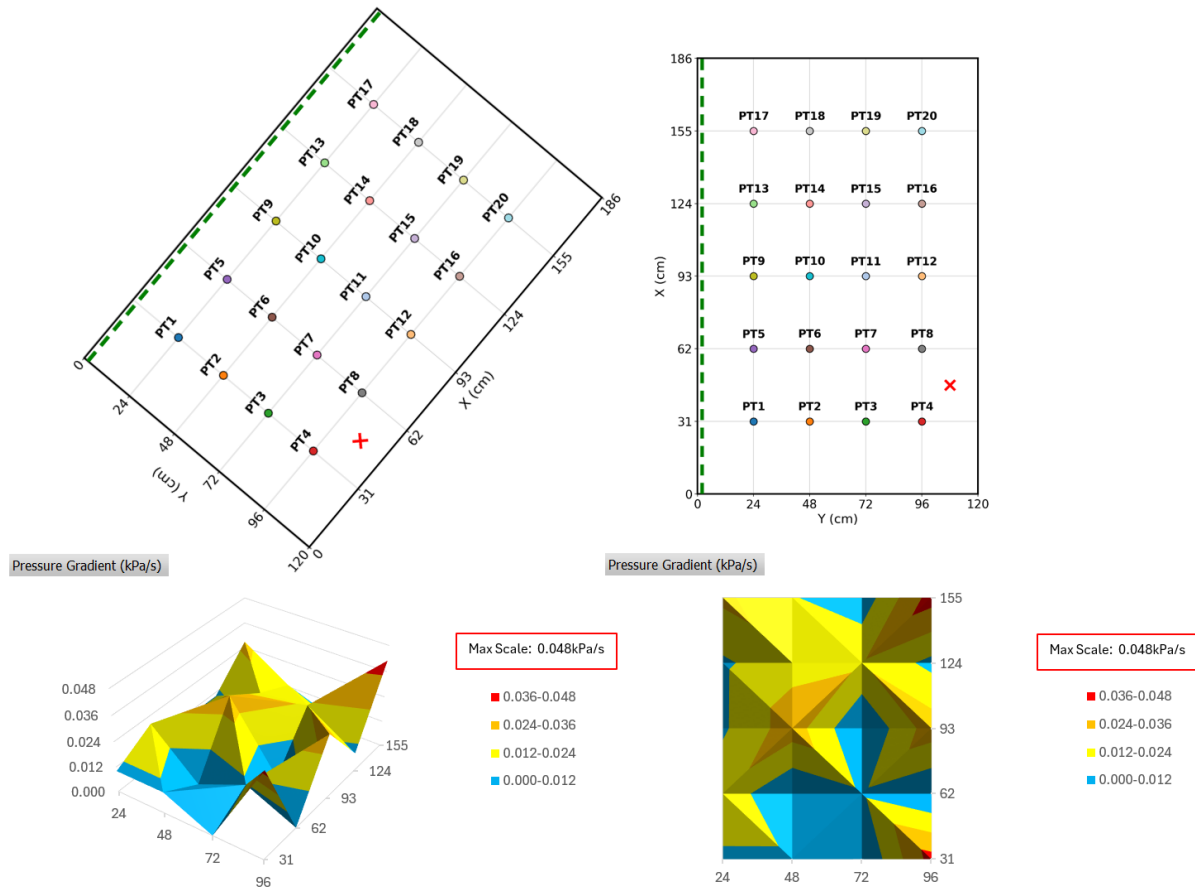


Figure 4.111: Contour map of dP/dt for $t = 557-558s$ (pre-puncture baseline), Experiment #14

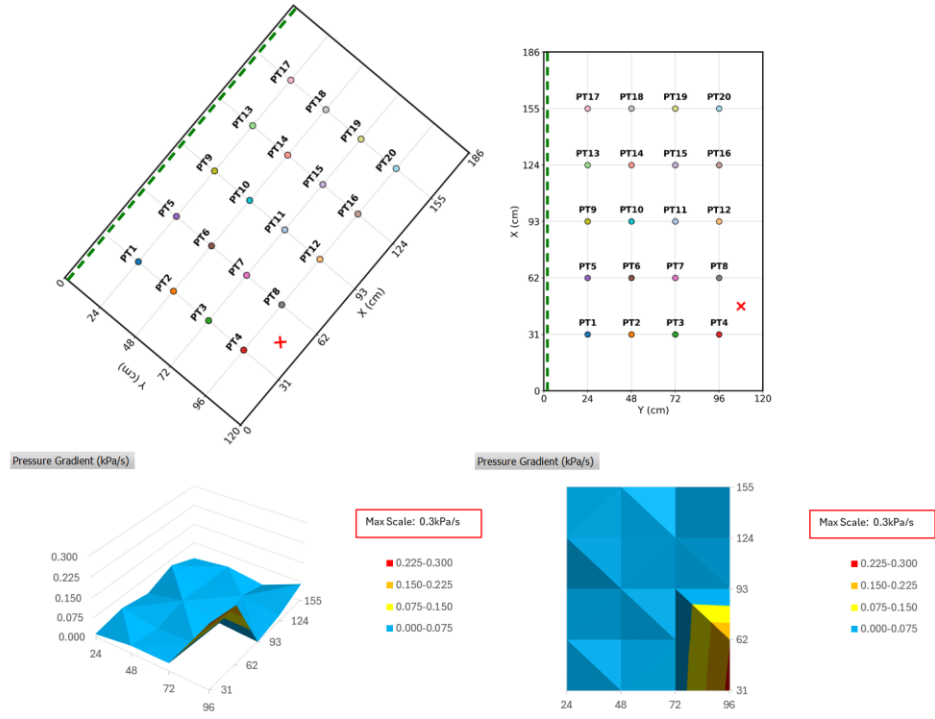


Figure 4.112: Contour map of dP/dt for $t = 559-560s$ (peak transient leak), Experiment #14

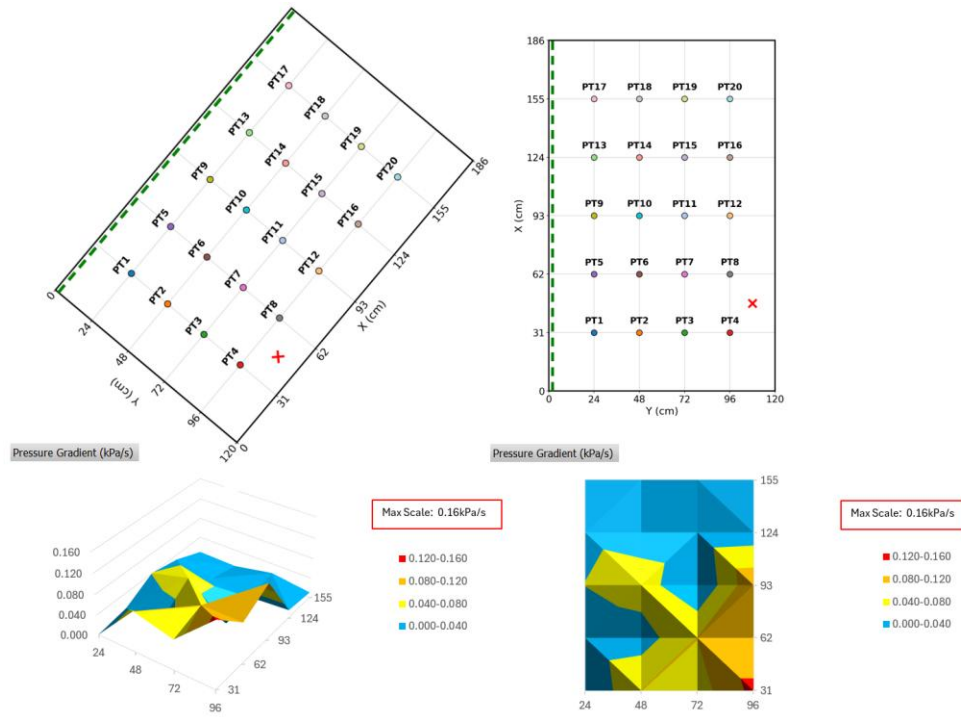


Figure 4.113: Contour map of dP/dt for $t = 560-561s$ (first second of steady leak), Experiment #14

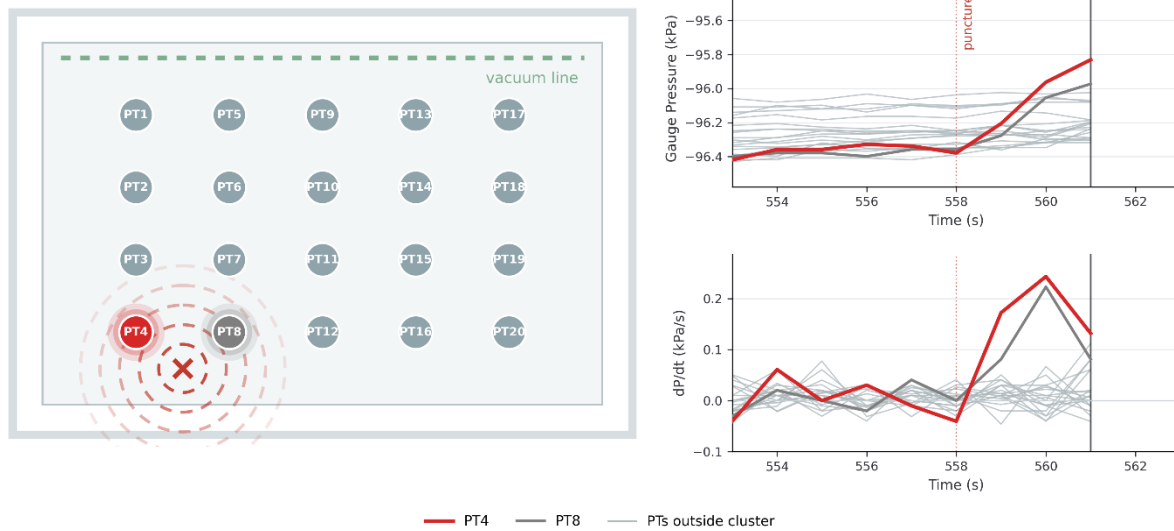


Figure 4.114: Localization window for Experiment #14 ($t=558$ to 561 s)

Chapter 5 Analysis and Discussion

5.1 Overview

This thesis aims at determining whether vacuum film leaks can be localized during vacuum-drop tests rather than merely detected. The proposed method uses direct pressure measurements taken across the fabric stack rather than flow measurements taken at boundaries. Twenty PTs were installed beneath the vacuum film at known positions and used for recording gauge pressures at 1Hz during pump-off vacuum-drop conditions. Chapter 2 identified two limitations to existing localization methods: their reliance on pump-driven flow and their dependence on boundary measurements. Chapters 3 and 4 developed and tested a distributed pressure-sensing approach intended to address this operating condition.

Fourteen experiments were conducted on the same 1.86m by 1.20m fabric stack. Each experiment introduced a pinhole at a known location and recorded PT array response during vacuum-drop tests and subsequent pressure evolution toward atmospheric pressure. Three experiments used a 0.25mm diameter needle while the remaining eleven experiments used a 0.14mm diameter needle. Pinholes were introduced at centre, edge, corner, outside-array and inter-sensor positions. Repeated centre punctures using the 0.14mm diameter needle provided a basis for assessing reproducibility, while one corner location was tested with both needle sizes for comparison.

Table 5.1 consolidates the results of all fourteen experiments, with its columns arranged in three groups. The first group lists experimental parameters: experiment number, pinhole coordinates on the fabric stack, and needle diameter. The second group reports vacuum-drop test results: time window over which the test ran, rise in array-averaged gauge pressure, and overall pass/fail. The third group describes induced leak test results. Four timing columns provide: time when the pump was turned back on to restore vacuum, time when the pump was turned off to reinitiate vacuum-drop test conditions for pre-puncture baseline, time of puncture, and time when the dP/dt response peaked. Six result columns provide: peak dP/dt gradient, PT that recorded it, PTs nearest the pinhole, pre-puncture noise, signal-to-noise ratio of peak against noise, and the resulting time taken to return to atmospheric pressure.

Table 5.1: Summary of experimental results

Parameters			Vacuum-Drop			Leak									
			Time	Result		Times				Results					
Exp #	Pinhole (x, y) (cm)	Needle dia. (mm)	(s)	(kPa)	P/F	Pump on (s)	Pump off (s)	Punct. (s)	Peak dP/dt (s)	Peak dP/dt (kPa/s)	Leading PT at peak	Nearest PTs	Noise (kPa/s)	Signal-to-noise	Time to atm. (s)
1	(93, 60)	0.25	186–486	4.36	P	493	708	731	731	3.20	PT10	PT10, PT11	0.039	83	2800
2	(170.5, 108)	0.25	30–330	5.53	F	341	728	744	744	0.70	PT20	PT20	0.027	26	4000
3	(170.5, 12)	0.25	65–365	4.04	P	366	720	730	731	0.38	PT17	PT17	0.027	14	5900
4	(93, 60)	0.14	131–431	3.41	P	555	735	784 & 905	785 & 906	0.40 0.82	PT11 PT11	PT10, PT11	0.029	28	5089
5	(93, 60)	0.14	184–484	4.52	P	485	795	838	839	0.77	PT11	PT10, PT11	0.027	29	4540
6	(170.5, 12)	0.14	131–431	4.67	P	432	670	726	727	0.79	PT17	PT17	0.023	34	4340
7	(93, 108)	0.14	85–385	3.27	P	390	550	603	605	0.86	PT12	PT12	0.027	32	5310
8	(15.5, 12)	0.14	448–748	3.92	P	753	926	981	982	0.47	PT1	PT1	0.026	18	5599
9	(93, 12)	0.14	227–527	4.65	P	528	850	932	934	0.67	PT9	PT9	0.032	21	4612
10	(46.5, 60)	0.14	38–338	2.66	P	339	460	503	505	0.20	PT2	PT2, PT3, PT6, PT7	0.022	9	7367
11	(93, 60)	0.14	15–315	2.70	P	316	903	955	956	0.31	PT11	PT10, PT11	0.022	14	7768
12	(139.5, 60)	0.14	81–381	2.82	P	382	608	666	668	0.20	PT18	PT14, PT15, PT18, PT19	0.026	8	6713
13	(15.5, 60)	0.14	74–374	2.78	P	375	549	602	603	0.22	PT2	PT2, PT3	0.024	9	6967
14	(46.5, 108)	0.14	36–336	2.24	P	337	505	558	560	0.24	PT4	PT4, PT8	0.025	9	7008

This chapter analyzes experimental results holistically. Section 5.2 evaluates localization accuracy and signal-to-noise ratio. Section 5.3 discusses the magnitude of leak signals and sources of variability, including needle-size effects and their significance. Section 5.4 interprets the spatial signatures of leaks induced at three positions relative to the array: close to a single PT, equidistant from two PTs, and equidistant from four PTs (a cell-centred leak). Section 5.5 examines an anomaly observed in Experiment #7. Section 5.6 compares the proposed method with existing leak-localization approaches. Section 5.7 defines the scope and limitations of the work.

5.2 Leak Localization Accuracy

The primary result of this work is that the distributed PT array localized the induced leak to the correct region of the vacuum bag assembly in all fourteen experiments, Figure 5.1. At the peak dP/dt gradient, PT(s) returning the largest gradient coincided with the sensors closest to the pinhole, systematically. Gradients were well above baseline noise, with peak signal-to-noise ratios from 8 to 83, Table 5.1.

The noise is the standard deviation of the per-second dP/dt gradient across the array during the steady pre-puncture interval, while the vacuum bag assembly is held under vacuum with no induced leak present. The signal-to-noise ratios in Table 5.1 are the peak dP/dt gradient at the leading PT divided by this noise.

PT spacing at 31cm by 24cm sets the cell size to which leaks are resolved; any leak lies at most 19.6cm diagonally from the PT that locates it. A leak beyond the outer edge can lie farther still as boundary PTs have no neighbours past them. Across the fourteen experiments, distances between pinhole and the PT that located it averaged 16.3cm. It was 12cm where the pinhole was midway between two column PTs and 19.6cm at cell-centred and off-array positions. These distances are set by PT spacing rather than sensing performance.

Locations were read from the PT with the largest peak dP/dt . This peak occurred in the same second as the puncture or the one after. Reading at the peak matters because the pressure rise takes about a second to spread from the puncture to the surrounding PTs, so the PT highest in the very first second is not always the one highest at the peak. Experiment #7 was the only case where the largest dP/dt required confirmation against the surrounding PTs, as examined in Section 5.5.

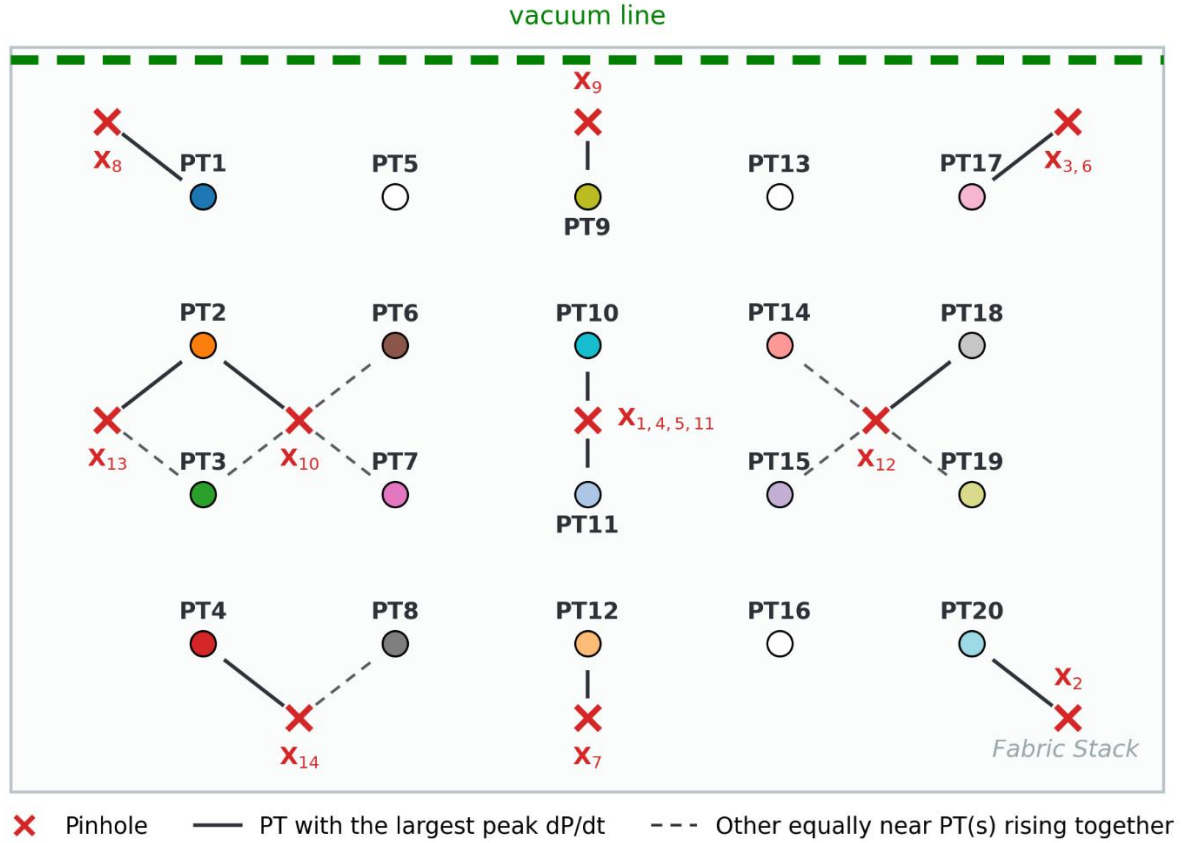


Figure 5.1: Each pinhole linked to the PT recording the largest dP/dt across the fourteen experiments

The centre of the fabric stack was punctured four times with the 0.14mm diameter needle, twice in Experiment #4 and once in each Experiments #5 and #11. All four cases identified the same PT10 and PT11 pair surrounding the centre, with PT11 leading each time. Localization rests on PT identification and is therefore unaffected by scatter in dP/dt magnitude.

5.3 Magnitude of Leak Signals

Peak dP/dt gradients varied widely across the fourteen experiments, from 3.20kPa/s down to 0.20kPa/s. The variability did not follow needle diameter: the largest gradient of all came from Experiment #1 with the 0.25mm diameter needle, yet Experiments #2 and #3 using the same needle fell within the range covered by the 0.14mm diameter needle experiments. Nor did the signal reproduce at a fixed location. PT11, the leading PT for the central punctures, peaked at 0.40kPa/s

and 0.82kPa/s in Experiment #4, 0.77kPa/s in Experiment #5, and 0.31kPa/s in Experiment #11. This scatter is a property of the puncture, its exact geometry and any partial resealing of the vacuum film around it, rather than of the array or the leak location.

This variability does not affect the localization method. Localization depends on which PT records the largest dP/dt gradient relative to its neighbours, not on the absolute size of that gradient. A peak of 0.20kPa/s localizes a leak as effectively as a peak of 3.20kPa/s. The absolute magnitude confirms that a leak is present without itself fixing its position.

5.4 Spatial Signatures and Geometry

The array's response to a puncture is a pattern defined across the twenty PTs, the shape of which depends on leak location. Three types of patterns appeared, determined by the number of PTs nearest to the leak.

When a single PT was nearest the leak, in Experiments #2, #3, #6, #8 and #9, that PT recorded a dP/dt gradient well above the rest. When the leak sat midway between two PTs, at the fabric stack centre in Experiments #1, #4, #5 and #11, along the left edge in Experiment #13, and along the bottom edge in Experiment #14, the two nearest PTs recorded the largest gradients. When the leak sat at the centre of a cell, equidistant from four PTs, in Experiments #10 and #12, the four bounding PTs recorded the largest gradients, comparable to one another. In each arrangement the leak fell within the region marked by the responding PTs. Experiment #7 was a single-PT case in which a measurement artifact distorted the pattern, as discussed in Section 5.5.

Locating a leak rests on the pattern across the array. The contour maps of Chapter 4 show this: the PTs that respond most strongly, and the shape of their response, mark where the leak lies.

5.5 Experiment #7 Anomaly

In Experiment #7 a leak was punctured at position X_7 , at the bottom-centre of the fabric stack nearest PT12. PT12 recorded the largest dP/dt gradient at 0.86kPa/s, correctly identifying leak location. PT13 followed closely at 0.71kPa/s, yet PT13 sits near the top-right of the array 90cm from the leak. Reading the single largest gradient alone would therefore have come close to

misleading: in the first second after puncture PT13 led, 0.30kPa/s against 0.28kPa/s, before PT12 overtook it at peak.

The full pattern across the array resolves the case. A genuine leak raises the dP/dt gradient at the surrounding PTs, whereas a single-channel fault does not. At peak, the PTs around PT12 rose with it (PT8, PT11 and PT16 at 0.37kPa/s, 0.13kPa/s and 0.27kPa/s), placing PT12 at the centre of a coherent local rise. The PTs around PT13 did not (PT9, PT14 and PT17 at 0.01kPa/s, -0.02kPa/s and 0.02kPa/s), marking the rise at PT13 as an isolated single-channel event rather than a pressure change. Figure 5.2 shows PT12 rising with its neighbours and PT13 rising alone.

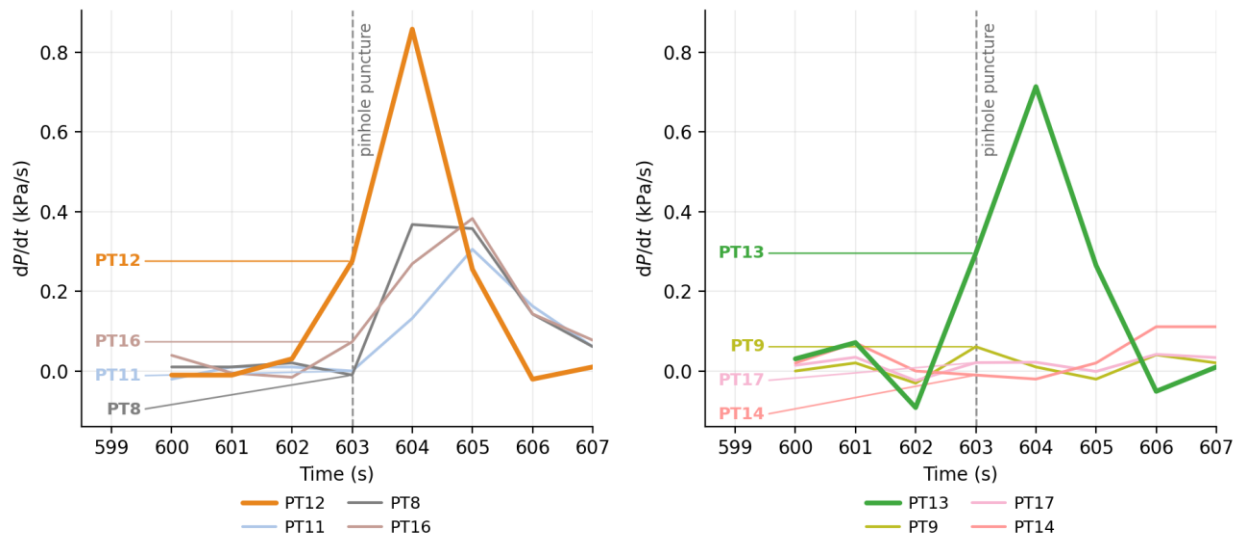


Figure 5.2: dP/dt gradients after puncture in Experiment #7. PT12 (left) rises with its neighbours; PT13 (right) rises alone

This is the basis of the method's robustness to single-channel faults. A genuine leak always appears across neighbouring PTs; an isolated single-PT spike can be rejected as an artifact rather than mistaken for a leak. Experiment #7 is the one case in this work where that distinction was tested and the array resolved it correctly.

5.6 Relation to Existing Methods

The vacuum leak detection methods reviewed in Chapter 2 locate a leak by measuring the flow rate during sustained vacuum and inferring its position from that flow rate. One approach fits a flow model to the measured flow rates and solves for position [9]. Another trains a machine-learning model on simulated flow data to predict it [12].

The present method differs in two ways. It senses pressure across the interior of the vacuum bag assembly rather than flow rate at its boundary, and it operates during the pump-off vacuum-drop test. The leak region is identified from the dP/dt gradient recorded across the array, the fastest-responding PTs marking the region nearest the leak.

No existing method combines all three characteristics of the present one: it senses across the fabric stack, works without pump-driven flow, and identifies the leak region from the dP/dt gradient pattern across the array.

5.7 Scope and Limitations

The findings come from a single experimental configuration. All experiments used a flat mould on which the vacuum film conforms readily and the fabric stack compacts evenly. The method was not tested on other fabric stack sizes, different fabric types, asymmetric fabric stacks, ply drops, preform inserts, fabric stacks with a core or with different PT spacings. Most production moulds are curved; air evacuation paths, air ingress paths, conformity of vacuum film, breather compressibility and local compaction will differ. The pressure distribution from a leak may differ with them altering localization.

Localization resolves a leak to an area, not to a specific coordinate. Finer localization would require interpolation and more closely spaced PTs. Leaks beyond the edge of the array are assigned to the nearest PT, so edge leaks carry a position bias toward the array itself.

The array's settled baseline changed steadily over the course of the experiments. The average gauge pressure reached before puncture decreased by one to two kPa, to a higher vacuum, and the time to reach atmosphere after puncture lengthened, Figure 5.3. A slow drift in the PTs, calibrated once at the start, may have added to the apparent baseline shift.

In most experiments the four row-averages separated in order, the row nearest the vacuum line was highest and the row farthest from the vacuum line was lowest (Figure 5.4, Experiment #9). Three runs departed from this, Experiments #10, #11 and #13 where the rows converged to within 0.1kPa to 0.2kPa and lost that order. As the seal tightened and the residual leak decreased, the pressure differences between rows decreased with it.

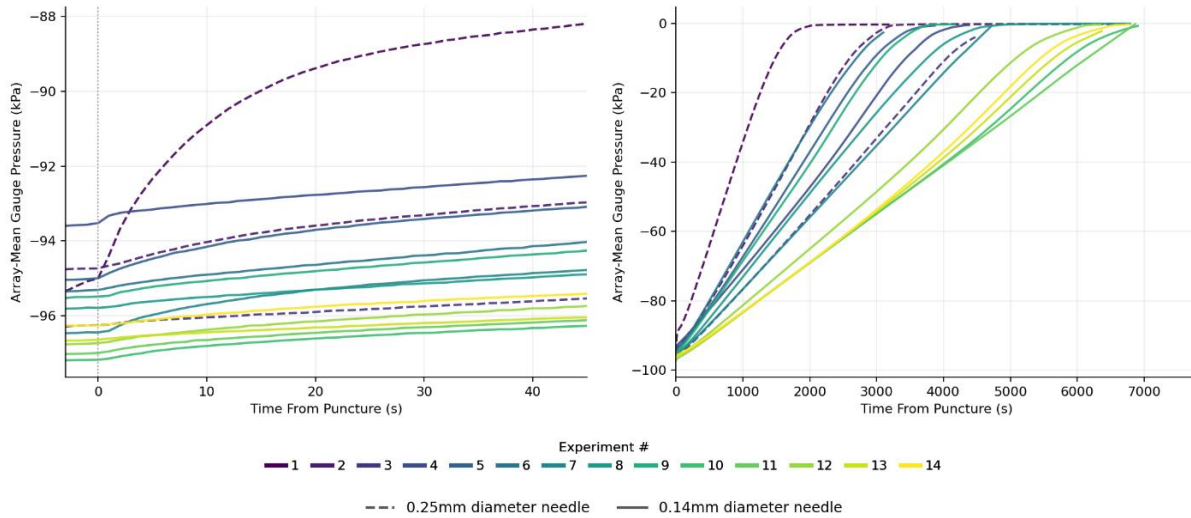


Figure 5.3: Array-mean gauge pressure from puncture, coloured by experiment number: first 45s (left) and full leak-down (right)

The smallest detectable leak was not approached. Even the weakest leak tested produced a peak dP/dt gradient about eight times the baseline noise, Table 5.1. How the method behaves for much weaker leaks near the threshold of a vacuum-drop test was not investigated and is left to future work.

The findings hold within the conditions described above. Within those conditions the array localized the leak to the correct region in each of the fourteen experiments and across the range of leak geometries tested. The conclusions and the directions for future work are drawn together in Chapter 6.

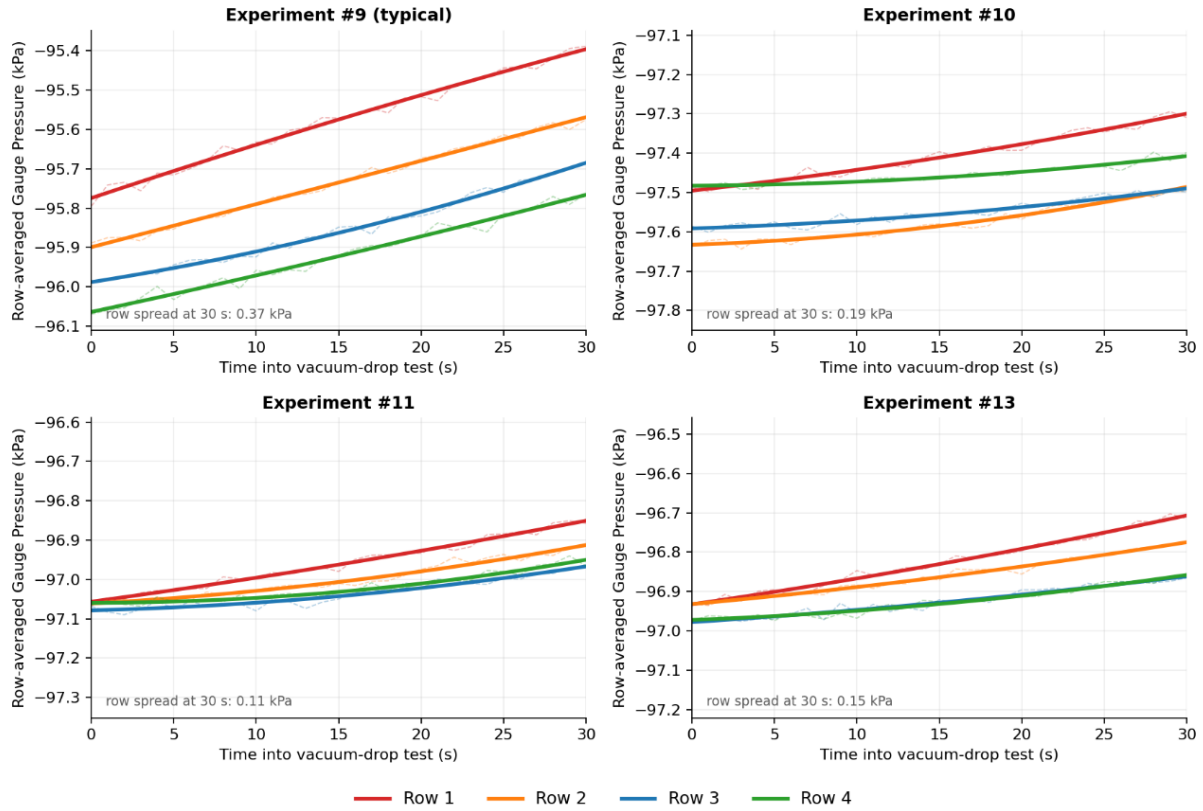


Figure 5.4: Row-averaged gauge pressure over the first 30s of the vacuum-drop test, for a typical experiment (#9) and the three where the row pattern breaks down (#10, #11, #13)

Chapter 6 Conclusions

This thesis investigated the feasibility of localizing vacuum film leaks during vacuum-drop tests in PMC manufacturing by infusion. To address this goal, a distributed pressure-sensing approach was developed and tested on a laboratory scale fabric stack. The main contributions of the thesis are:

- A distributed vacuum measurement system was developed using twenty PTs installed beneath the vacuum film and connected to a data-acquisition system capable of recording local gauge pressures during vacuum-drop tests.
- Vacuum film leaks were localized during pump-off vacuum-drop tests for both residual and induced leaks, by identifying the nearest PT(s) in a robust manner.
- Analysis demonstrated that leak localization should focus on the distribution pattern of dP/dt gradients across the PT array rather than on local pressure magnitudes or distribution patterns of pressure magnitudes alone.

6.1 Principal Findings

Across all fourteen experiments performed on a single fabric stack, a distributed array of twenty PTs localized the region of induced vacuum film leak during the vacuum-drop test. In every experiment, PT(s) recording the largest peak dP/dt gradient response were nearest the known pinhole location. This result held for both needle diameters and for all pinhole locations tested including centre, edge, corner, outside-array and cell-centred positions. The leak was assigned to the correct sensor region in every experiment with an average distance of 16.3cm between the known pinhole and leading PT. This distance was set by PT spacing rather than by the pressure sensing principle itself.

The four objectives set out in Section 1.3 were met. The first objective was addressed through the array of twenty PTs described in Chapter 3. This array was installed beneath the vacuum film using industrial grade ancillaries and standard data acquisition hardware suitable for vacuum-drop testing.

The second objective was met through the pinhole procedure and acquisition setup described in Chapter 3. This protocol introduced controlled vacuum film leaks of known position and size and allowed the pressure response across the array to be compared systematically across fourteen experiments.

The third objective was to distinguish a leak's dP/dt gradient signature from two other sources of spatial variation across the array: edge effects and single-channel sensor faults. A puncture of the vacuum film raised the dP/dt at the nearest PT together with its neighbours, distinguishing it from a single-channel fault, which raises one PT alone. Edge effects appeared as a slow pattern in the pre-puncture baseline rather than as a sharp rise in dP/dt at the moment of puncture.

The fourth objective was addressed through localization results reported and analyzed in Chapters 4 and 5. Across the tested positions, localization succeeded within two seconds of an induced leak.

6.2 Contribution Summary

The thesis addresses two shortcomings of the published methods reviewed in Chapter 2.

Firstly, it senses across the interior of the vacuum bag assembly rather than only at its boundary. The leak region is inferred from dP/dt gradient patterns measured by PTs distributed beneath the vacuum film. The fastest responding PT(s) identify the nearest sensor region directly without requiring a flow model or trained network to invert.

Secondly, the method operates during the pump shutdown phase of the vacuum-drop test. Measurements are taken with the pump isolated and the vacuum bag assembly sealed, which is a crucial phase of infusion PMC manufacturing that flow based methods cannot use. When a leak opens, the nearest PT(s) return identifiable signals within one to two seconds. When a leak is already present as the vacuum-drop test begins, the corresponding response builds more gradually over the opening tens of seconds, rather than as a sharp transient. Both delays are much shorter than those used in industrial practice. Residual leaks in the vacuum line, present throughout the campaign and located by the PT array, provided clear evidence of this detection capability for inherent leaks that are not introduced suddenly.

In both cases the localization used dP/dt rather than gauge pressure values. A per-sensor offset drifting away from its calibration shifts that PT's reading but not its dP/dt , so localization is robust to per-sensor drift in a way that localization based on pressure magnitude would not be. The fourteen experiments were run by a single operator over several months using low-cost PTs calibrated once at the start of the campaign. Over that period the baseline vacuum drifted and the gauge pressure readings grew less consistent between experiments, yet the nearest-PT identification held in every one. Localization tolerated the variation of a single operator, a single calibration of each PT at the start rather than before each experiment, and drift in inexpensive sensors and ageing acquisition hardware over several months. The fact that the method stayed reliable under conditions that progressively blunted absolute pressure readings is itself a very useful practical result, directly relevant to deployment on shop floor and large-scale industrial settings.

The distributed layout also lets the array check itself. A real leak raises dP/dt gradients at the nearest PTs and their neighbours, together, so a single PT that rises alone can be recognized as a sensor fault rather than a leak. A single boundary flow meter does not offer any means to verify nor equivalent checks, hence spatial redundancy gives the distributed array further fault tolerance that single-sensor measurements cannot.

6.3 Future Work

Limitations identified in Chapter 5 point to several next steps. The first is the study of multiple and distributed leaks. Almost every experiment introduced a single pinhole, the exception being Experiment #4, in which a second puncture followed the first at the same PT. Real vacuum film defects may occur simultaneously or extend along a seam. How dP/dt gradients from simultaneous leaks may interact remains an open question. A controlled repeatability study using repeated punctures made using the same needle at the same location would also help separate true leak size effects from puncture-to-puncture variability.

A second direction for future work is scale. Moving from the 1.86m by 1.20m laboratory stack used in this work to production parts such as a wind turbine blade shell or hull panel, where a failed vacuum-drop test is most costly, would test whether the capability survives at substantially larger scales. At such scale a dense array is perhaps less practical, so the question becomes where

to position a limited number of PTs. A related consideration is curved geometry and the presence of inserts. The method presented here was established using a flat mould and controlled conditions, while production parts are curved. The air evacuation paths, vacuum film conformity over corners, double curvature surfaces and local fabric compaction all differ in industrial cases. Repeating the experiments on a representative curved mould would show how to make the localization capability transfer.

A third direction for future work is industrialization. In this work, dP/dt gradients were computed and interpreted after each test, whereas a deployable version would compute dP/dt gradient field live during manufacturing and flag leak regions immediately and autonomously, paired with wireless PTs and more developed signal analysis. Technicians could correct leaks much faster and more effectively.

A further direction for future work concerns the vacuum-drop test itself. Pass/fail thresholds are not standardized across industry and the relationship between measured dP/dt gradients and final laminate quality remains insufficiently defined. Infusing fabric stacks across a controlled range of measured leak rates and characterizing the resulting porosity, fibre volume fraction and mechanical performance would help establish science-based, quality-referenced vacuum-drop thresholds. This would provide the industry with a better defined basis for accepting or rejecting vacuum bag assemblies before infusion.

6.4 Practical Applicability and Closing Remarks

The practical case for further work and deployment rests on what a failed vacuum-drop test costs. On large vacuum infused fabric stacks and parts, a failed vacuum-drop test can initiate a manual search for leaks that occupies skilled operators and delays production. Current hands-on methods only get slower as parts grow. The approach developed here operates within the vacuum-drop test that most manufacturers already perform. It localizes leaks, beyond only assessing the final pass/fail result of the test.

With further work above, the method proposed and demonstrated in this thesis offers a credible route to becoming a practical and economical companion to techniques already in production, covering the vacuum-drop phase that flow based methods are not designed to address.

References

- [1] A. I. Haschenburger, “Influence and detection of vacuum bag leakages in composites manufacturing,” PhD thesis, Delft University of Technology, 2022. doi: 10.4233/uuid:03637286-f682-4602-9890-2ac1c0102599.
- [2] Composites Research Network, “Vacuum Bagging for Vacuum Infusion (P173),” CKN Knowledge in Practice Centre, University of British Columbia, <https://compositeskn.org/KPC/P173> (last edited 16 July 2024).
- [3] A. Haschenburger, N. Menke, and J. Stüve, “Sensor-based leakage detection in vacuum bagging,” *The International Journal of Advanced Manufacturing Technology*, vol. 116, pp. 2413–2424, Jul. 2021. doi: 10.1007/s00170-021-07505-5.
- [4] A. Hindersmann, “Confusion about infusion: An overview of infusion processes,” *Composites Part A: Applied Science and Manufacturing*, vol. 126, p. 105583, Aug. 2019. doi: 10.1016/j.compositesa.2019.105583.
- [5] Y. R. Esmaeili, B. Cosco, and H. Najjaran, “Vacuum bag leak detection for resin infusion: an electric current–based analogy,” *The International Journal of Advanced Manufacturing Technology*, vol. 124, no. 5, pp. 1775–1786, 2023. doi: 10.1007/s00170-022-10552-1.
- [6] B. Yenilmez, M. Senan, and E. M. Sozer, “Variation of part thickness and compaction pressure in vacuum infusion process,” *Composites Science and Technology*, vol. 69, no. 11–12, pp. 1710–1719, Sep. 2009, doi: 10.1016/j.compscitech.2008.05.009.
- [7] A. Baumann, D. May, and J. Hausmann, “Characterization of metallic bushings in RTM-made composites by in-situ leak detection under mechanical loading,” *Composites Part C: Open Access*, vol. 7, p. 100226, Dec. 2022. doi: 10.1016/j.jcomc.2021.100226.
- [8] D. Modi, N. Correia, M. Johnson, A. Long, C. Rudd, and F. Robitaille, “Active control of the vacuum infusion process,” *Composites Part A: Applied Science and Manufacturing*, vol. 38, no. 5, pp. 1271–1287, May 2007. doi: 10.1016/j.compositesa.2006.11.012.
- [9] A. I. Haschenburger et al., “Computational methods for leakage localization in a vacuum bag using volumetric flow rate measurements,” *Production Engineering*, vol. 16, pp. 823–835, Apr. 2022. doi: 10.1007/s11740-022-01129-8.
- [10] C. Brauer, A. Hindersmann, and T. de Wolff, “Voronoi-based vacuum leakage detection in composite manufacturing,” arXiv:2603.29980 [math.MG], Mar. 2026. <https://arxiv.org/abs/2603.29980>
- [11] B. A. Cosco, “A novel application of Schlieren imaging: Leakage localization in composite manufacturing vacuum bags,” MASc thesis, University of British Columbia, Apr. 2023. <https://open.library.ubc.ca/soa/cIRcle/collections/ubctheses/24/items/1.0431040>

- [12] Y. R. Esmaili, "Intelligent machine learning-based leakage detection and localization in vacuum-assisted composite manufacturing," PhD thesis, University of Victoria, Department of Mechanical Engineering, 2025.
<https://dspace.library.uvic.ca/items/d4525457-61ba-4738-8081-e69aada721dc>
- [13] V. Buchinger and Z. S. Khodaei, "Vacuum assisted resin transfer moulding process monitoring by means of distributed fibre-optic sensors: A numerical and experimental study," *Advanced Composite Materials*, vol. 31, no. 5, pp. 467–484, Nov. 2022. doi: 10.1080/09243046.2021.2001910.
- [14] N. A. Siddig, C. Binetruy, E. Syerko, P. Simacek, and S. Advani, "A new methodology for race-tracking detection and criticality in resin transfer molding process using pressure sensors," *Journal of Composite Materials*, vol. 52, no. 29, pp. 4087–4103, 2018. doi: 10.1177/0021998318774829.
- [15] B. Caglar, D. Salvatori, E. M. Sozer, and V. Michaud, "In-plane permeability distribution mapping of isotropic mats using flow front detection," *Composites Part A: Applied Science and Manufacturing*, vol. 113, pp. 275–286, Oct. 2018. doi: 10.1016/j.compositesa.2018.07.036.
- [16] F. Robitaille and R. Gauvin, "Compaction of textile reinforcements for composites manufacturing. I: Review of experimental results," *Polymer Composites*, vol. 19, no. 2, pp. 198–216, 1998, doi: 10.1002/pc.10091.
- [17] S. G. Advani and E. M. Sozer, *Process Modeling in Composites Manufacturing*, 2nd ed. Boca Raton, FL, USA: CRC Press, 2010, doi: 10.1201/b13142.
- [18] A. Endruweit, A. C. Long, F. Robitaille, and C. D. Rudd, "Influence of stochastic fibre angle variations on the permeability of bi-directional textile fabrics," *Composites Part A: Applied Science and Manufacturing*, vol. 37, no. 1, pp. 122–132, 2006, doi: 10.1016/j.compositesa.2005.04.014.
- [19] R. Agogu , M. Shakoor, P. Beauch ne, and C. H. Park, "Analysis and minimization of race tracking in the resin-transfer-molding process by Monte Carlo simulation," *Materials*, vol. 16, no. 12, p. 4438, Jun. 2023. doi: 10.3390/ma16124438.
- [20] H. S. Sas, P.  im  ek, and S. G. Advani, "A methodology to reduce variability during vacuum infusion with optimized design of distribution media," *Composites Part A: Applied Science and Manufacturing*, vol. 78, pp. 223–233, Nov. 2015. doi: 10.1016/j.compositesa.2015.08.014.
- [21] Environment and Climate Change Canada, *Historical Climate Data — Hourly Data*, Ottawa Macdonald-Cartier Int'l A (Station ID: 6106001). Government of Canada. Available: <https://climate.weather.gc.ca/>

Appendix A: PT Calibration Certificate

合格证 Calibration

品名NAME 压力传感器Pressure transmitter	
年月DATE	2024. 12
型号TYPE 85Y-100KV0GF	批号S/N 2412XXXX

检测参数Specifications

量程Capacity	0~-100 kPa
输出Output	0~5 VDC
供电Supply voltage	8~30 VDC
精度Accuracy	1 %F. S
安全过载Safe overload	150 %F. S

注：0V对应0kPa，5V对应-100kPa。

接线图Wiring

航空插. 电缆出线

赫斯曼

4~20mA
电流输出 (2线制)

红
黑

0~5/1~5V
0.5~4.5V
0~10V
电压输出 (3线制)

红
黑
黄

赫斯曼

Figure A.1: PT calibration certificate.

Appendix B: Vacuum-drop Tests

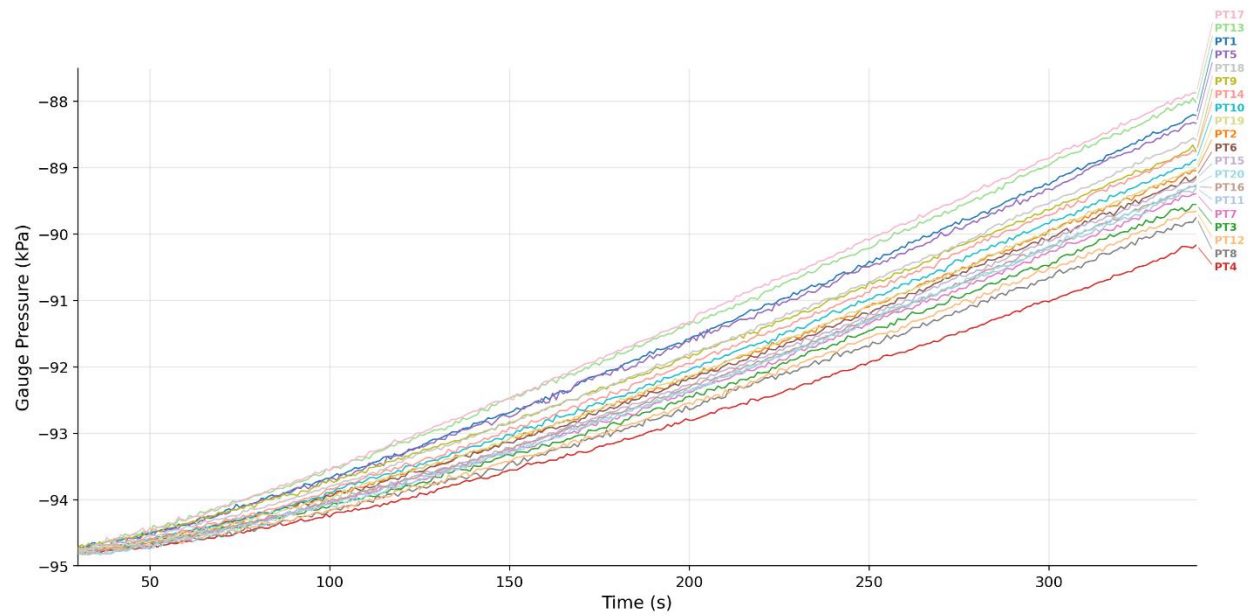


Figure B.1: Vacuum-drop test, Experiment #2

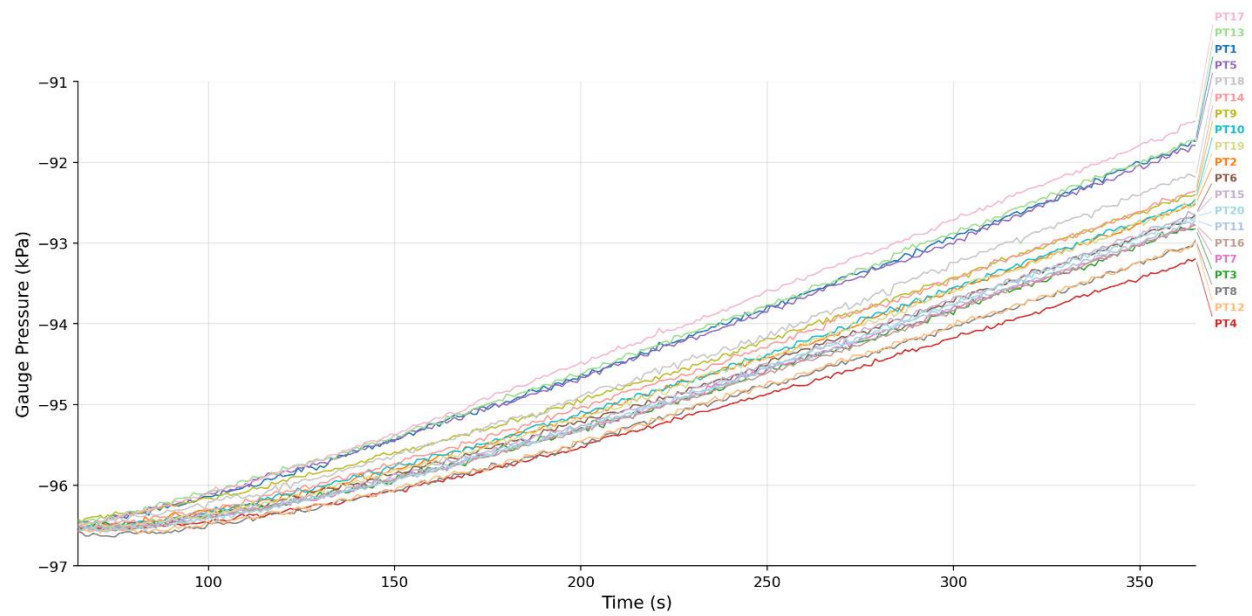


Figure B.2: Vacuum-drop test, Experiment #3

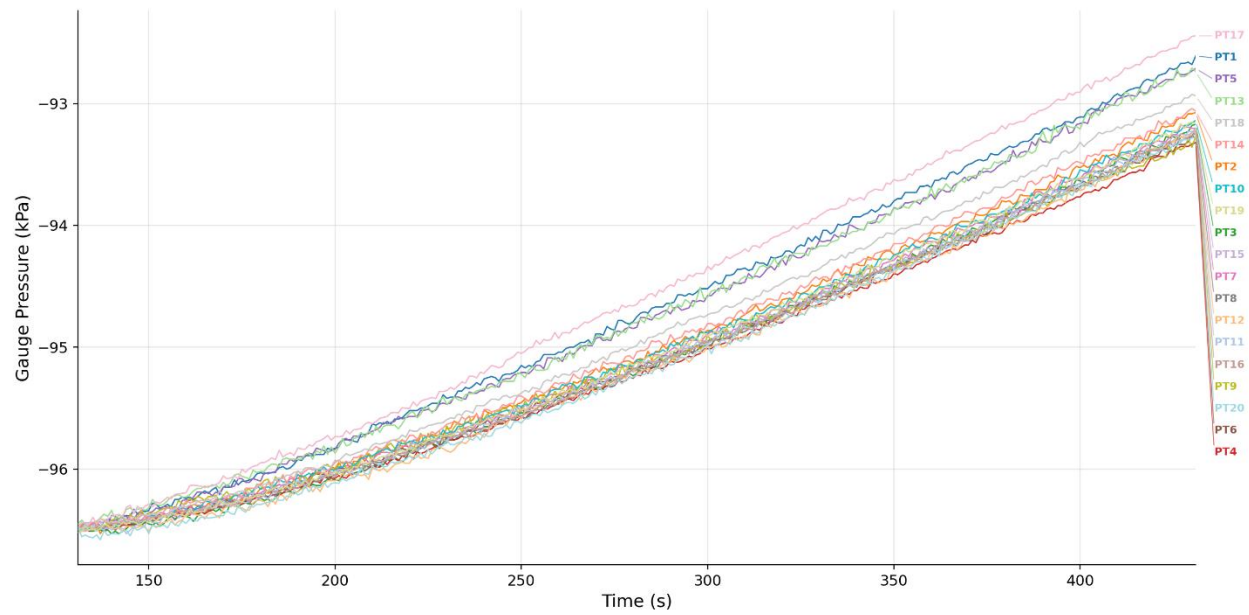


Figure B.3: Vacuum-drop test, Experiment #4

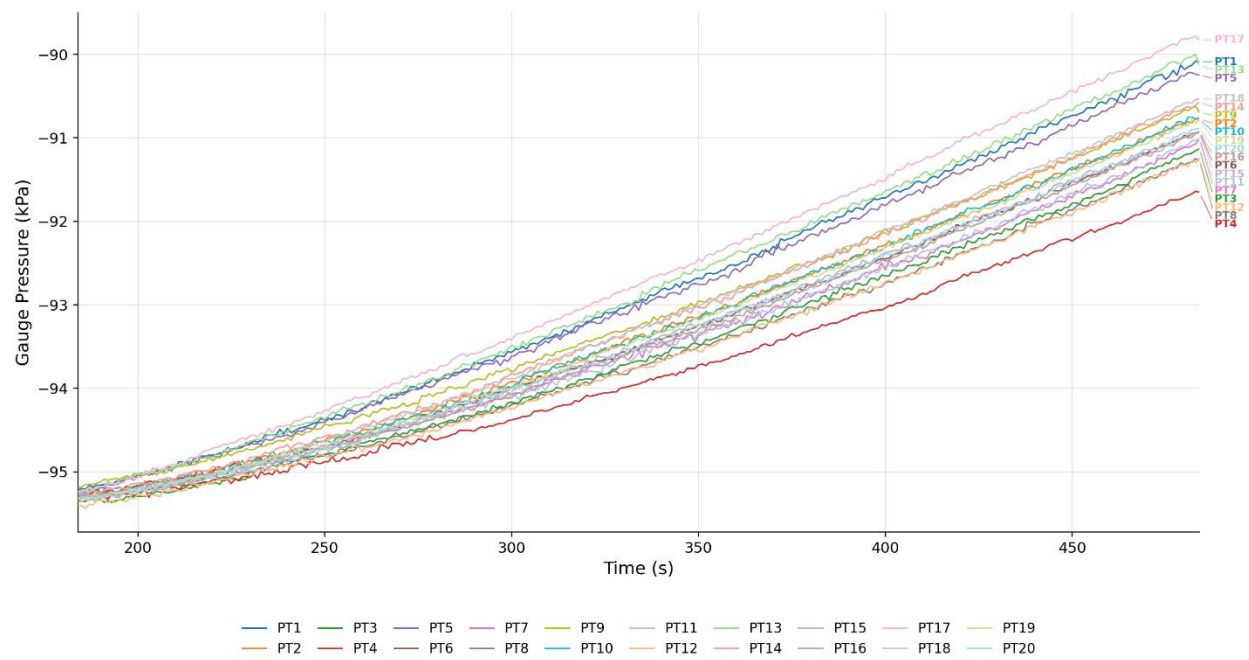


Figure B.4: Vacuum-drop test, Experiment #5

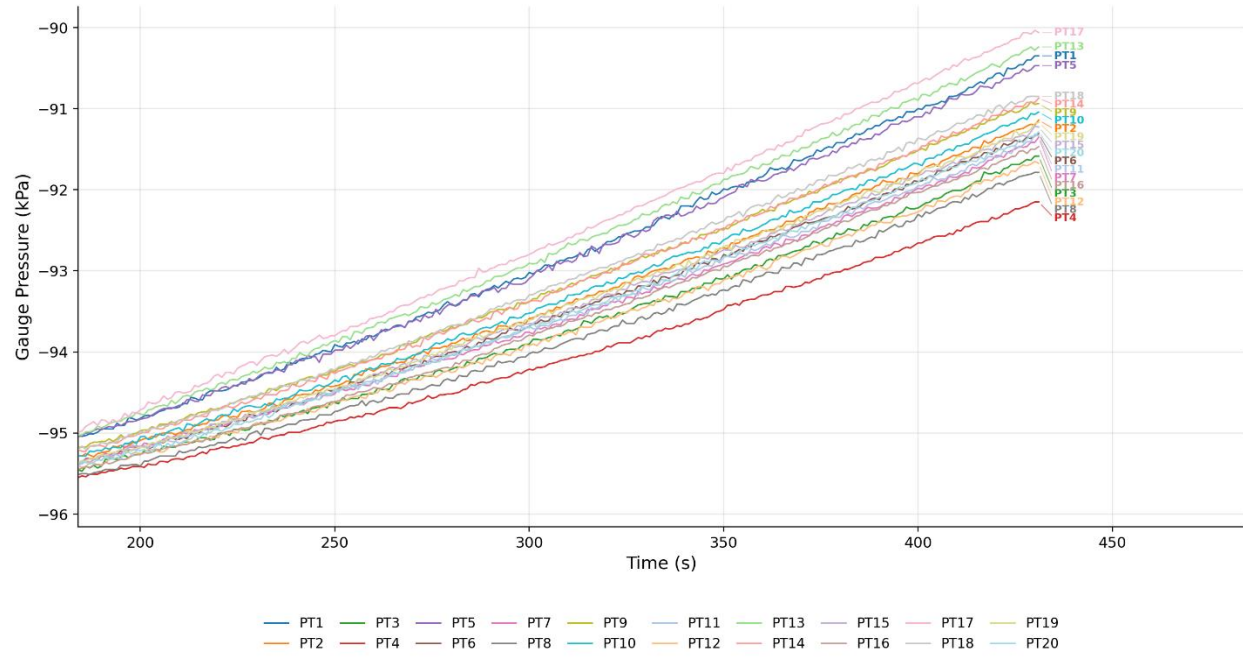


Figure B.5: Vacuum-drop test, Experiment #6

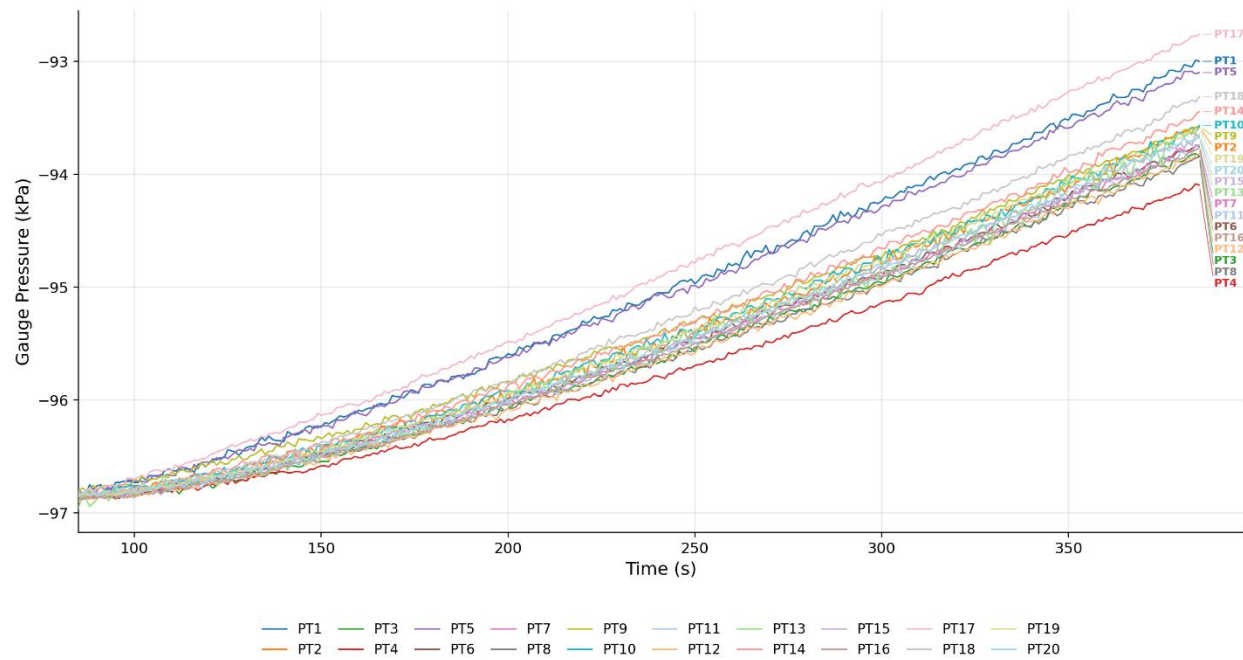


Figure B.6: Vacuum-drop test, Experiment #7

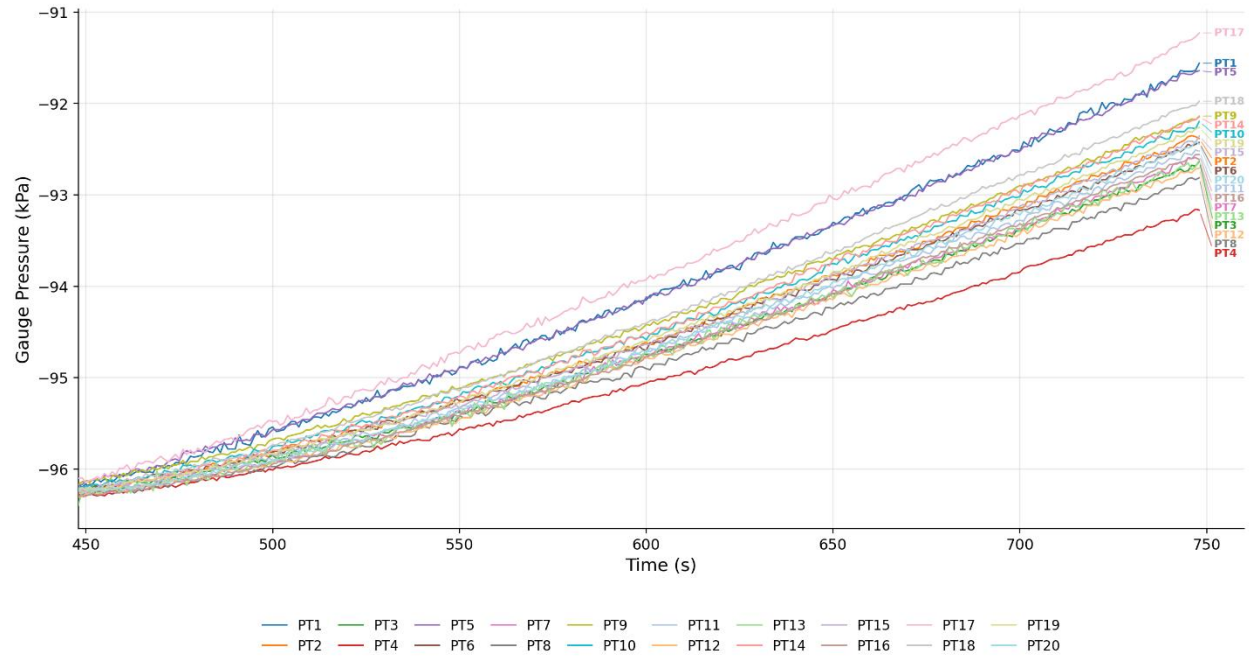


Figure B.7: Vacuum-drop test, Experiment #8

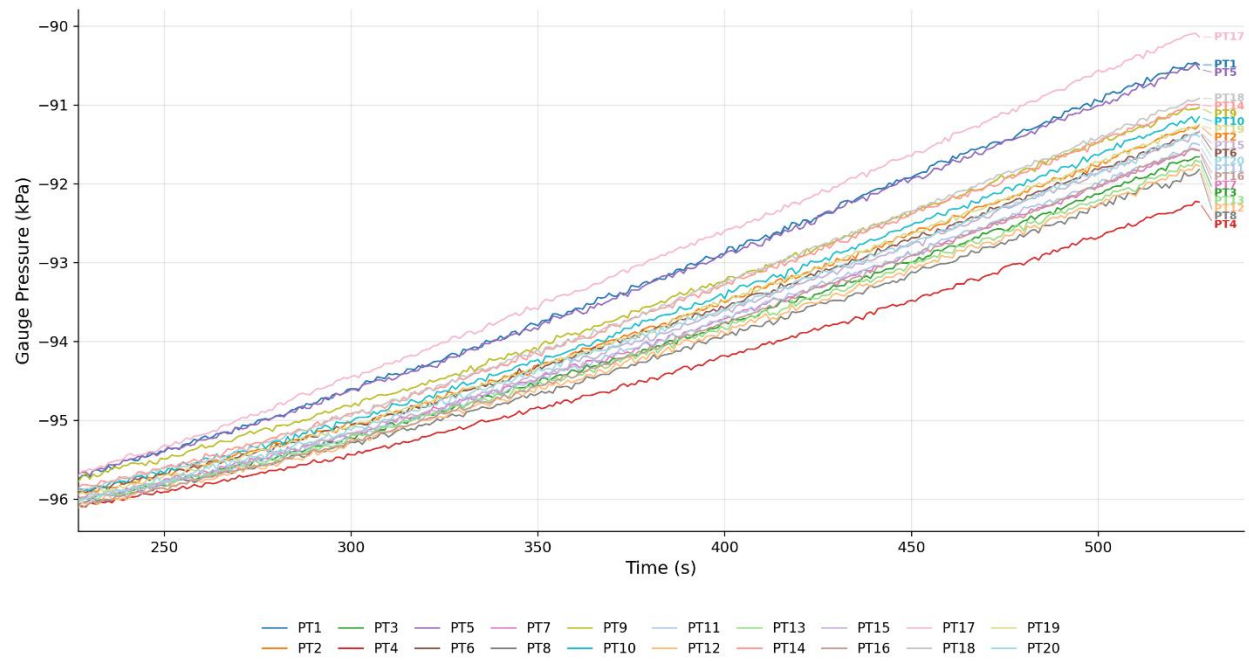


Figure B.8: Vacuum-drop test, Experiment #9

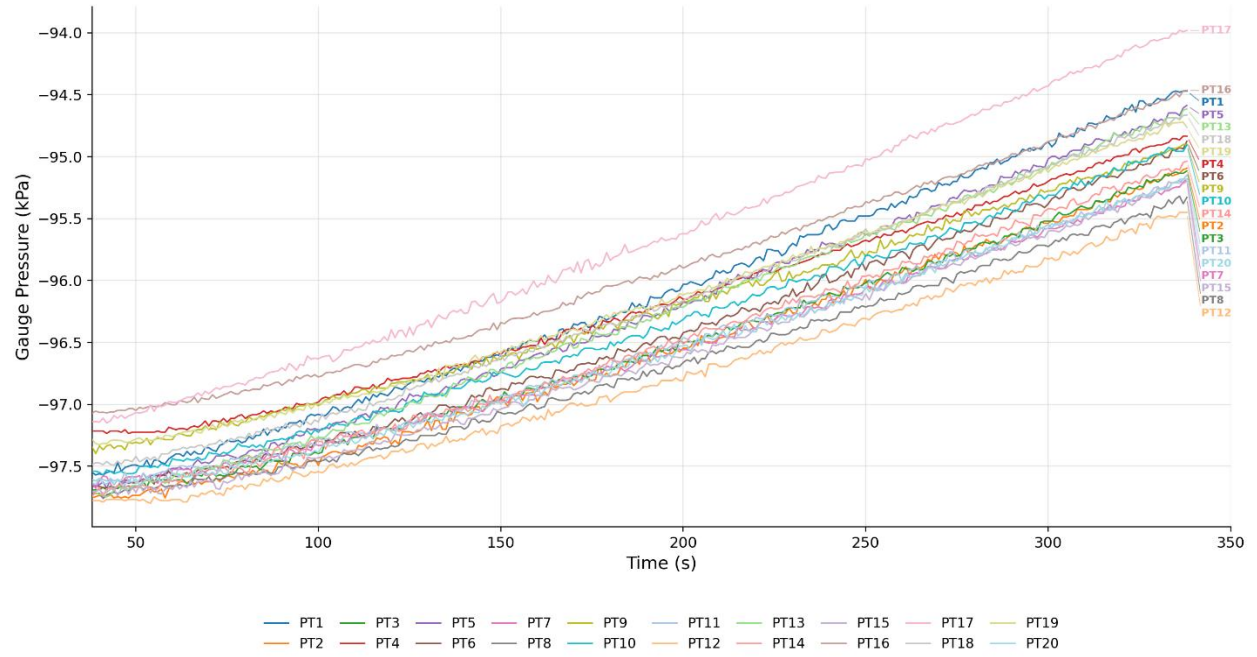


Figure B.9: Vacuum-drop test, Experiment #10

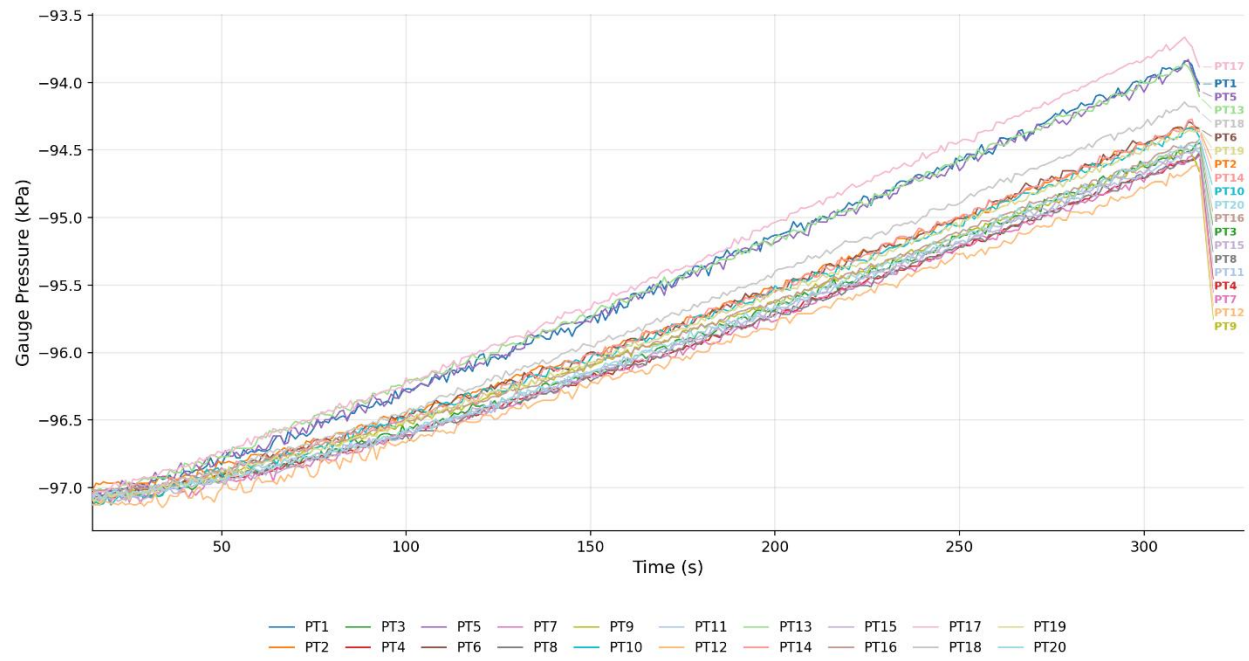


Figure B.10: Vacuum-drop test, Experiment #11

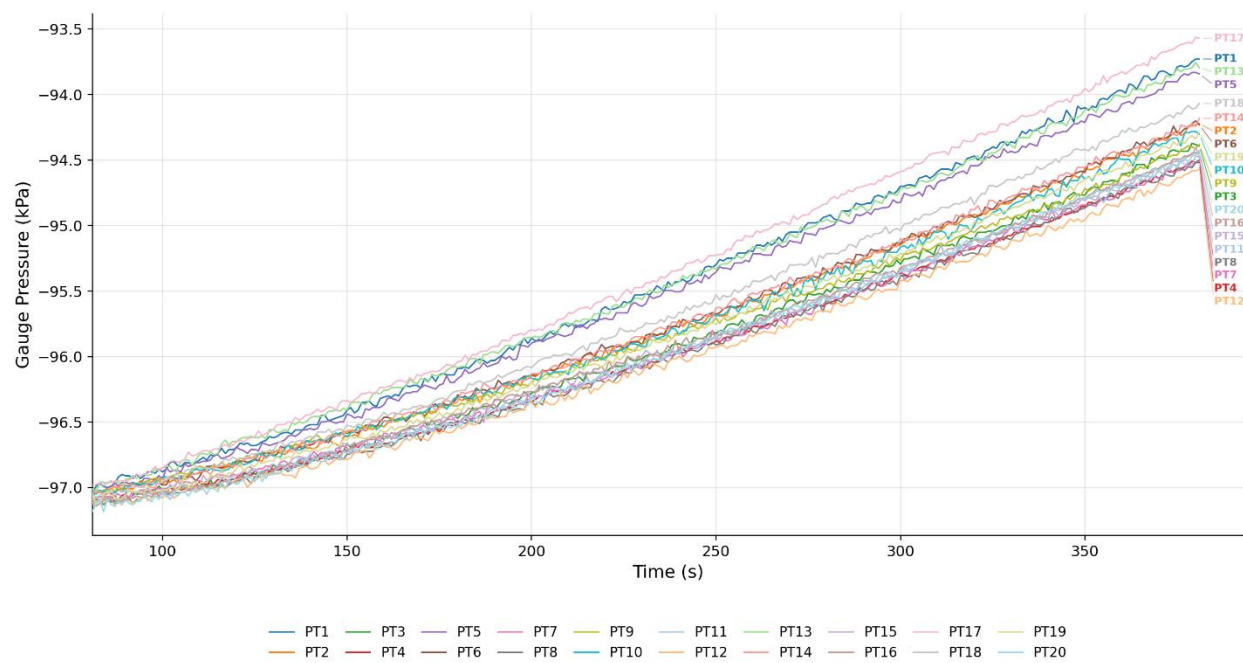


Figure B.11: Vacuum-drop test, Experiment #12

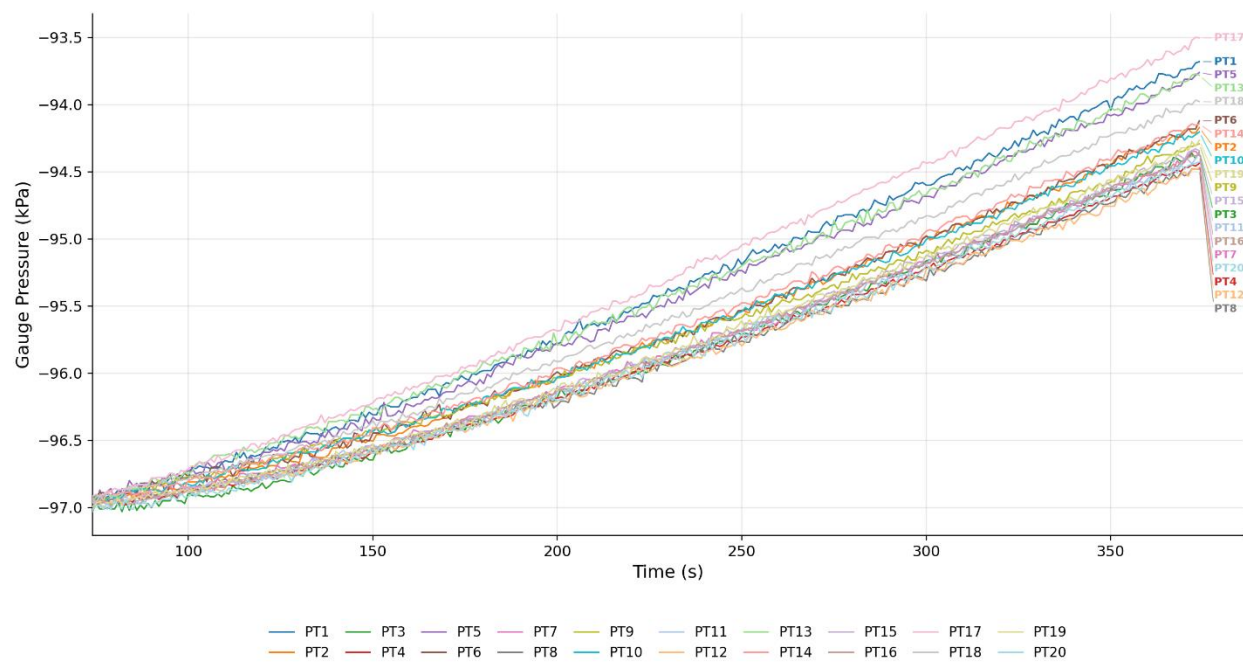


Figure B.12: Vacuum-drop test, Experiment #13

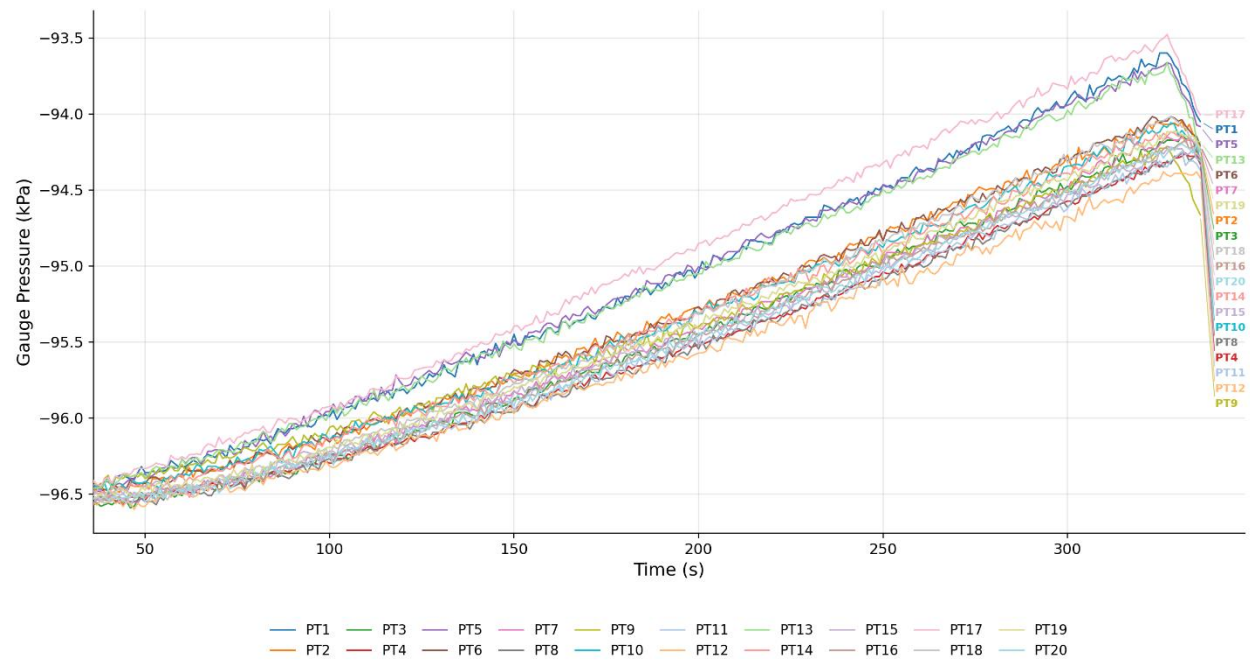


Figure B.13: Vacuum-drop test, Experiment #14

Appendix C: First Thirty Seconds of Vacuum-drop Tests

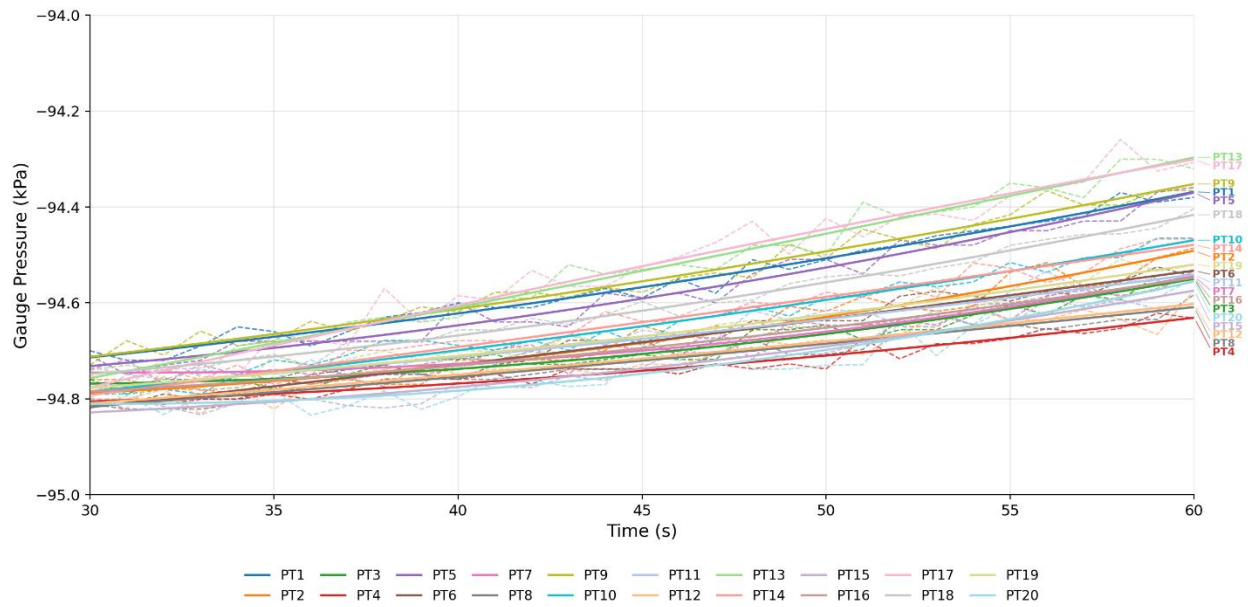


Figure C.1: Vacuum-drop test, first 30s, Experiment #2

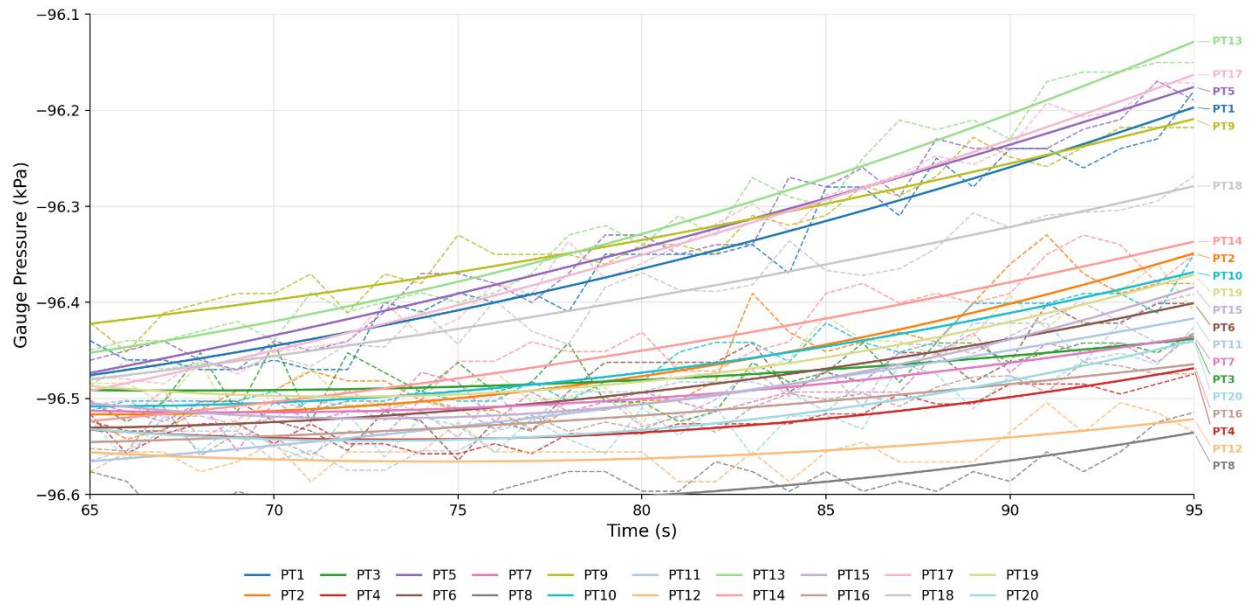


Figure C.2: Vacuum-drop test, first 30s, Experiment #3

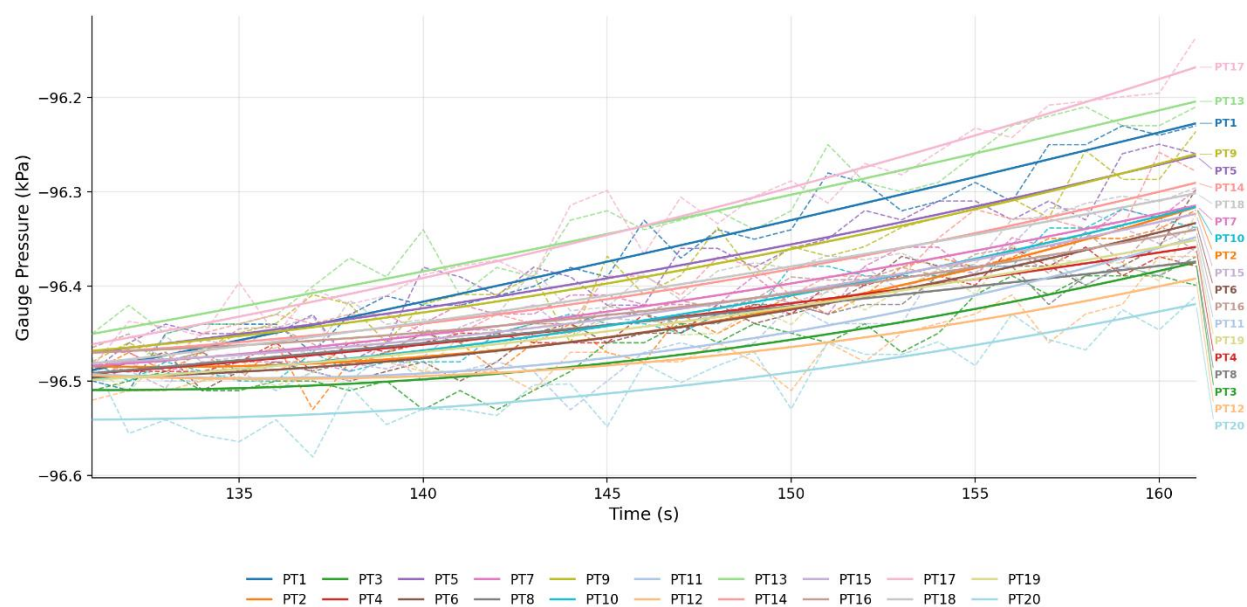


Figure C.3: Vacuum-drop test, first 30s, Experiment #4

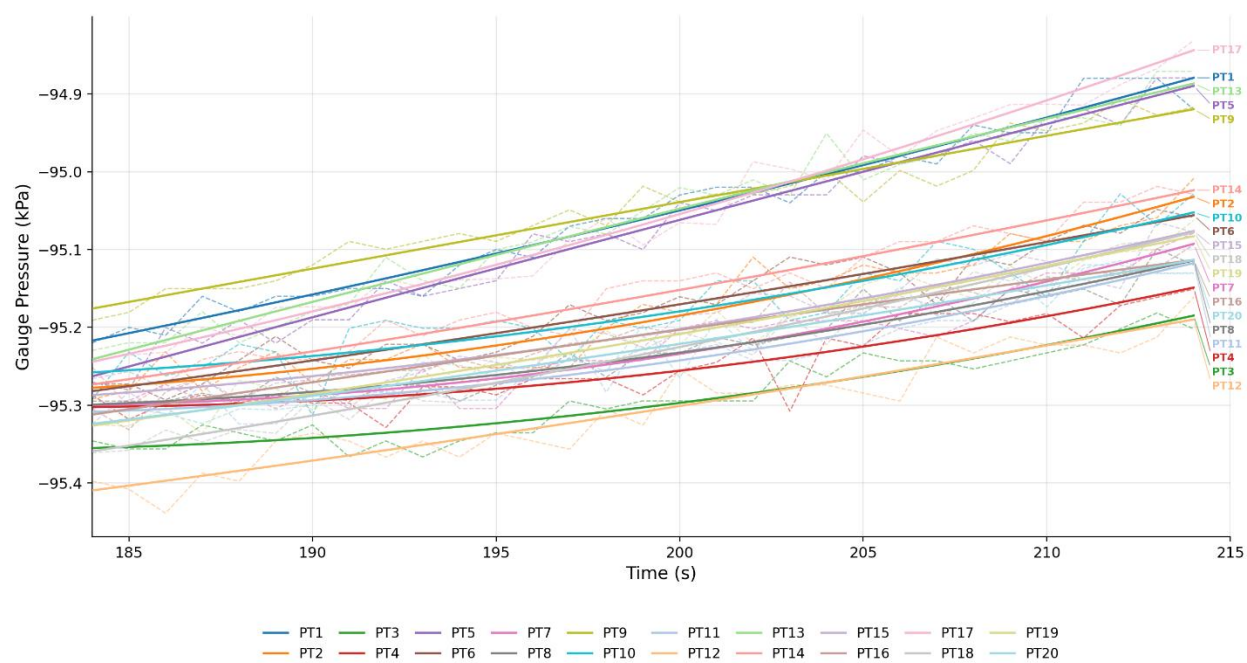


Figure C.4: Vacuum-drop test, first 30s, Experiment #5

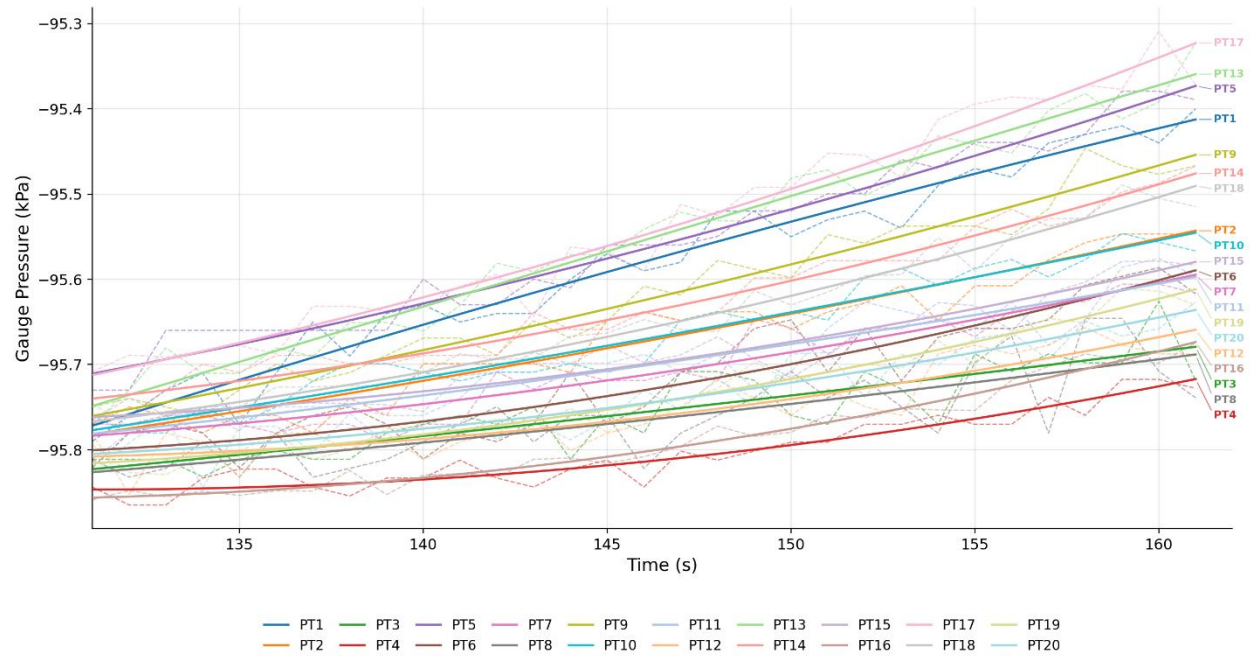


Figure C.5: Vacuum-drop test, first 30s, Experiment #6

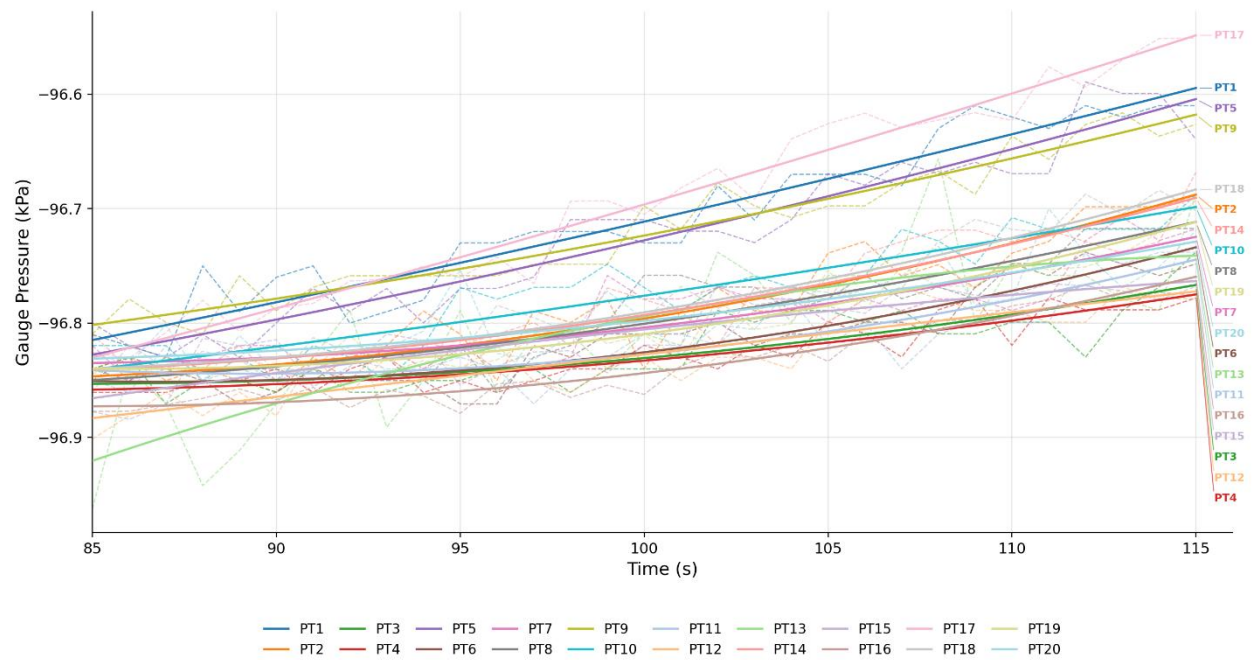


Figure C.6: Vacuum-drop test, first 30s, Experiment #7

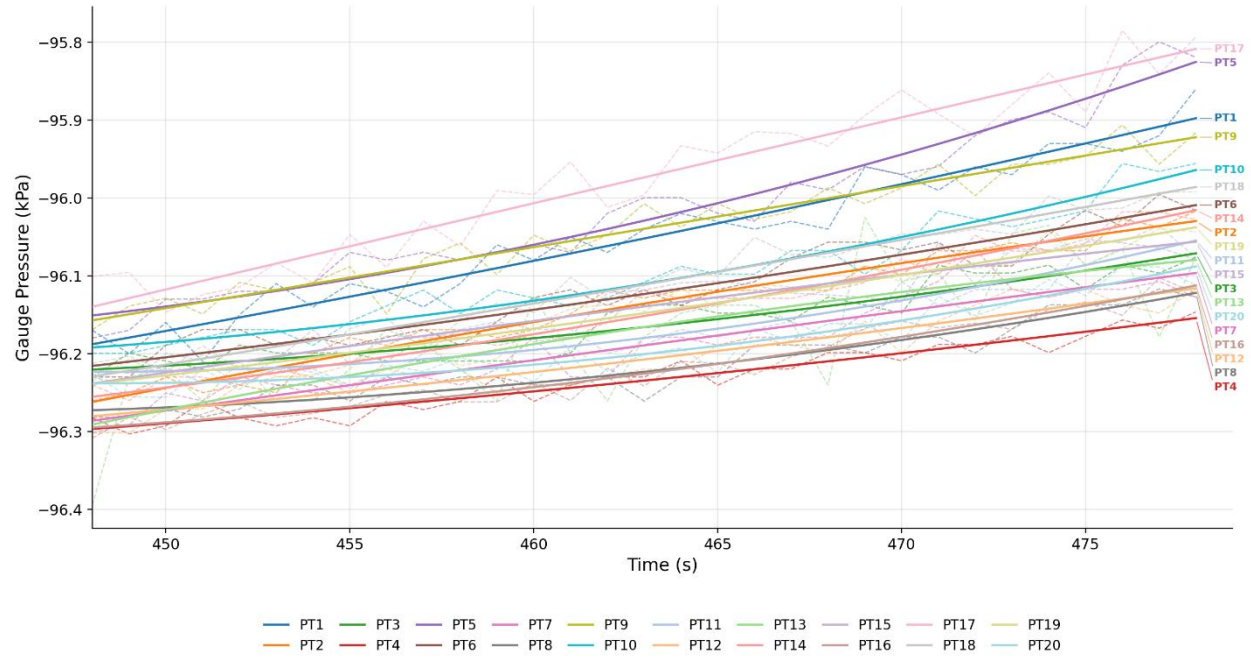


Figure C.7: Vacuum-drop test, first 30s, Experiment #8

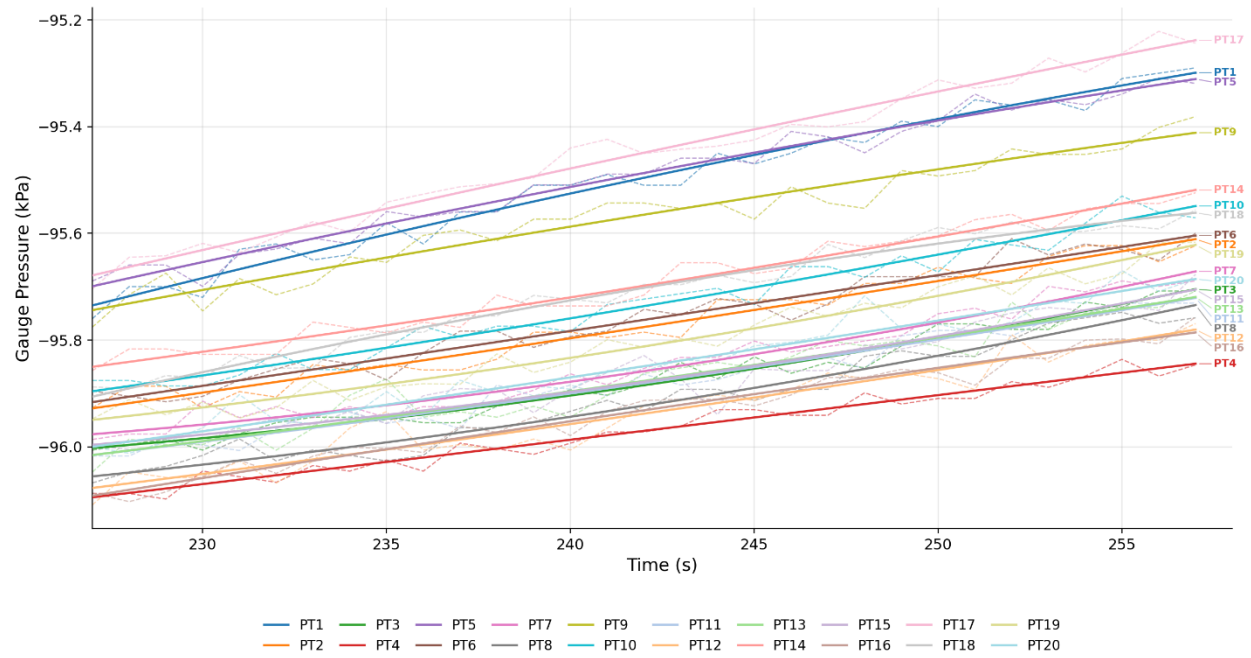


Figure C.8: Vacuum-drop test, first 30s, Experiment #9

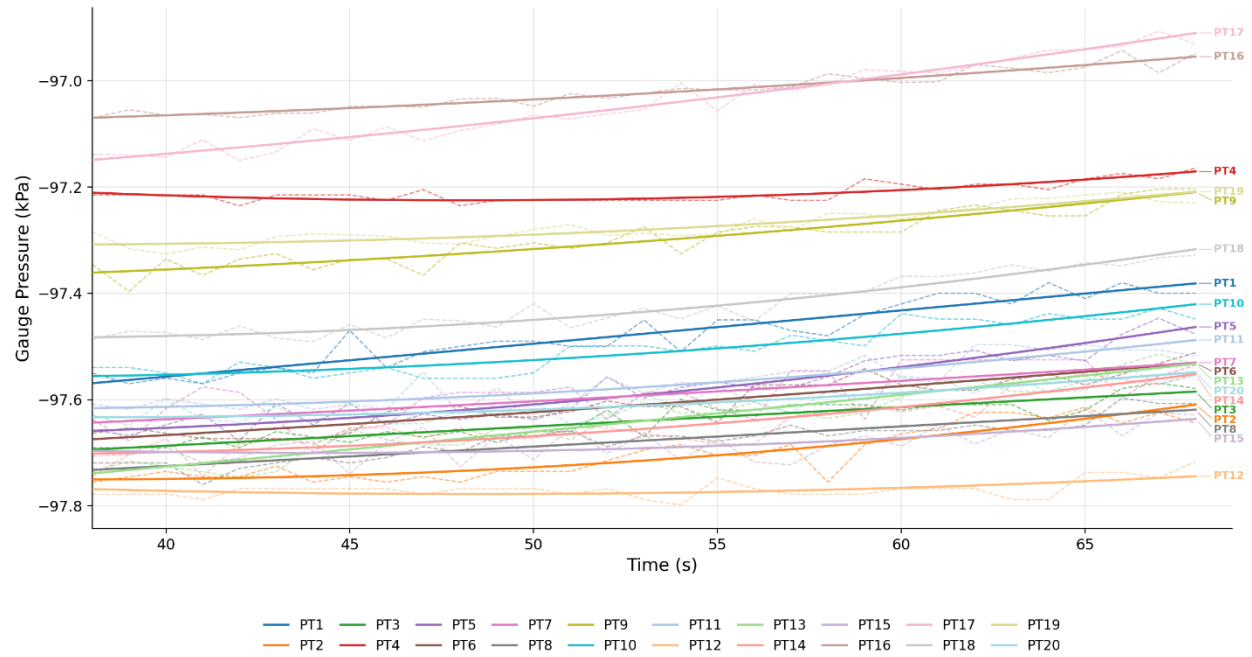


Figure C.9: Vacuum-drop test, first 30s, Experiment #10

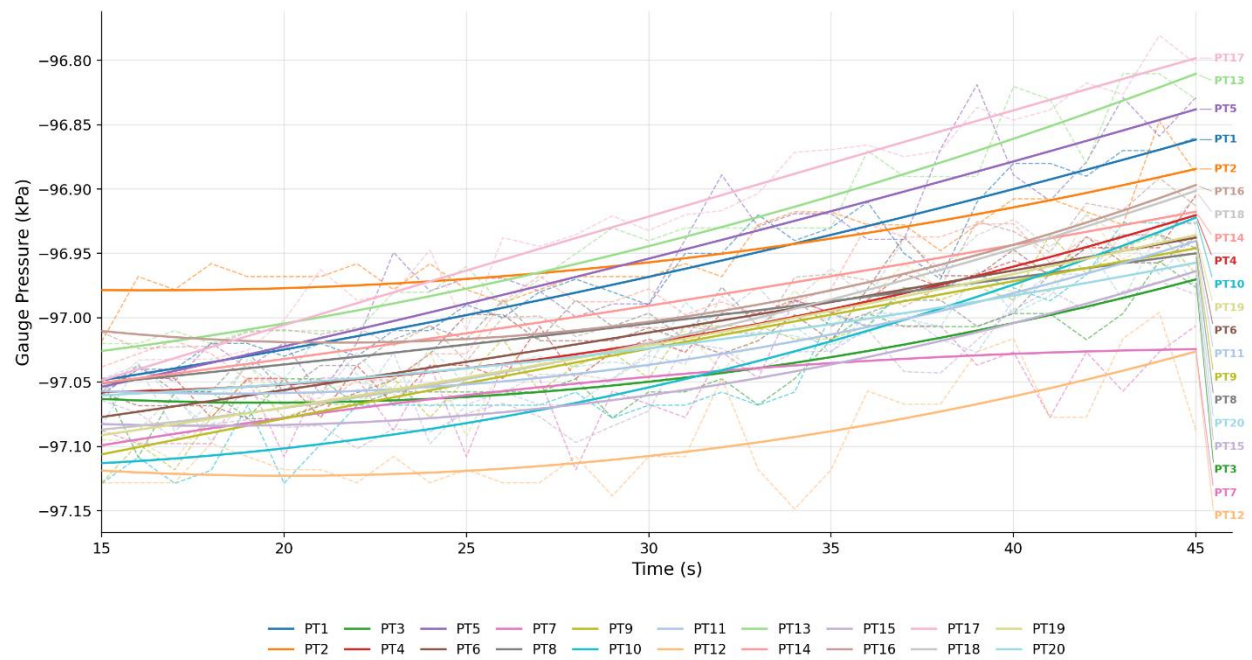


Figure C.10: Vacuum-drop test, first 30s, Experiment #11

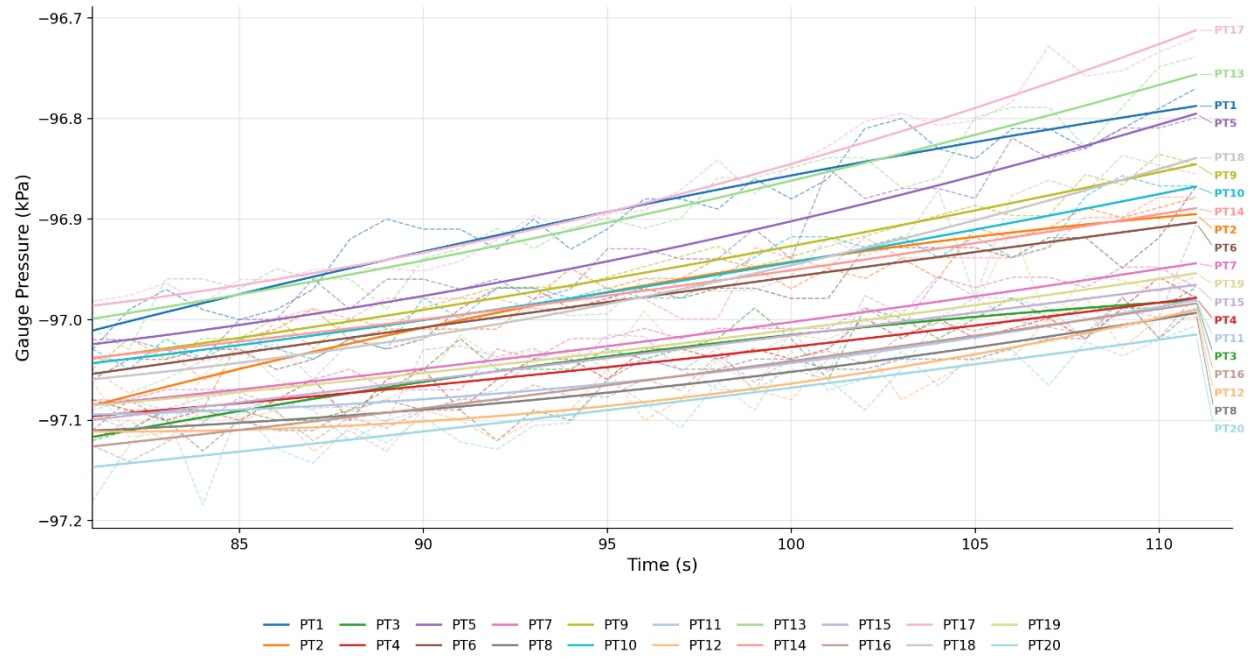


Figure C.11: Vacuum-drop test, first 30s, Experiment #12

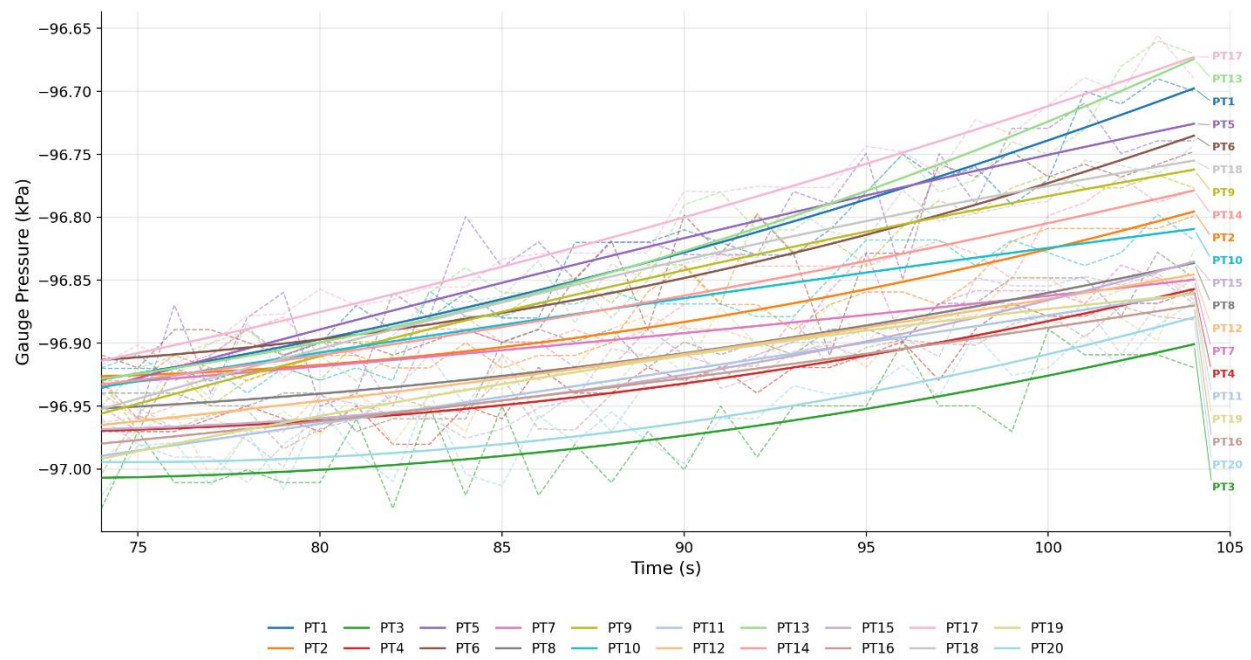


Figure C.12: Vacuum-drop test, first 30s, Experiment #13

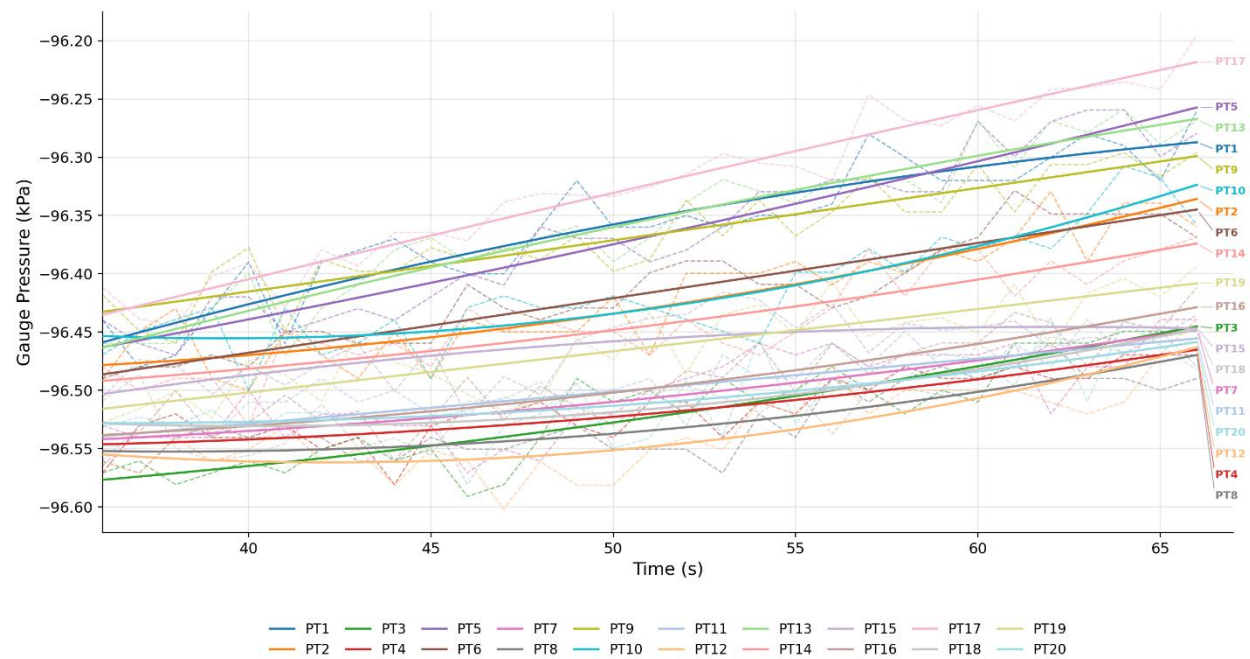


Figure C.13: Vacuum-drop test, first 30s, Experiment #14

Appendix D: Row-averaged Gauge Pressure In Vacuum-drop Tests

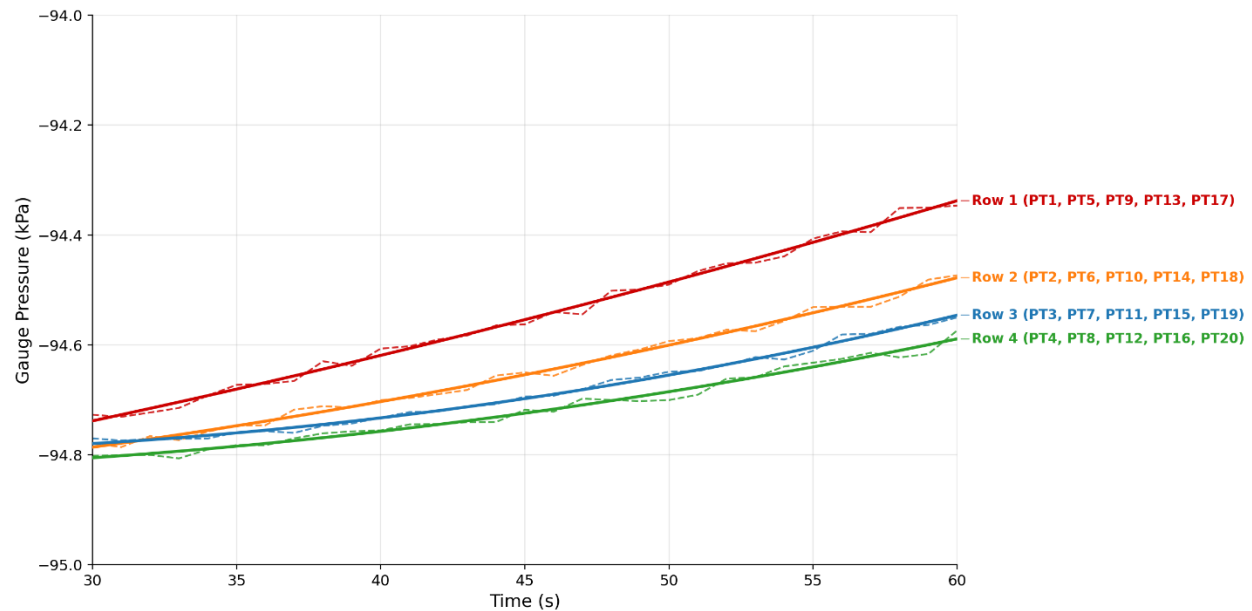


Figure D.1: Row-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #2

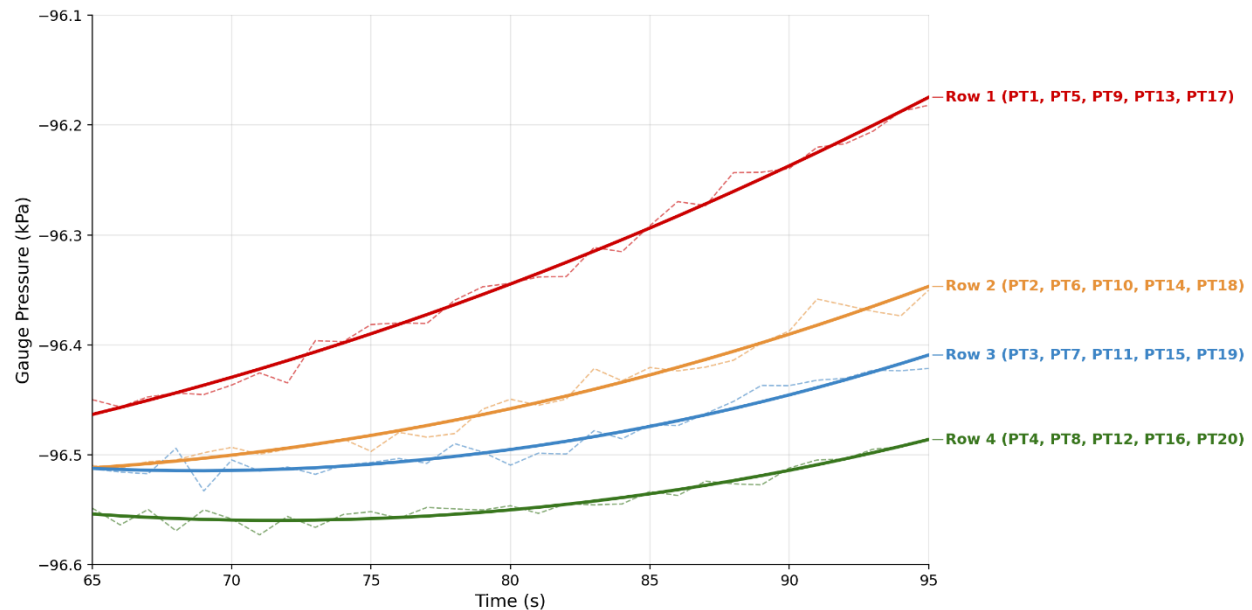


Figure D.2: Row-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #3

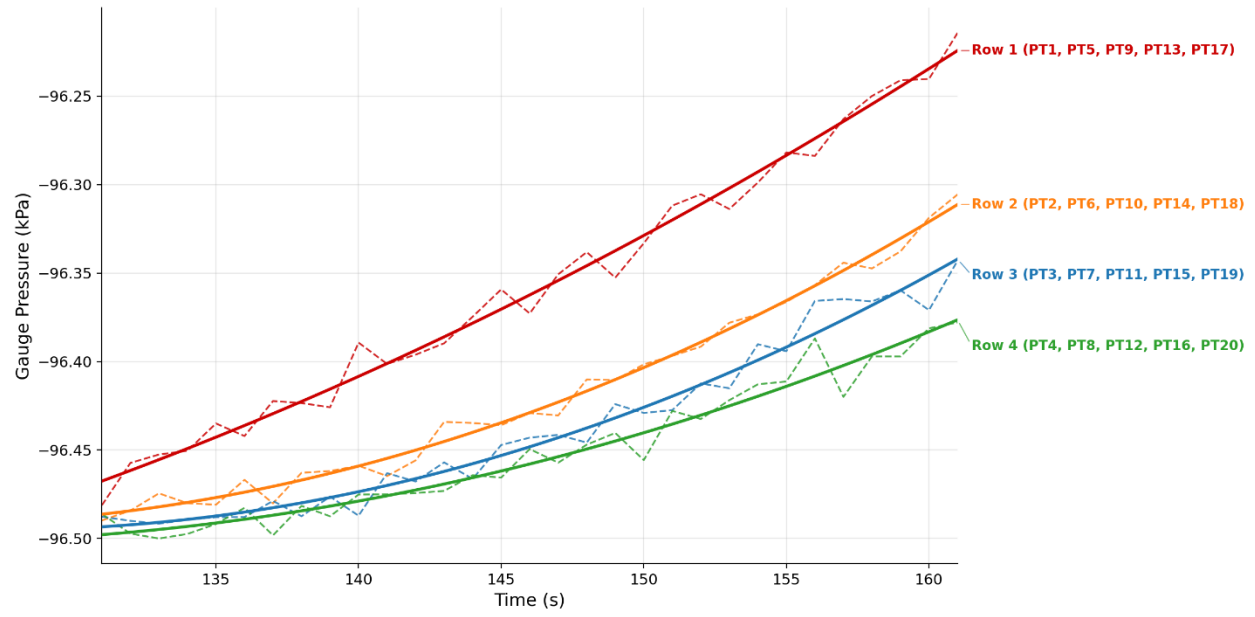


Figure D.3: Row-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #4

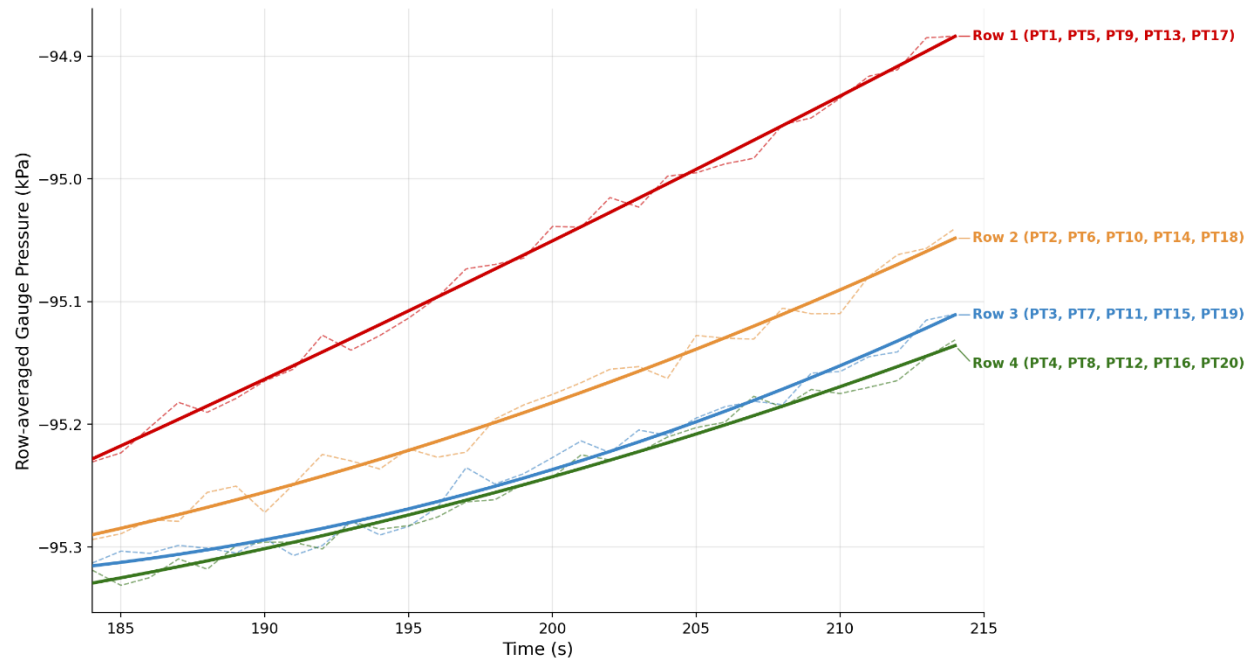


Figure D.4: Row-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #5

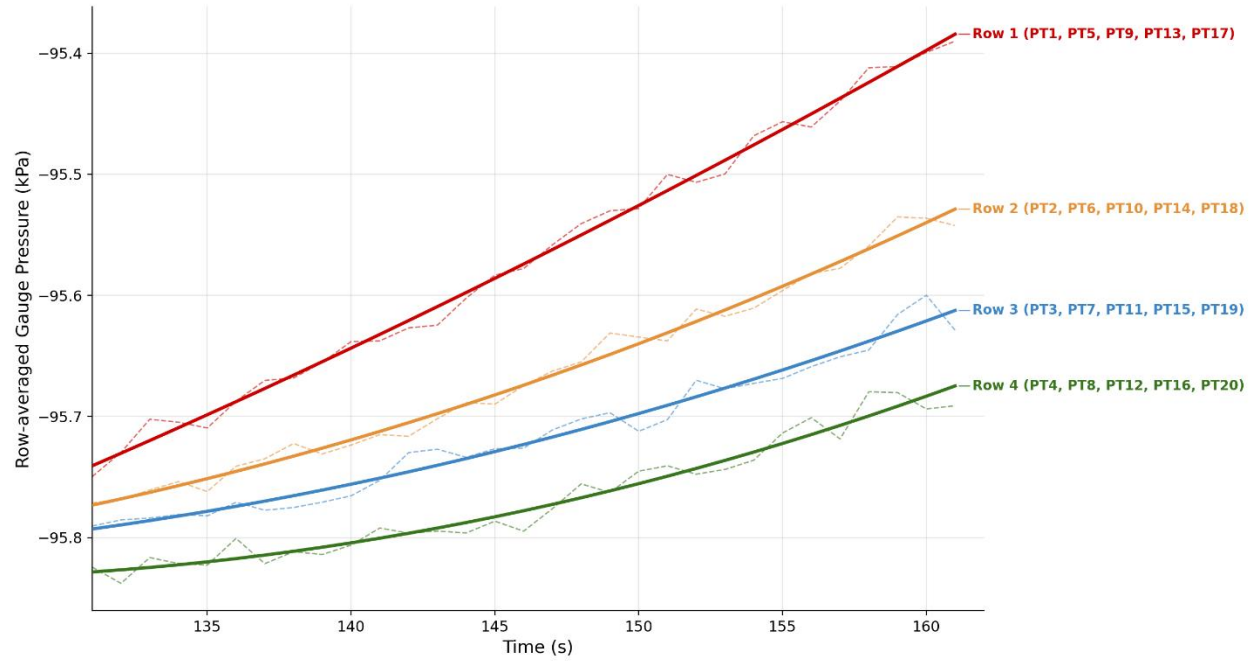


Figure D.5: Row-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #6

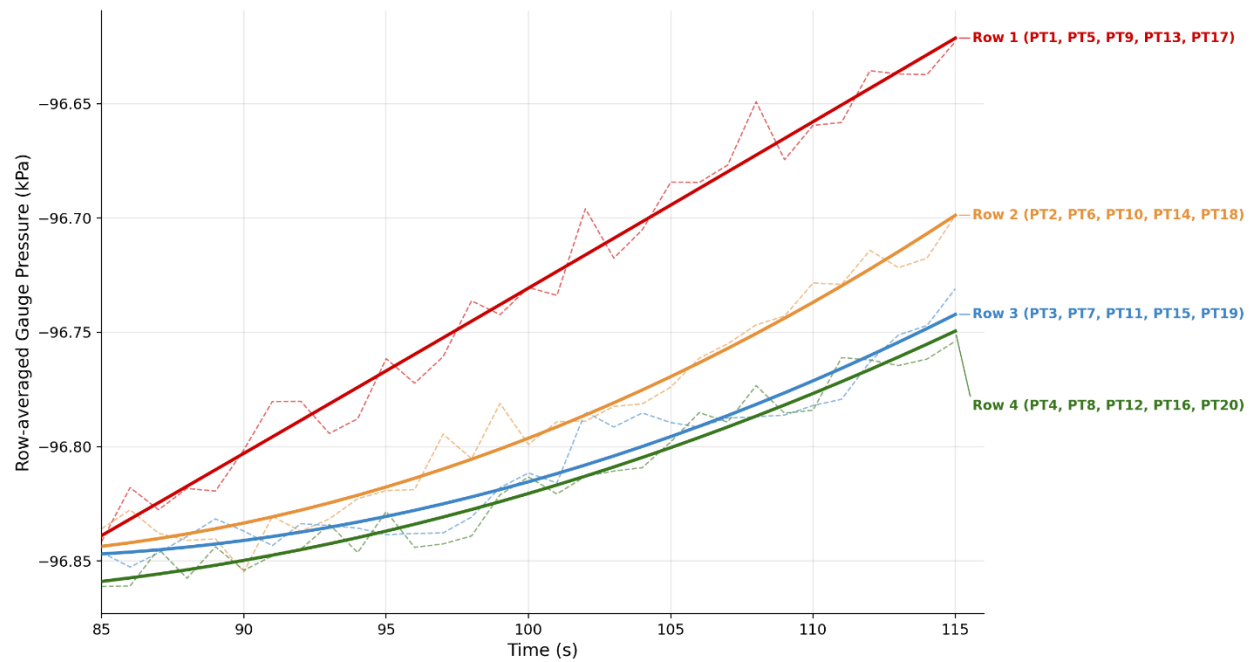


Figure D.6: Row-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #7

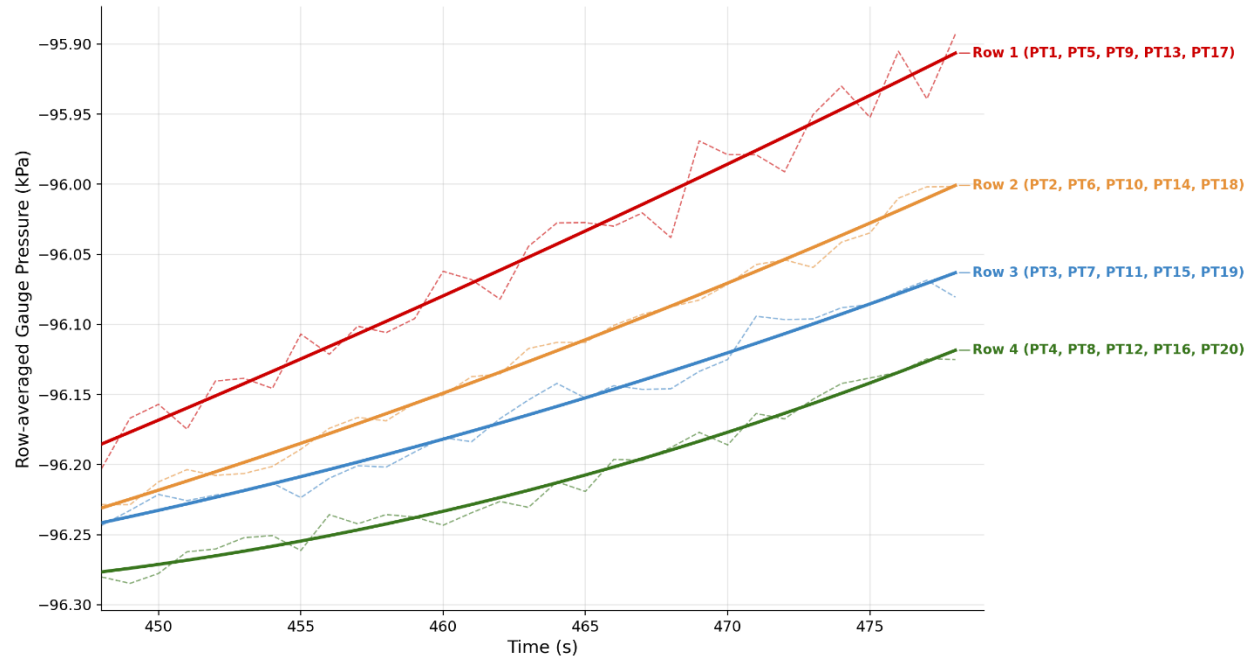


Figure D.7: Row-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #8

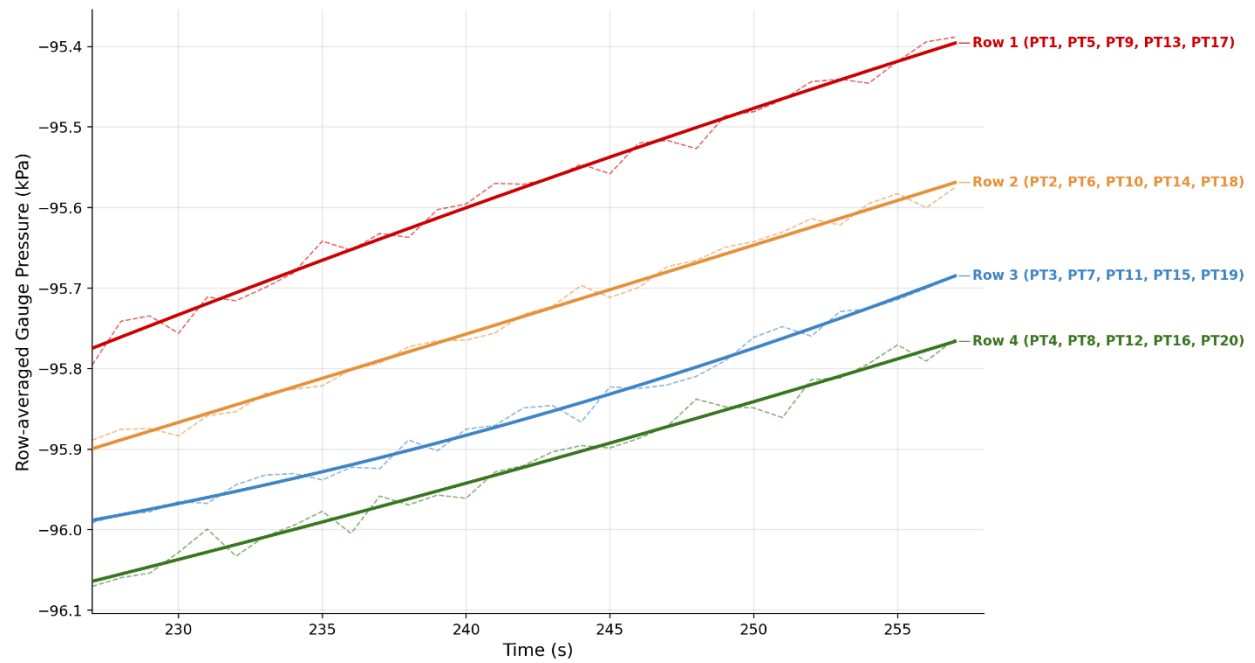


Figure D.8: Row-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #9

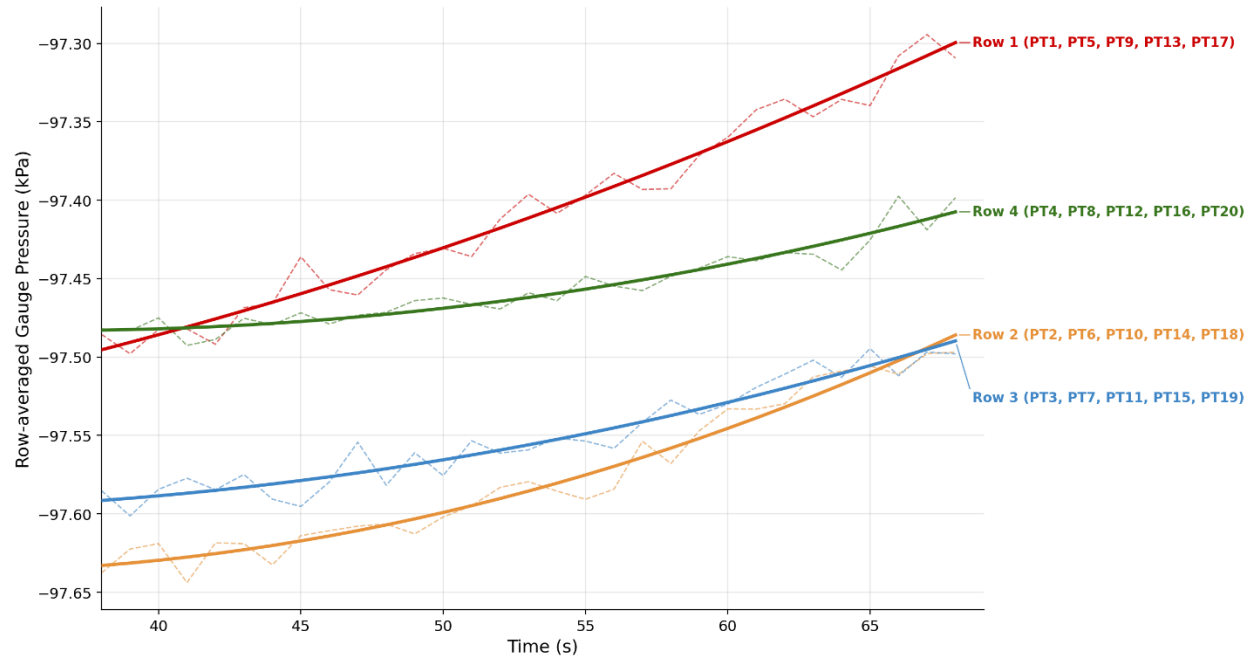


Figure D.9: Row-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #10

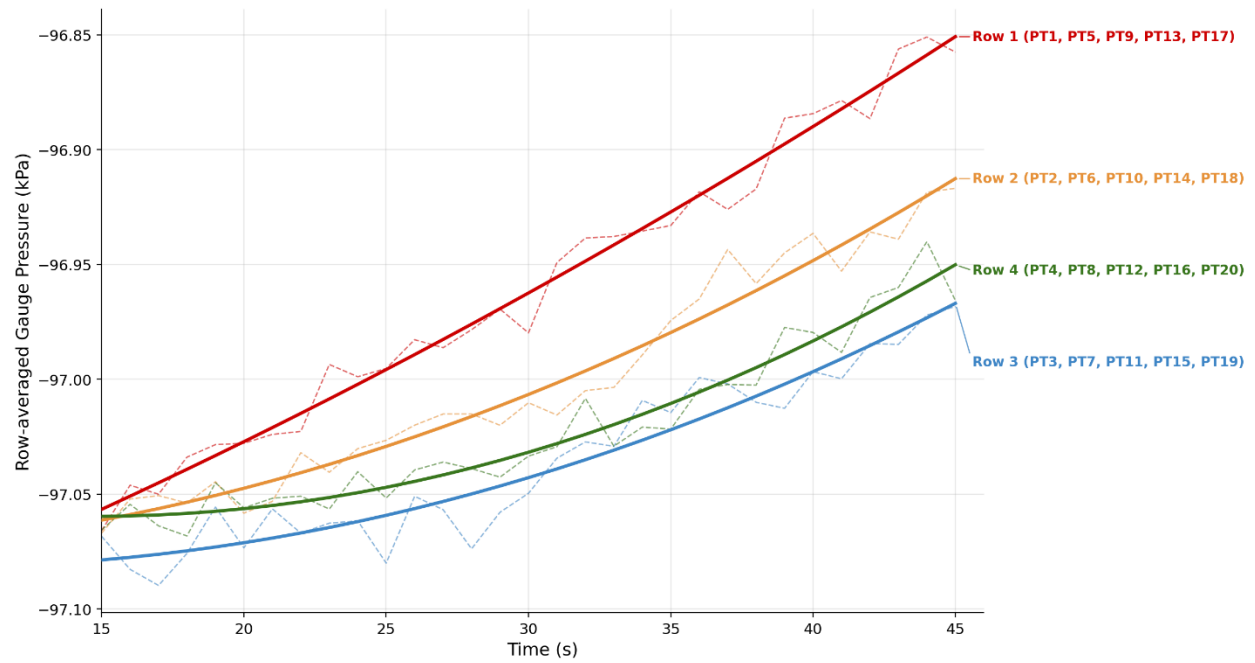


Figure D.10: Row-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #11

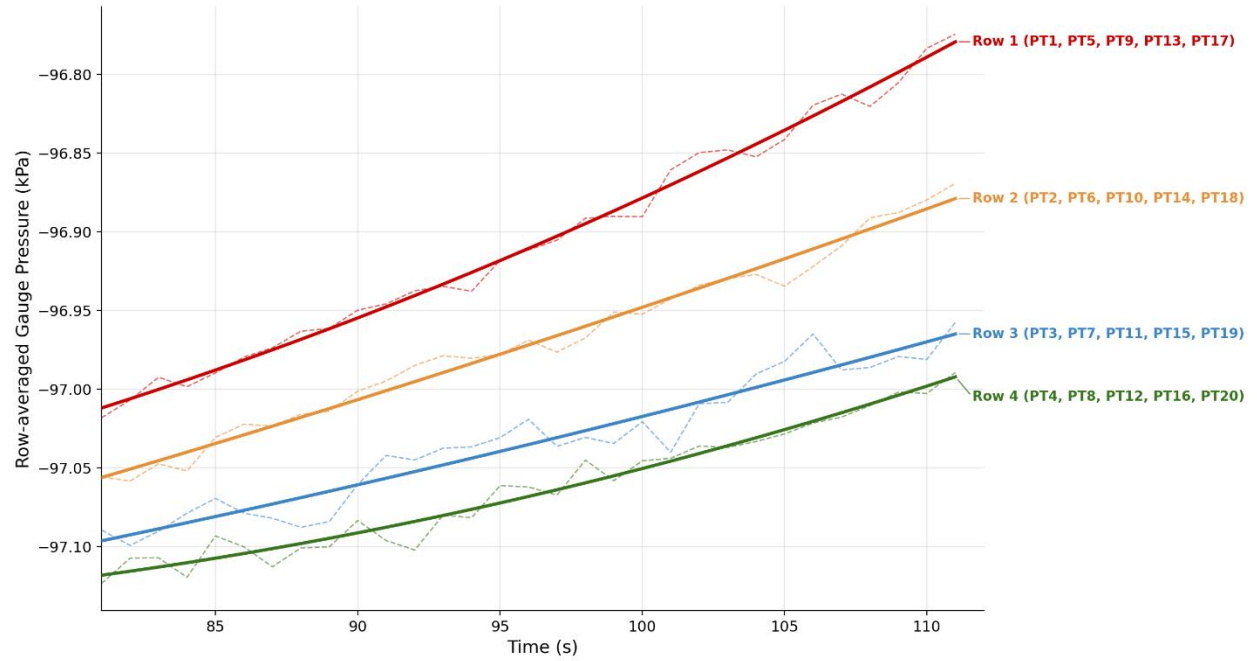


Figure D.11: Row-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #12

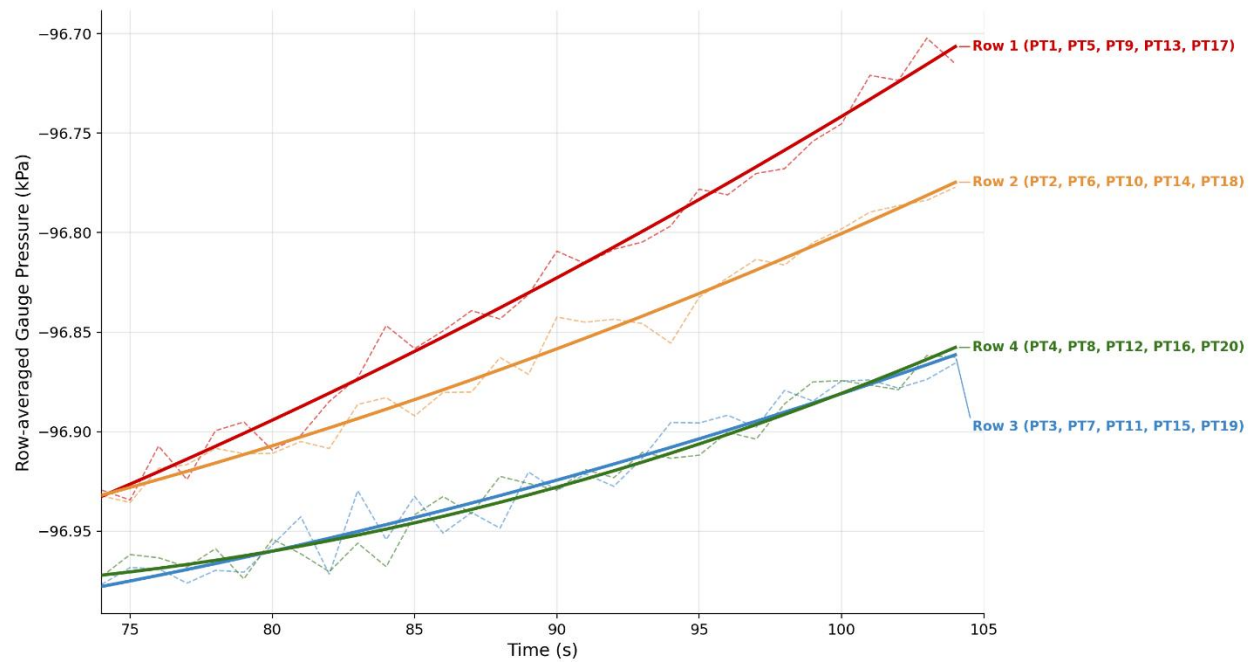


Figure D.12: Row-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #13

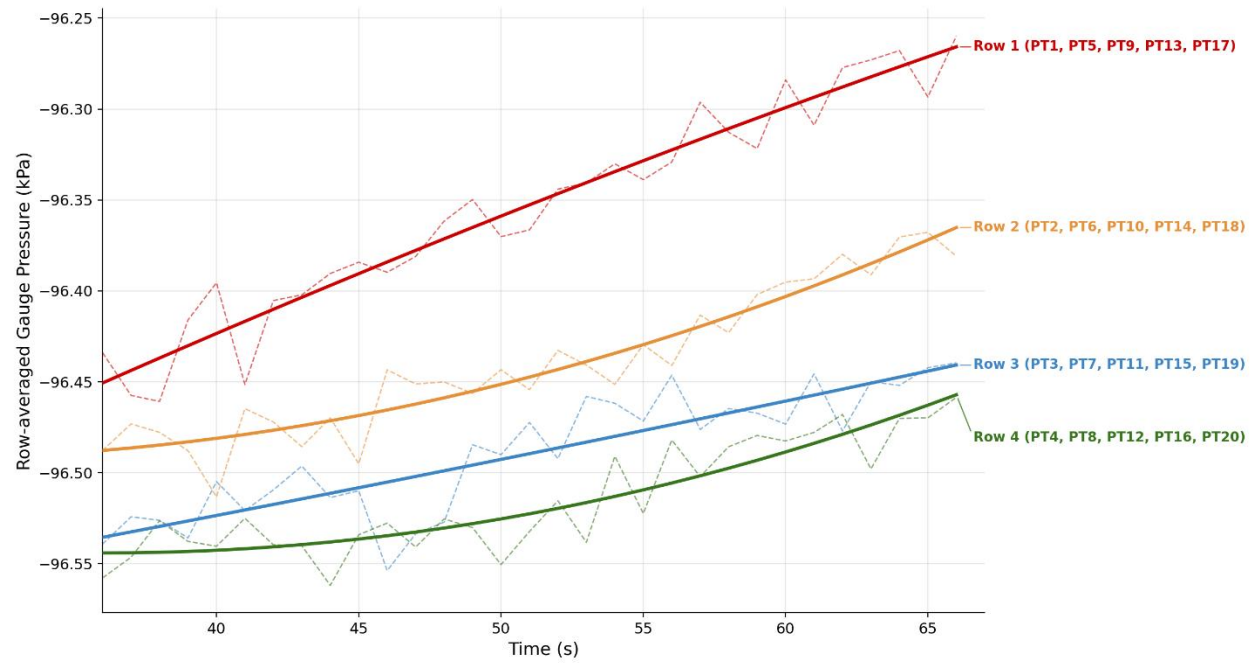


Figure D.13: Row-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #14

Appendix E: Column-averaged Gauge Pressure In Vacuum-drop Tests

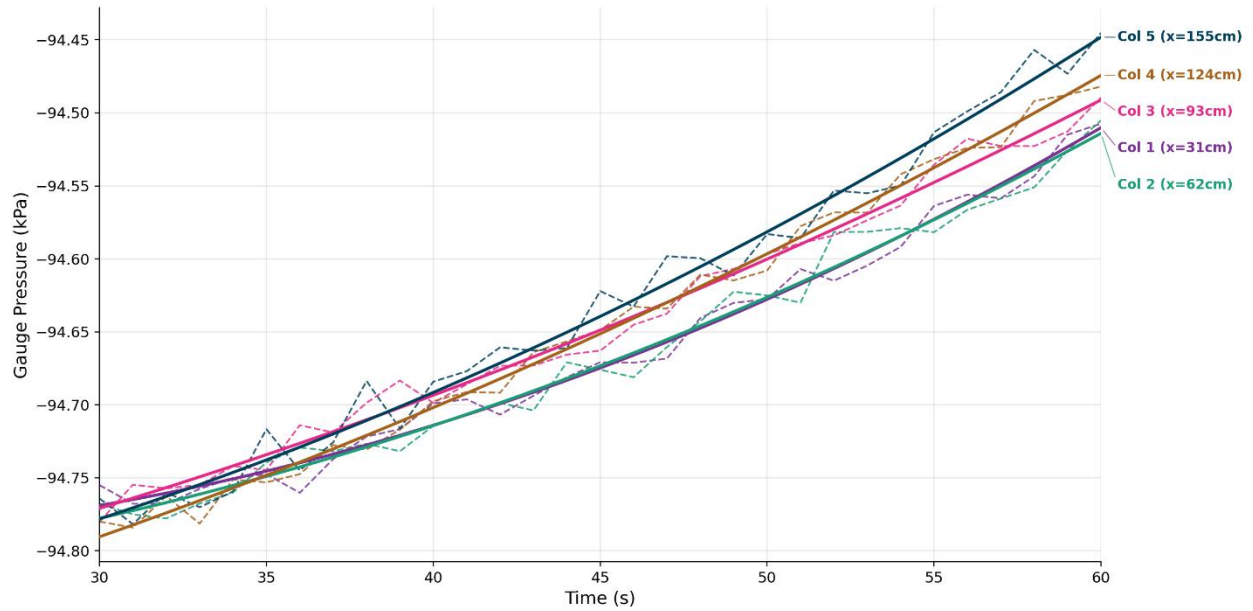


Figure E.1: Column-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #2

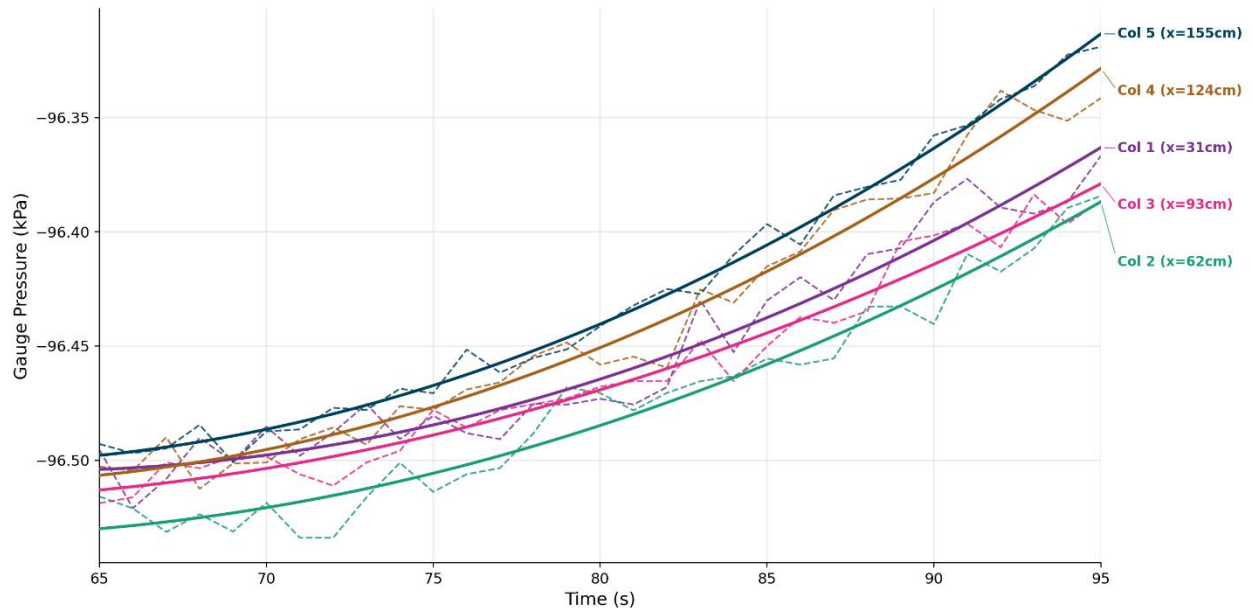


Figure E.2: Column-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #3

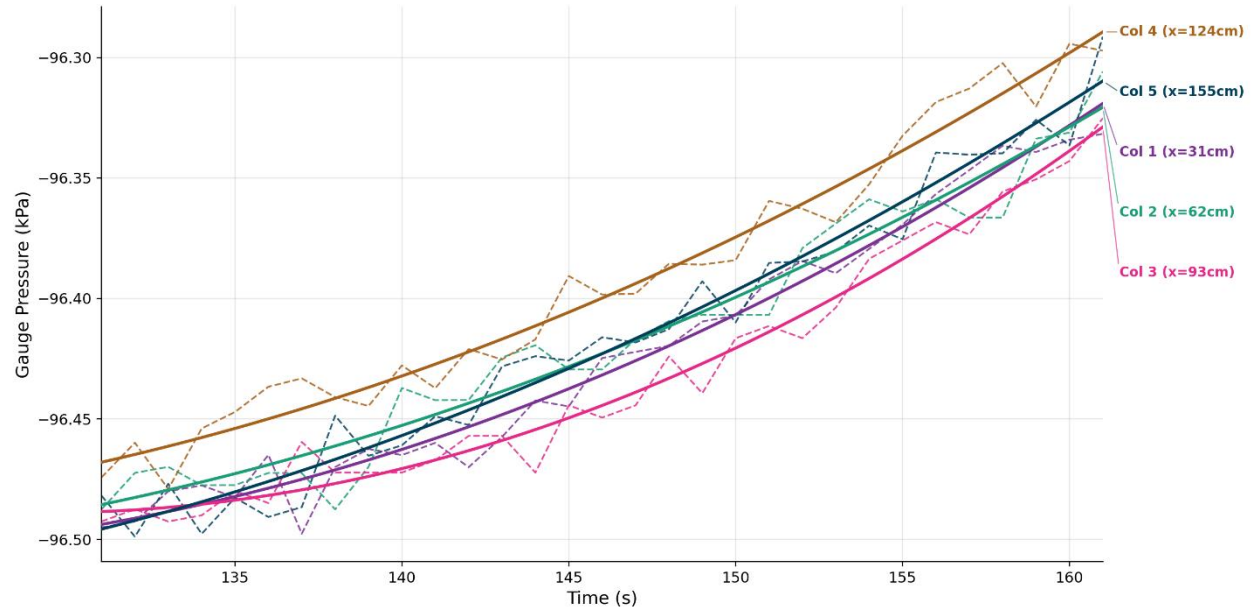


Figure E.3: Column-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #4

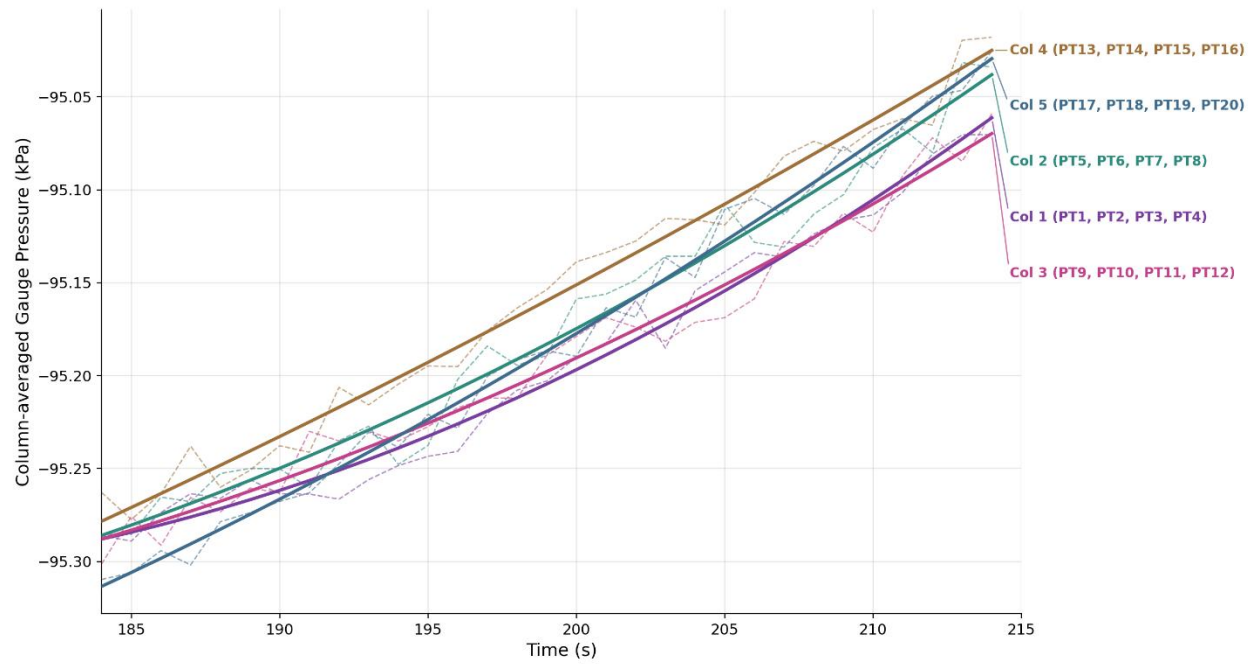


Figure E.4: Column-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #5

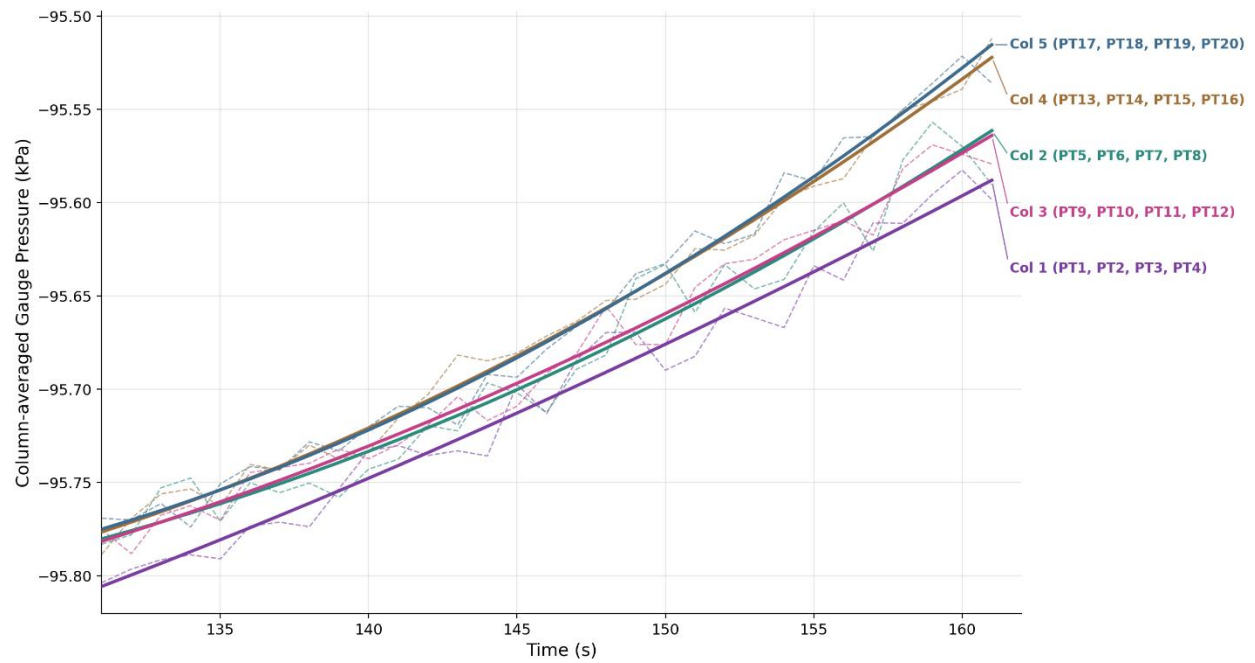


Figure E.5: Column-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #6

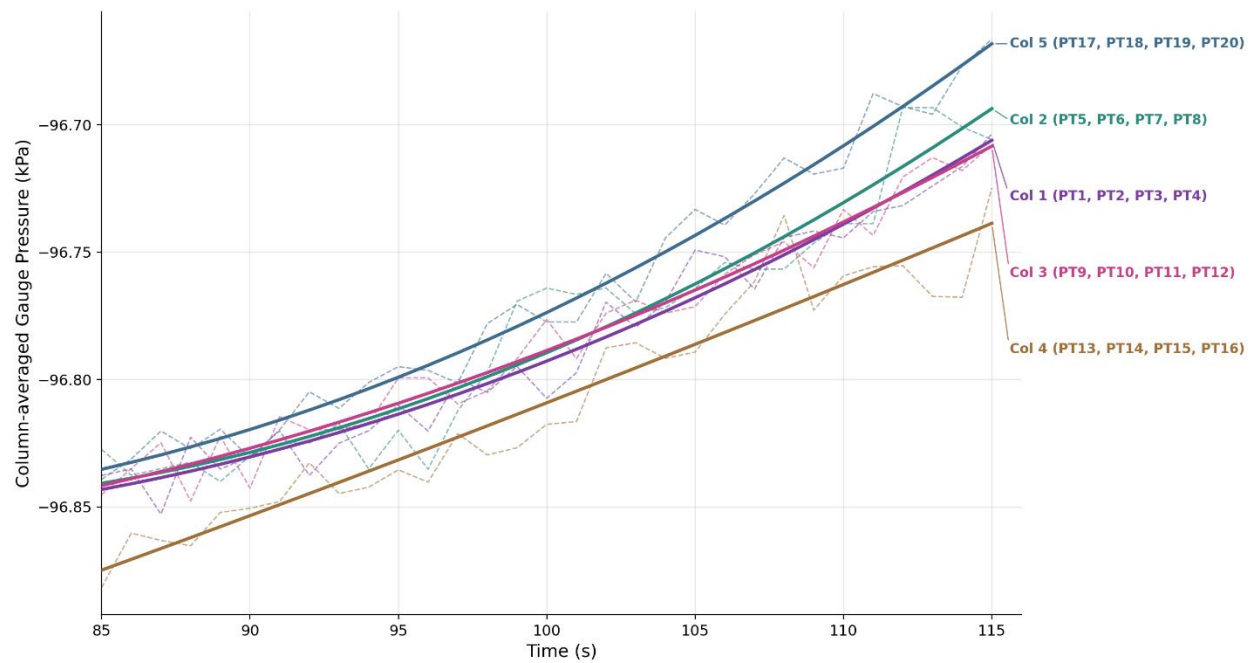


Figure E.6: Column-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #7

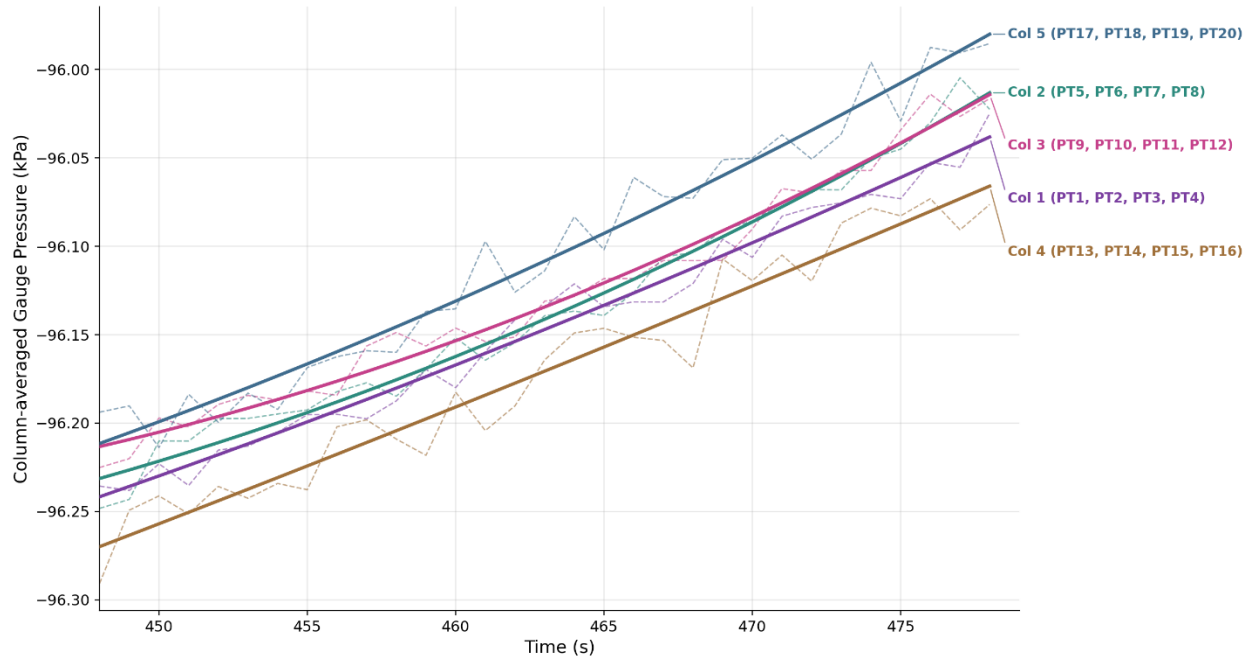


Figure E.7: Column-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #8

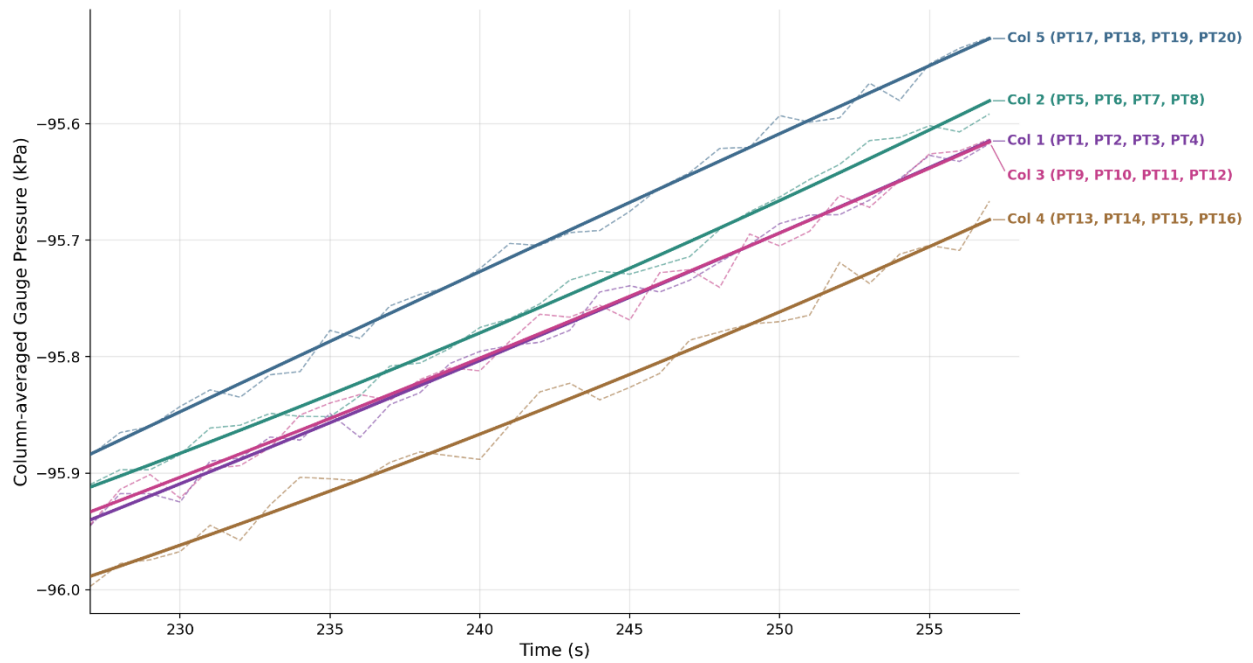


Figure E.8: Column-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #9

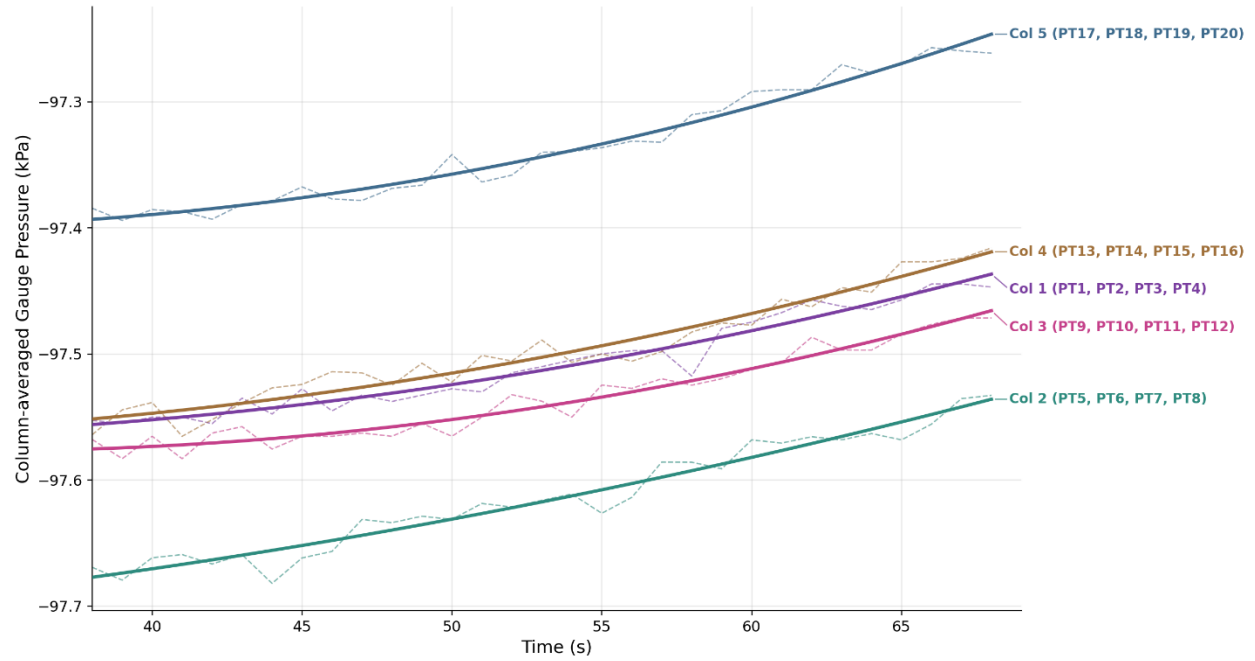


Figure E.9: Column-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #10

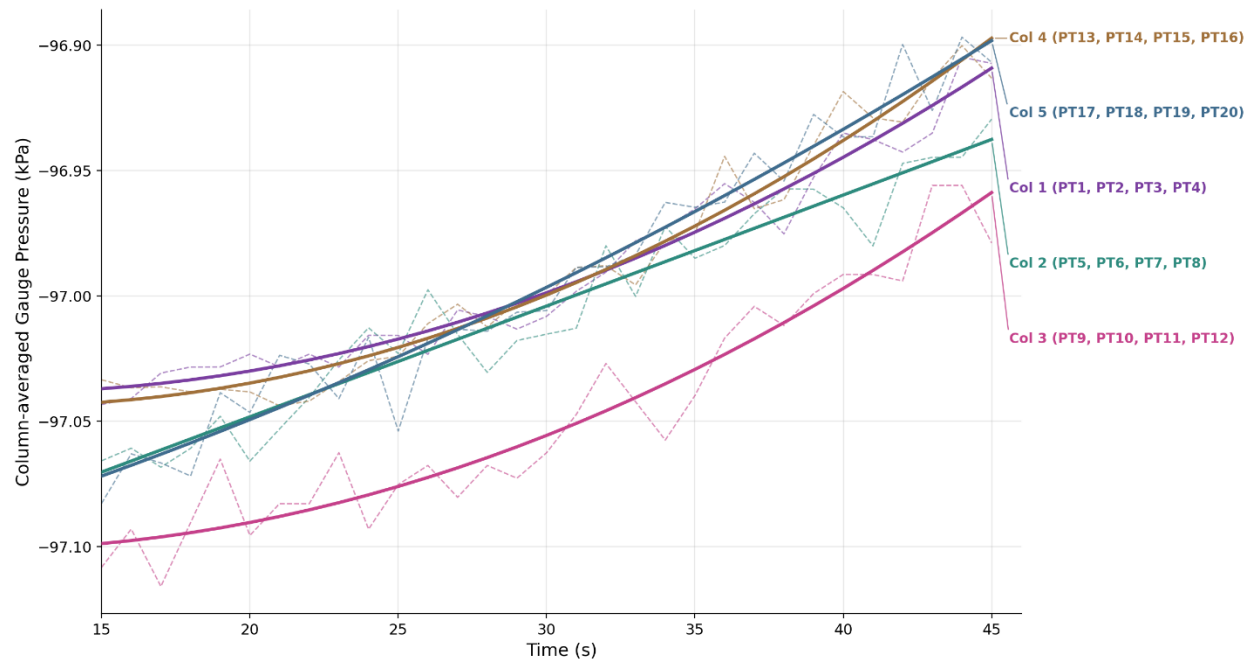


Figure E.10: Column-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #11

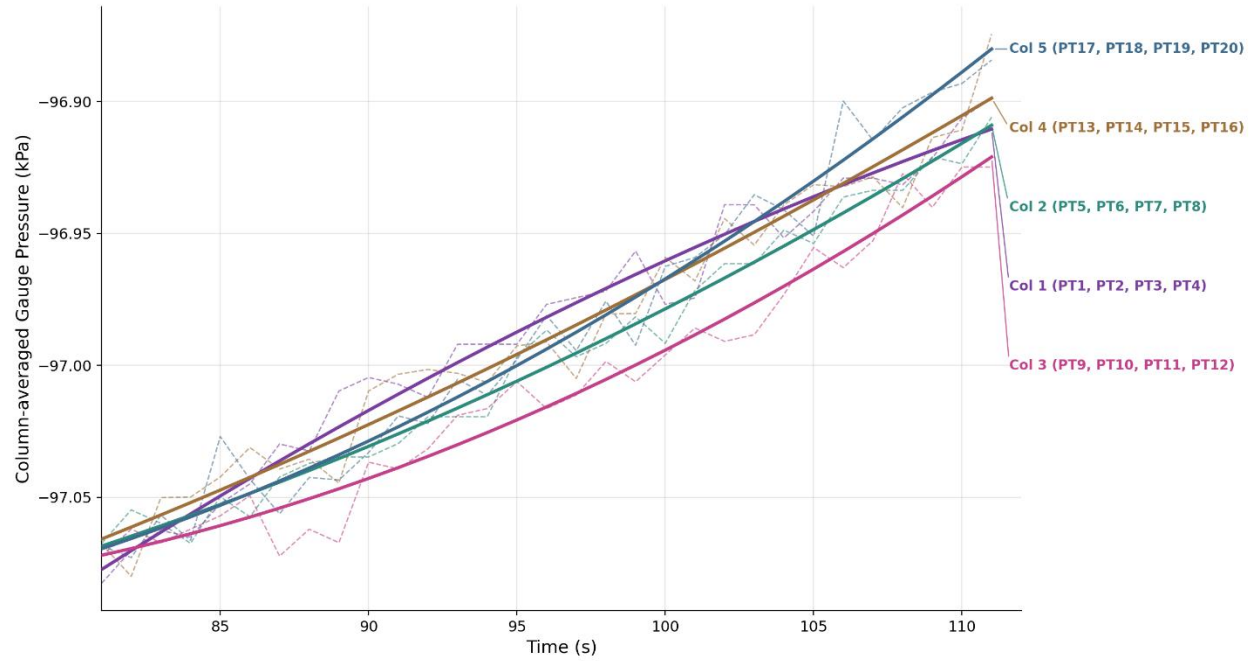


Figure E.11: Column-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #12

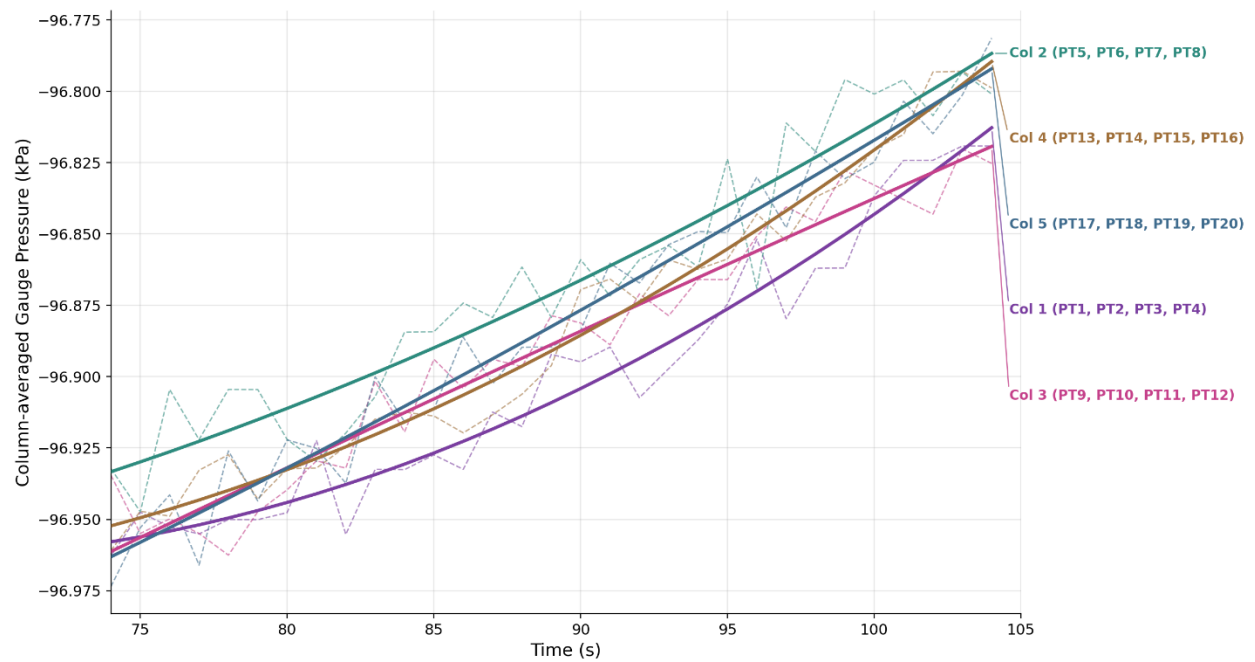


Figure E.12: Column-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #13

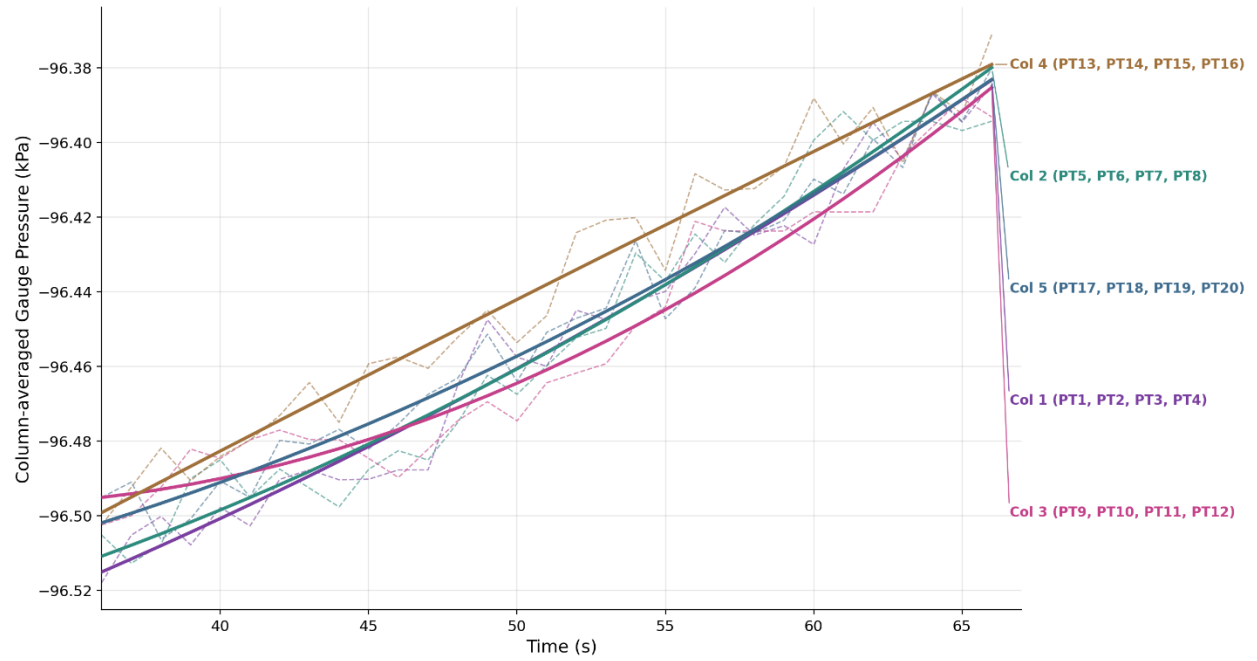


Figure E.13: Column-averaged gauge pressure, first 30s of vacuum-drop test, Experiment #14