A TECHNOLOGICAL AND INTELLECTUAL HISTORY

History of Technical Diagnostics, Observability, and Debugging

From proof testing, strain measurement, and failure analysis to nondestructive evaluation, structural health monitoring, digital twins, and AI-assisted prognosis

— evidence, causality, and the changing craft of explanation —

Concept and direction by Dmitry Vostokov, DumpAnalysis.org

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Historical synthesis with 129 references, chronology, glossary, and evidence taxonomy

Abstract

When we examine a damaged component or an abnormal measurement, we have the results of physical processes. We still need to find out what happened. A bearing may be hot because of poor lubrication, excessive load, misalignment, or a measurement problem. Here we review how technical diagnostics acquired the methods needed to distinguish such explanations, from inspection and proof testing to instrumented monitoring and analysis of materials.

By technical diagnostics, we mean the examination of physical structures, systems, and components for problems with their function or integrity. We follow the scope of the Handbook of Technical Diagnostics, which brings together failure physics, measurement methods, machinery diagnostics, structural-health monitoring, and examination of cultural objects [1]. The history includes stress and strain measurement, vibration, nondestructive evaluation, failure analysis, and the interpretation of condition over time. Computing appears where it supports these activities. Diagnosis of electronic devices and computers belongs primarily to the companion hardware history.

We consider this history as the development of several related approaches to diagnostic problem solving. Inspection provides observations. Mechanics and materials science provide possible mechanisms. Metrology makes measurements comparable, and maintenance supplies additional evidence about behavior before and after intervention. New instruments extend what we can observe, but we also need to understand their limitations. Throughout the history, the main problem remains the same: how to move from a diagnostic sign to an explanation supported by the available artifacts and measurements.

How to read this history

Here we follow related threads of development rather than a sequence of products. A publication date, patent, standard, or investigation marks a documented event. It does not mean that every industry adopted the method at that time. We also find older methods inside modern diagnostic procedures. A walk-around inspection, tap test, maintenance log, or examination of a removed component can provide information missing from continuous monitoring.

The handbook provides our scope, including both functional performance and structural integrity [1]. We distinguish several activities within that scope. Nondestructive testing examines an item for indications without impairing its intended use. Condition monitoring follows measured condition over time. Failure analysis investigates how damage occurred. Structural-health monitoring applies repeated or continuous observation to structures. Prognostics uses present condition and assumptions about future operation to estimate what may happen next. These activities often use the same data, but they ask different questions.

References in square brackets identify the sources for historical and technical claims. Interpretations and diagnostic examples explain the significance of those claims. They should not be read as statements made by every cited author. We use primary publications, standards, official investigations, and institutional records where available. The chronology provides selected milestones, the glossary explains the terminology, and the evidence taxonomy helps compare the capabilities and limitations of different observations. The dates of cited standards identify the documents discussed; this history is not an instruction to use an old edition for current engineering work.

Neighboring practices and their primary questions

Table 1. Related practices and the questions they address.

Practice	Primary question	Characteristic evidence
Inspection and proof testing	Does the item meet an acceptance criterion now?	Direct observation, dimensions, load or pressure response, witness records
NDE / NDT	Is a relevant discontinuity or material variation detectable without impairing use?	Indications, images, waveforms, calibration blocks, probability-of-detection evidence
Condition monitoring	Is operating condition departing from a qualified baseline?	Trends, spectra, process variables, alarms, operating-state context
Technical diagnostics	What fault, damage mechanism, or state best explains the observations?	Correlated symptoms, residuals, causal tests, competing hypotheses
Failure analysis	How and why did damage or failure occur?	Fracture surfaces, microstructure, chemistry, loads, sequence and provenance
Structural-health monitoring	Has an asset-scale structure changed, where, and with what consequence?	Distributed sensors, modal or strain fields, environmental normalization, models
Prognostics / PHM	How will condition evolve, and when will intervention be required?	Degradation models, uncertainty bounds, remaining-useful-life estimates, decisions

Recurring developments

- Sensory signs become measurable physical variables.
- Repeated examinations establish condition histories.
- Internal and microstructural evidence extends surface inspection.
- Detection of damage supports intervention before loss of function.
- Different measurements are interpreted with models and operating context.
- Records connect components with asset and fleet histories.
- Pattern recognition is supported by explicit mechanisms and verifiable analysis.

Contents

Seven parts · 35 chapters · three reference appendices

Table 2. Contents and opening pages.

PART I

Foundations of technical diagnostics

1. Vocabulary, scope, and historical method

Consider a stain near a pipe joint. It may indicate an active leak, residue from an earlier leak, or material left during maintenance. We have a diagnostic sign, but several possible explanations. The same problem occurs when we examine a vibration peak or a crack in a coating. Technical diagnostics relates such observations to the condition of a physical object. The handbook organizes this work around failure physics, diagnostic methods, failure analysis, machinery, structures, and cultural heritage [1].

We need to distinguish the stages of that reasoning. An indication is a response produced by an examination. A feature is a property extracted from the response. An anomaly is a departure from a reference condition. Further analysis may identify a fault or damage state and then its mechanism. Consequence assessment asks what that state means for continued use. For example, a hot region in a thermal image is an indication. Calling it delamination requires additional evidence. A classifier output does not remove the need for this distinction.

We use debugging in an extended sense for controlled problem isolation and correction in physical systems. Engineers vary loads, isolate sections, substitute components, and compare the resulting behavior. However, such actions can change the object being investigated. Disassembly may disturb an alignment, and cleaning may remove deposits that explain a failure. We therefore need to preserve the initial evidence and distinguish what was observed before intervention from what appeared afterward. This distinction will recur in the case studies.

2. Craft inspection, proof testing, indicators, and records

Builders and operators could recognize abnormal behavior before they could measure it precisely. They compared sound, appearance, temperature, leakage, deformation, and resistance to movement. Tapping a casting, checking a clearance, or applying a proof load provided information about a particular object. Galileo's 1638 discussion of beam strength and fracture helped bring these practical questions into mathematical mechanics [2]. Such theoretical work did not replace inspection. It provided additional ways to interpret what inspection revealed.

The steam-engine indicator is an early example of converting behavior into a diagnostic artifact. The indicator associated with Watt's engine practice recorded cylinder pressure in relation to piston motion. Engineers could compare the resulting diagrams and investigate differences in performance [3]. Richards's 1862 design reduced the indicator piston's travel and the diagram distortion caused by its inertia [4]. Valve timing, leakage, and other operating effects could then be considered through the shape of a recorded cycle. We can also read such a diagram as a trace of activity, provided we know how it was acquired and what part of the machine's behavior it represents.

Records made comparisons possible beyond the duration of a single observation. Boiler logbooks, railway defect records, ship surveys, and maintenance cards connected symptoms with earlier work and later outcomes. Their value depended on what was recorded. An entry saying that a bearing was replaced tells us little about why it was replaced or what condition was found. Asset identity, operating conditions, repair details, and unsuccessful investigations are part of the diagnostic history. Without them, repeated problems may appear unrelated.

3. Strength of materials and the localization of stress

Strength-of-materials theory made it possible to relate an external load to internal stress and deformation. Beam theory, elasticity, stress concentration, and energy methods developed through interactions between calculation, experiments, and engineering practice. Timoshenko's historical account follows these developments [5]. For diagnostics, they supplied expectations about where damage could occur. We could compare the observed location of a crack with the load path and the geometry of the component.

Consider a plate containing a hole. Its nominal stress describes an average over a chosen section, while the stress near the hole may be much higher. A calculation based only on the nominal value can therefore miss the location where damage starts. The same reasoning applies to weld toes, joints, notches, and changes in section. Models help us select areas for examination. Measured strain, in turn, helps check whether the assumed restraints and load paths describe the actual structure.

We should treat the model as part of the investigation. Unexpected deflection may indicate damage, but it may also reveal settlement, connection slip, an incorrect material property, or a boundary condition omitted from the calculation. A model that agrees with one measurement is not necessarily the only explanation. Comparing several measurements under different loads can help distinguish alternatives. This reciprocal use of models and observations became a recurring feature of technical diagnostics.

4. Metrology, gauges, tolerances, and traceability

Interchangeable manufacture required measurements made in different workshops to be comparable. Reference artifacts, gauges, dimensional tolerances, and calibration procedures provided the means of comparison. The Metre Convention of 1875 established an international basis for uniform measurement [6]. For diagnostic work, this history matters whenever we compare a new reading with an older one or send a component to another laboratory. A numerical difference is useful only if the measurements refer to compatible quantities and conditions.

An instrument produces a measurement through a particular arrangement. Its resolution, sensitivity, drift, bandwidth, alignment, and environmental response affect the result. We therefore include the instrument and setup among the possible sources of an abnormal reading. For example, an apparent change in strain may result from a temperature change or a damaged connection. Calibration and reference checks help us examine this measurement path before interpreting the reading as a change in the structure.

Measurement also needs an account of uncertainty. The Guide to the Expression of Uncertainty in Measurement provides a framework for combining contributions from the measurement process [7]. This is different from adding a general warning that measurements may be inaccurate. We need to identify the quantity being measured, the assumptions used to obtain it, and the uncertainty relevant to the decision. A small apparent increase in crack depth may be unresolved if it is comparable with the uncertainty of the two examinations.

The International Vocabulary of Metrology gives traceability a specific meaning: a measurement result is related to a reference through a documented, unbroken calibration chain, with uncertainty contributions along that chain [8]. We distinguish this from the provenance of an image or file. Both are needed, but a complete maintenance record does not establish metrological traceability. Similarly, a calibrated gauge does not establish that a photograph belongs to the stated component. Acceptance then requires a separate comparison with the applicable limits and decision rule.

5. Boiler explosions, inspection law, and diagnostic institutions

Steam power made the consequences of poor construction and maintenance visible on a large scale. Boiler explosions involved materials, joints, corrosion, pressure, water level, and operating practices. A local repair could address one damaged boiler without preventing similar failures elsewhere. Inspection associations, insurers, engineering societies, and public authorities gradually organized the accumulated experience into inspection requirements and construction rules.

ASME traces the initiative for a uniform Boiler and Pressure Vessel Code to 1911 and its first edition to 1914–1915 [9]. Its history of steam engineering also describes the connection between failures, testing, design margins, and inspection [10]. We can see a change in the object of investigation. The damaged plate or joint remained important, but engineers also had to examine the procedures that allowed the equipment to be built and operated in that condition.

Similar developments occurred in aviation, railways, pipelines, and civil infrastructure. An investigation could produce a new explanation, followed by revised design requirements, inspection procedures, training, and records. Such knowledge remained conditional on the materials and service conditions considered. A standard may provide a useful starting point while leaving a new degradation mechanism outside its original scope. Historical diagnosis therefore includes how knowledge was recorded, transmitted, and revised after further failures.

PART II

Failure physics and the measured response

6. Fatigue and cumulative damage

Repeated loading introduced a problem that a single proof test could not answer. A component might survive a large load and later fail under smaller repeated loads. Wöhler's nineteenth-century railway-axle experiments related stress amplitude to the number of cycles before failure [11]. These experiments contributed to stress–life curves and endurance testing. For diagnosis, the important addition was the history of loading. Present appearance and nominal strength were insufficient descriptions of remaining condition.

Griffith's 1921 energy treatment explained how flaws could govern brittle fracture [12]. Miner's 1945 rule provided a way to combine fatigue exposure at different load levels [13]. These models address different aspects of failure, and we should retain their assumptions when applying them. A cumulative damage value does not preserve the order of every load cycle. Residual stress, load sequence, environment, and manufacturing variation may change the behavior of a real component.

In a fatigue investigation, we reconstruct the loading, identify possible initiation sites, examine the crack, and estimate how it could have grown. Inspection contributes evidence about its location, orientation, and size. A negative result has several possible interpretations: no crack was present, the crack was below the demonstrated detection capability, or the examination did not cover it adequately. Inspection intervals therefore connect two kinds of knowledge, crack-growth behavior and the ability to find the crack before it becomes critical.

7. Fracture mechanics and damage tolerance

Fracture mechanics allowed engineers to describe an existing crack quantitatively. Irwin related loading and crack geometry to the stress field near the crack tip [14]. Paris and Erdogan's 1963 work related fatigue-crack growth to stress-intensity range [15]. Together with fracture-toughness measurements, these developments supported damage-tolerance approaches. We can assume that flaws may be present and then ask what examination and operating limits are needed to prevent them from reaching a critical condition.

This approach changes the diagnostic requirements. Reporting that a crack exists is insufficient when the decision depends on its depth, orientation, remaining ligament, and loading. The same nominal crack size can have different consequences at different positions. We also need to distinguish the measured size from the uncertainty of sizing. Qualification specimens and comparisons with independently established dimensions help determine how much confidence can be placed in an inspection result.

The fracture surface provides another artifact of the process. Beach marks, striations, cleavage facets, dimples, deposits, and arrest features can help reconstruct initiation and propagation. We must preserve these features before cleaning or handling changes them. Fractography and fracture mechanics then provide complementary information. One examines the evidence left by a particular failure; the other evaluates the behavior expected under specified material and loading conditions. Their agreement strengthens an explanation without making every visible mark an exact clock.

8. Creep, corrosion, wear, and interacting degradation

Other degradation processes require different descriptions of time and exposure. Weibull's work provided a statistical description of variability in strength and failure [16]. Larson and Miller related creep-rupture behavior to time and temperature [17]. These approaches help explain why apparently similar components do not necessarily reach the same condition together. Manufacturing differences, temperature histories, stresses, and environments can produce different outcomes within one population.

Wear and corrosion direct our attention to interacting surfaces and their surroundings. Archard related wear to load, sliding distance, hardness, and an empirical coefficient [18]. Tribological investigations also examine lubrication, surface fatigue, debris, and changes in contact. Pipeline corrosion engineers formed NACE in 1943, creating an institutional means of sharing corrosion knowledge [19]. NACE and SSPC joined to form AMPP in 2021 [20]. The observed damage can therefore require both a mechanical explanation and an account of the local chemistry.

Several mechanisms may operate together. A corrosion pit can become a fatigue-crack initiation site. Poor lubrication can increase friction and temperature, while overheating changes the material and accelerates further degradation. NASA's discussion of physics-of-failure methods concerns reliability assessment of electronics through stresses and failure mechanisms [21]. Here we apply the same question to mechanical degradation: which process could connect the observed conditions with the damage? We should therefore look for observations that describe different parts of the process. Vibration, lubricant chemistry, contact damage, and operating history may together explain what none of them establishes separately.

9. Reliability and inspection planning

Reliability engineering extended the study of individual failures to populations and systems. The bathtub curve represents possible changes in failure rate over life, but it should not be imposed on every mixture of mechanisms [22]. Failure-mode and effects analysis works from components and their possible failures toward system consequences. MIL-STD-1629A, issued in 1980, is an influential historical formulation of this procedure [23]. Its diagnostic value is the explicit connection between a failure mode, its effects, and the means of detecting it.

Fault-tree analysis starts with an unwanted event and examines combinations of contributing events. NASA's handbook describes this approach and the importance of system boundaries and assumptions [24]. Comparing a fault tree with available tests can expose gaps in coverage. Two nominally redundant channels may share a power supply, environment, or maintenance error. Counting channels alone would miss that common cause. The analysis helps us ask what observation could distinguish the relevant combinations.

Risk-based inspection uses estimated likelihood and consequence to allocate inspection effort. API RP 580 describes such programs for pressure-containing equipment [25]. The resulting ranking depends on the degradation mechanisms considered, the effectiveness of examination, and the assumptions about consequences. We should read it as a model to be revised with field evidence. A precise risk number does not compensate for an omitted mechanism or an inspection method that cannot reach the location of interest.

Reliability-centered maintenance adds the question of which maintenance task is appropriate for a particular failure mode and its consequences. Nowlan and Heap's 1978 report is an important milestone in this development [26]. NASA's later maintenance guide applies the approach to facilities and collateral equipment [27]. A detectable change may support condition-based maintenance. A hidden protective-function failure may require a functional test. Age-based replacement, redesign, or an explicitly justified run-to-failure policy may be appropriate in other cases. Diagnosis and maintenance selection are related activities, but they are not interchangeable.

10. Measuring strain

Strain measurement made local deformation available for comparison with structural calculations. Mechanical extensometers provided local readings, while electrical resistance and later optical sensors extended the available methods. Glisic reviews the electrical and optical developments [28]. Simmons began resistance-wire work in 1936, and Ruge developed a bonded resistance gauge in 1938 [29]. Simmons's material-testing patent was filed in 1940 and granted in 1942 [30]. Ruge's strain-gauge patent was filed in 1939 and granted in 1944 [31]. These are separate patents with individual inventors. The measurements could now be made on structures under representative loads.

Photoelasticity provided a view of a field rather than a reading at one position. Polarized light produced fringe patterns in suitable transparent models, from which stress differences could be investigated. Coker and Filon's 1931 treatise consolidated this experimental approach [32]. Consider a hole or a fillet in a loaded component. A full-field view can show a concentration that a gauge placed elsewhere would miss. The spatial arrangement of measurements is therefore part of the diagnostic method.

Digital image correlation later used changes in image texture to estimate displacement and strain [33]. It extended full-field measurements to actual surfaces and dynamic tests, while introducing dependencies on calibration, optics, lighting, surface texture, and the chosen analysis regions. Out-of-plane movement can also affect a result intended to describe in-plane deformation. We need to retain the images, coordinates, loading, and processing choices so that the field can be checked against another explanation.

11. Vibration and modal diagnosis

Vibration provides information about forcing, stiffness, mass, damping, clearances, and rotating parts. Rayleigh's nineteenth-century Theory of Sound brought together important theoretical descriptions of vibration and waves [34]. Electrical transducers and analyzers made it possible to record and compare motion. Cooley and Tukey's 1965 FFT paper was a major milestone in making digital spectral calculations practical [35]. Frequency analysis could then become part of routine investigation rather than a calculation reserved for a few experiments. Mitchell's history records that FFT analyzers had replaced time-compression analyzers by the late 1970s and that route-based portable data collectors appeared between 1982 and 1984 [36].

Machine analysis developed ways to examine shaft orders, harmonics, sidebands, bearing-related frequencies, resonances, and transients. ISO 20816 provides guidance for measuring and evaluating machine vibration [37]. However, an overall vibration value is not a mechanism. We may need its direction and phase, the machine speed and load, and the earlier trend. A peak that changes with operating speed requires a different interpretation from a feature that remains tied to a structural resonance.

Modal testing estimates natural frequencies, mode shapes, and damping from measured responses. Ewins connects these measurements with excitation, processing, and model validation [38]. Operational modal analysis uses ambient or operating excitation when a controlled test is difficult. In both cases, we need to compare like conditions. Temperature, loading, restraint, and operating state can change the response without damage. A baseline that includes such variation helps us decide whether a later difference requires a structural explanation.

PART III

Nondestructive evaluation and the failure-analysis laboratory

12. Visual and surface examination

Nondestructive examination developed from practices in several trades into a discipline with its own terminology and qualifications. ASNT traces its origin to the American Industrial Radium and X-Ray Society, founded in 1941 [39]. ASTM E1316 provides terminology used across examination methods [40]. The distinction between an indication, a discontinuity, and a defect is particularly useful. An observed response may have an innocent explanation, and a real discontinuity need not violate the acceptance requirements.

Visual examination gives access to surface condition, geometry, leakage, and evidence of movement. Lighting, magnification, and remote viewing extend its usefulness [41]. Comparison with earlier records adds a history to the visible condition. Liquid penetrant testing makes surface-breaking discontinuities easier to see. Its history includes oil-and-whiting practices in railway work and the later development of fluorescent methods. Switzer's patent documents part of that development [42,43]. Cleaning, dwell time, developer, and surface condition affect the resulting indication.

Magnetic-particle testing uses leakage fields associated with discontinuities in ferromagnetic materials [44]. Hoke's 1922 patent describes detecting defects with a magnetic field and finely divided magnetic material [45]. The direction and strength of magnetization affect which flaws can produce useful indications. Geometry, coatings, permeability, and residual fields can also change the response. We therefore need more than a photograph of a suspicious line. The record should identify the surface, orientation, scale, preparation, examination procedure, and acceptance basis. Otherwise, a later analyst may be unable to reproduce or interpret the observation.

13. Industrial radiography

Röntgen's 1895 communication introduced X-rays as a means of investigating otherwise hidden structure. Its contemporary English translation and the Nobel historical account document the discovery [46,47]. Industrial radiography subsequently used X-ray tubes and radioactive sources to examine welds, castings, assemblies, and pressure boundaries [48]. Differences in attenuation could reveal internal geometry and discontinuities without cutting the component. This added a new class of diagnostic artifact to direct surface observations.

A radiograph combines information along the radiation path. We should therefore interpret it as a projection. Source size, energy, object thickness, orientation, scatter, and detector response affect contrast and resolution. A planar flaw can be difficult to detect in an unfavorable orientation, while a change in geometry can resemble a material discontinuity. Image-quality indicators and technique records help establish the capability of that particular examination. They do not make all possible flaws equally detectable.

Film provided a physical record that could be reviewed after the examination. Computed and digital radiography changed acquisition, processing, storage, and comparison. They also made it easier to alter the displayed appearance of an image. Contrast adjustment may reveal a feature, but it cannot recover information lost through saturation or inadequate acquisition. We should preserve the original data and processing history together with the displayed result. This allows a later investigation to distinguish object features from display artifacts.

14. Ultrasonic examination

Pulse-echo ultrasonics relates reflected waves to internal geometry and discontinuities. Firestone's 1942 patent describes an early flaw-detecting device using this principle [49]. Subsequent developments included piezoelectric probes, angle-beam examination, immersion scanning, and arrays [50]. ASTM E127 specifies ultrasonic reference blocks containing flat-bottomed holes [51]. Time of flight and amplitude became measurements from which an analyst could infer possible reflectors. Phased arrays and later reconstruction techniques added controlled beam steering, focusing, and more extensive spatial sampling. Portable, battery-powered phased-array instruments entered industrial use in the 1990s [52].

The indication depends on the complete acoustic path. Coupling, surface condition, wave velocity, attenuation, grain structure, frequency, refraction, and flaw orientation affect the response. Consider calibration on a smooth artificial reflector followed by examination for a rough service crack. The two may respond differently even when their nominal dimensions are similar. Qualification must connect the reference target with the actual inspection problem. A successful calibration is necessary evidence about the equipment, but it does not by itself establish complete service-flaw coverage.

Array displays can resemble direct pictures of the interior. Their construction still depends on sampled signals, geometry, focusing laws, and reconstruction assumptions. Dead zones and inaccessible regions may remain. Encoded position, scan plans, calibration checks, and retained waveforms help us evaluate the displayed result. Independent examination becomes particularly useful when a sizing result will determine whether a component can remain in service.

15. Eddy-current and electromagnetic diagnosis

Electromagnetic testing detects changes through the interaction of fields with material and geometry. The method family includes eddy current, alternating-current field measurement, remote field, and pulsed eddy current [53]. Historical accounts relate the development of eddy-current inspection to Hughes's nineteenth-century experiments and later impedance-plane instruments [54]. These methods made it possible to investigate conducting or magnetic components without relying on a visible opening in the surface.

An eddy-current response can change with a crack, conductivity, permeability, thickness, heat treatment, or probe lift-off. We therefore have several possible mechanisms for an apparent anomaly. Frequency selection, reference specimens, probe arrangements, and phase information help discriminate among them. Repeating the examination with a changed probe orientation or setup can provide additional evidence. The useful diagnostic pattern is the response under known conditions, including how it changes when those conditions change.

Specialized probes extend electromagnetic examination to tubing, fastener holes, rails, wire rope, and pipelines. Each arrangement has a particular coverage and set of limitations. Arrays and model-based inversion can provide spatial estimates, but these estimates depend on material properties and geometry. A crack-like display should therefore be accompanied by the detection conditions, estimated location and dimensions, uncertainty, and relevant alternative explanations. This information connects the indication with an engineering assessment.

16. Acoustic emission

Acoustic-emission testing observes transient elastic waves generated by activity in the object. Possible sources include crack growth, fiber breakage, friction, leakage, and corrosion processes. Kaiser's 1950 work and the effect named after him are milestones in the method's development [55]. Instead of scanning every location with an external probing signal, an examination can monitor activity from several sensors while the structure is loaded.

Arrival times help locate sources, while event amplitudes, counts, frequency content, and their relation to loading provide additional information. Propagation through a real structure changes the signals through attenuation, dispersion, reflection, and mode conversion. Mechanical and electrical noise can produce competing indications. Grosse and Ohtsu treat source mechanisms, sensors, processing, and applications together [56]. This system view is needed because an apparent source pattern can be partly a pattern of wave propagation and sensor placement.

Absence of emission does not establish absence of damage. A crack that remains inactive during the observation may produce no detectable signal. Previous loading can also affect when emission resumes. We should interpret a quiet interval in relation to the applied load, sensor coupling, background noise, and demonstrated sensitivity. When activity is localized, targeted examination by another method can help establish what is present. Acoustic emission supplies evidence about activity, while a follow-up scan may supply evidence about geometry.

17. Infrared thermography

Herschel's experiments in 1800 demonstrated invisible radiation beyond the red part of the visible spectrum [57]. Later detector, optical, and computing developments made thermal fields available for diagnostic analysis. Passive thermography examines the radiation associated with existing operating conditions. Active thermography applies an excitation and observes the response. These approaches can investigate heating in equipment, insulation losses, and changes in the heat flow through a material.

The displayed thermal image requires interpretation. Emissivity, reflected radiation, atmosphere, viewing angle, focus, detector calibration, and timing affect the result. Maldague explains the heat-transfer and experimental principles of infrared nondestructive testing [58]. For example, a bright region may correspond to higher temperature, a different surface finish, or a reflected source. Comparing the thermal image with a visible image and the operating state helps separate these possibilities.

Thermography provides a spatial view without contact with the inspected surface. It can support surveys of electrical connections or examination of a panel after controlled heating. However, a defect must affect the observed thermal response under the test conditions to become detectable. We should record the radiometric data, excitation, load, environment, timing, and surface assumptions. A comparison region is useful only when its material and boundary conditions make the comparison meaningful.

18. Computed tomography and X-ray microdiagnostics

Computed tomography reconstructs cross-sections or volumes from multiple radiographic projections. It reduces the superposition that complicates a single radiograph and allows internal geometry to be examined in three dimensions. Industrial CT developed during the late twentieth century and found applications in castings, composites, manufactured parts, and assemblies. ASTM E1441 provides guidance for the method [59]. The reconstructed volume became an artifact that could be revisited with different sections and measurement questions.

CT supports examination of porosity, wall thickness, cracks, and the arrangement of internal parts. De Chiffre and colleagues review its industrial development in metrology and nondestructive evaluation [60]. We need to distinguish voxel spacing from the ability to detect a particular feature. Energy, magnification, noise, scan time, material combinations, and reconstruction artifacts also matter. A small voxel does not guarantee that a narrow crack is resolved or that a segmented boundary has the stated measurement accuracy.

Digital records require stable connections between the data and the object. ASTM E2339 describes DICONDE, which adapts medical-imaging concepts to the exchange of nondestructive-examination images and metadata [61]. Component identity, orientation, acquisition parameters, calibration, and processing history should accompany the image or volume. Otherwise, a future analyst may have a detailed picture without enough information to compare it with a later examination or establish which component it represents.

X-ray microdiagnostics also includes techniques that use scattering and refraction rather than attenuation alone. Müller and Hentschel describe synchrotron methods for relating internal microstructure to material properties [62]. This extends the history beyond increasing the resolution of familiar radiographs. Different interactions provide sensitivity to different features. We should therefore ask which property produced the contrast and how representative the examined volume is of the component as a whole.

19. Failure analysis and material examination

A failure investigation usually begins with the object as received and the circumstances in which it was found. Photographs, deposits, witness marks, matched fracture surfaces, records, and comparison parts may all be relevant. Cleaning, cutting, or testing can remove some of this evidence. The ASM handbook and Dennies's account describe the organization of investigations from collection through analysis to corrective action [63,64]. The order of examinations is therefore itself a diagnostic decision.

Optical microscopy, hardness measurements, mechanical tests, electron microscopy, and chemical analysis answer different questions about a specimen. Ruska's early electron microscopes were transmission instruments; his 1931–1933 work helped establish electron microscopy beyond optical resolution [65]. Later scanning electron microscopy became especially useful for fracture-surface examination. We should not treat these developments as the invention of one interchangeable method. Specimen preparation, the sampled region, and the interaction producing the signal determine what each image can establish.

Surface chemistry may distinguish contamination, oxidation, and an altered layer from a change in the bulk material. X-ray photoelectron spectroscopy is sensitive to near-surface composition and chemical states; its interpretation depends on charging, reference data, preparation, and sampling conditions [66]. Unger and Hodoroaba place surface chemical analysis explicitly within technical diagnostics [67]. An elemental result from one location should not automatically be generalized to the entire component. Surface and bulk measurements can differ because they examine different material volumes.

Österle's treatment of subsurface microstructural analysis shows why thin layers beneath an operating surface deserve separate attention [68]. Local cross-section preparation, including focused-ion-beam methods, can connect a selected surface feature with the material beneath it. Such preparation changes the specimen even when the affected region is small. We need to preserve the original location, orientation, and as-found observations so that the microscopic evidence remains connected with the larger failure.

ASTM E2332-04 is a historical practice for investigating physical-component failures that has since been withdrawn [69]. Its withdrawal should not be presented as though any one ASTM examination standard replaced the entire investigation process. The applicable examination standards and investigation guidance must be selected for the problem. We distinguish the initiating damage from consequential damage, the physical mechanism from contributing organizational conditions, and established findings from recommendations. Retaining untested material also allows later questions to be investigated.

PART IV

Machines, plants, and mobile systems

20. Rotating machinery and condition monitoring

Rotating machinery provided many opportunities to observe condition during operation. Shaft motion, bearing acceleration, temperature, current, speed, process variables, and sound could be compared with expected behavior. Some faults produce useful precursors in these signals; others remain difficult to observe. ISO 17359 describes the organization of a condition-monitoring program around the machines, their criticality, and relevant failure modes [70]. Selecting a sensor is therefore one part of a larger diagnostic design.

Portable analyzers and permanently installed systems supported routes, trends, spectral comparisons, order tracking, and envelope analysis. Jardine, Lin, and Banjevic's 2006 review brings together acquisition, processing, diagnostics, and maintenance decisions [71]. ISO 13374-1, published in 2003, organized the data-processing and communication functions of condition monitoring [72]. These developments made it easier to connect a measured waveform with a health assessment while retaining the intermediate steps.

Automation also introduced diagnostic problems of its own. A replaced sensor may create a step in a trend. A changed operating regime may repeatedly cross a fixed alarm threshold. Missing samples can distort a spectrum or conceal an event. NIST's PHM roadmap identifies measurement, validation, false alarms, and data exchange as continuing concerns [73]. We need speed, load, sensor identity, configuration, and processing history to decide whether an apparent change belongs to the machine or the monitoring system.

The maintenance result provides a further test of the interpretation. Suppose bearing replacement reduces the vibration. This supports a connection, but the work may also have changed alignment, lubrication, and fastening. Recording the as-found condition and the individual actions makes the comparison more informative. Reliability-centered maintenance also reminds us that monitoring is useful only when a suitable response can be completed before the relevant functional failure [27].

21. Lubricant analysis and wear debris

Lubricant carries evidence from regions that may be inaccessible during operation. Viscosity, water, oxidation, acidity, additives, particle counts, elemental composition, and debris shape describe different aspects of lubricant and machine condition. Ferrography separates and presents wear debris for examination. NASA's 1977 bearing-fatigue work illustrates its use in characterizing particles produced during rolling-element tests [74]. We can then compare the observed debris with possible rubbing, cutting, fatigue, or severe-sliding mechanisms.

An oil sample is also the result of a transport and sampling process. Flow, settling, filters, top-up, and the sampling location affect which material reaches the bottle. After an oil change, a lower debris concentration may describe the changed lubricant rather than recovery of the damaged contact. Consistent sampling and a record of interventions are essential for trending. Filter examination, vibration, temperature, and direct inspection can supply evidence that the sample alone lacks.

Tribological analysis relates surface changes to the function of the contact. Archard's relation provides a useful model, but it does not uniquely identify a wear mechanism [18]. Scuffing, rolling-contact fatigue, micropitting, corrosion, and contamination may occur together. We look for agreement between debris morphology, material composition, lubricant condition, contact geometry, and loading. Disagreement can also be useful. It may indicate that the sample contains debris from another source or that the current hypothesis explains only part of the problem.

22. Pressure equipment, pipelines, and leak testing

Process equipment combines pressure, temperature, chemistry, cyclic operation, and complex access conditions. Welds, insulated regions, dead legs, supports, and changes of service require different examination strategies. API 570 describes the managed inspection and maintenance of in-service piping [75]. Risk-based inspection adds a way to prioritize the work by mechanism and consequence [25]. A general inspection interval is therefore only a starting point when local conditions can produce a different degradation rate.

Pipelines add the problem of locating and comparing observations over long distances. Patrols, cathodic-protection surveys, leak monitoring, in-line inspection, pressure tests, excavations, and material examinations provide different kinds of evidence. Magnetic-flux leakage, ultrasonic thickness, and geometry tools do not measure the same property. Run-to-run comparison also requires position matching. A change in reported depth is difficult to interpret if the two records do not describe the same feature.

Leak testing deserves a separate place in this history because it examines the passage of a fluid across a boundary. Bubble methods, pressure change, and tracer gases such as helium provide different ways to detect or locate leakage [76]. A pressure boundary may pass a structural examination and still leak through a seal. Conversely, a tight component may contain damage that has not formed a through-path. Temperature, test medium, pressure difference, stabilization, and detection sensitivity belong in the test record.

The interpretation then connects local evidence with system behavior. A corrosion colony has dimensions and a position, while its consequence also depends on material, pressure history, neighboring defects, and loading. An operating alarm may detect a loss of containment without locating its cause. An in-line indication may identify metal loss without showing whether corrosion remains active. Comparison with excavations, material records, and subsequent examinations helps connect these observations and test the inferred growth rate.

23. Electric power and nuclear plants

Power plants combine mechanical, thermal, electrical, chemical, and structural diagnostic questions. Turbine vibration, generator behavior, boiler chemistry, wall thickness, leakage, and settlement belong to different observation systems. Nuclear applications add safety classification, qualified instrumentation, surveillance tests, and defense in depth. We need to know which function each measurement supports before interpreting it as evidence about overall plant condition.

The IAEA's 2008 publication describes online process and component monitoring in nuclear plants [77]. The IAEA's 2007 condition-based-maintenance guidance connects the measurements with work selection, acceptance criteria, trends, and the wider maintenance program [78]. Online observation can reveal behavior between outages, while periodic inspection and functional tests answer other questions. Continuous measurement of an accessible variable does not establish the condition of every inaccessible component.

Monitoring must also distinguish instrument problems from plant changes. Sensor drift can resemble slow degradation, while a common process change can move several channels together. Configuration control, independent measurements, and explicit sensor-fault hypotheses help make the distinction. An early warning, confirmed damage, an operability judgment, and a safety decision require different evidence. Combining them in one alarm label can hide the uncertainty that an operator or engineer needs to understand.

Dissolved-gas analysis provides an example of diagnosis through chemical products of electrical and thermal activity. IEC 60599:2022 addresses interpretation of dissolved and free gases in mineral-oil-filled electrical equipment, including transformers [79]. The guidance is specific to the insulating system and should not be transferred unchanged to other liquids. Gas patterns, rates of change, loading, maintenance, and other examinations must be interpreted together. A gas-based indication supports investigation; it does not by itself establish the full condition of the equipment.

24. Aerospace structures and fleet evidence

Aircraft combined repeated loading, low structural weight, limited access, and severe failure consequences. The Comet investigations used recovered wreckage and full-scale cabin testing to investigate fatigue and structural details [80]. The significance for diagnostics was the connection between several artifacts and experiments. No isolated observation supplied the complete sequence. Damage-tolerance and fatigue-assurance practices subsequently gave greater attention to service loading, likely initiation locations, and the ability to detect damage in time.

Aircraft inspection became a program spanning individual components, aircraft, and fleets. Visual examination, eddy current, ultrasonics, radiography, borescopes, debris analysis, and recorded repairs provided complementary observations. Aloha Airlines Flight 243 showed how multiple-site fatigue, corrosion, aging, and inspection-program assumptions could interact [81]. The unit of comparison could no longer be only a nominally identical part. Its cycles, service environment, repairs, and position in the aircraft mattered.

Onboard health monitoring added operating signals, maintenance messages, exceedance records, and prognostic estimates. Such data still require aircraft identity and configuration. Part swaps, sensor replacements, maintenance, and software changes can alter the recorded behavior. Fleet analysis can identify a recurrent pattern, but the explanation must be checked against exposure and as-found condition. A repeated message becomes useful engineering evidence when it is connected with a physical location and a verified outcome.

Composite structures extended this problem beyond the crack-growth models commonly used for metals. Matrix cracking, delamination, fiber damage, disbonding, moisture, and impact can affect different scales of a structure. Small visible damage may accompany a larger internal region. FAA AC 20-107B, issued in 2009 and amended in 2010, connects composite design, manufacturing, inspection, and maintenance [82]. We therefore need representative damage cases and examinations suited to the material and joint. A method effective for a metal crack does not automatically establish the integrity of a composite bond.

25. Railways and vehicles

Railway diagnostics developed from examination of rails, wheels, axles, and bearings into a combination of onboard and wayside systems. Ultrasonic rail inspection, geometry measurements, wheel-impact monitors, hot-bearing detectors, and acoustic measurements observe different aspects of service behavior. The wheel–rail contact connects material condition with load, traction, contamination, profile, temperature, and maintenance. A recurrent indication may therefore belong to a vehicle, a track location, or their interaction.

At Hatfield in 2000, rolling-contact fatigue led to extensive rail cracking and fragmentation. The later engineering review examined the damage mechanism [83]. The official investigation also documented failures in inspection, maintenance, and rail renewal [84]. Recognizing the damage was only part of the required response. Classification, work planning, access, replacement material, and completion of the work had to follow. This case helps us distinguish diagnostic knowledge from the organizational ability to act on that knowledge.

Road-vehicle diagnosis similarly combines onboard measurements with inspection, fluid analysis, alignment, brake and tire examination, and noise or vibration analysis. Fleet records provide comparisons, but we need to retain route, load, weather, component position, maintenance, and calibration. For example, an outlier in one route's data may disappear when compared with vehicles carrying the same load on the same surface. Population comparison is useful when the relevant operating differences remain visible.

PART V

Structures, infrastructure, and manufacturing health

26. Buildings, bridges, dams, and structural-health monitoring

Buildings and civil infrastructure remain in service for long periods under changing environments and loads. They are rarely available for experiments under fully controlled conditions. Visual inspection, surveys, crack measurements, load tests, cores, ultrasonic methods, radar, impact echo, acoustic emission, and vibration provide different views of their condition. NIST's work on installed building materials and concrete service-life assessment documents this combination of examination methods [85,86]. The choice depends on the material, access, suspected mechanism, and decision to be made.

The United States developed a national bridge-inspection system following the 1968 Federal-Aid Highway Act [87]. The Silver Bridge investigation showed the consequences of a critical flaw in an inaccessible eyebar detail [88]. The later I-35W investigation identified inadequate gusset-plate capacity, demonstrating that condition inspection alone cannot establish the correctness of a design calculation [89]. These cases distinguish three questions: what is damaged, what can be examined, and whether the structure has adequate capacity under its actual loads.

Structural-health monitoring organized repeated observations into a process of detecting and interpreting structural change. Farrar and Worden described this as statistical pattern recognition [90]. The Los Alamos review examined vibration-based damage identification [91], and the later SHM axioms emphasized the relationships among damage, features, and environmental variation [92]. Daum's handbook chapter connects concepts with assessment [93]. FHWA's long-term bridge program adds a practical example of collecting comparable evidence over the life of structures [94].

Dams require an additional combination of structural and geotechnical observations. Piezometers, seepage measurements, surveys, and deformation instruments help relate behavior to reservoir level, rainfall, foundation conditions, and time. The Bureau of Reclamation's instrumentation and monitoring guidance describes this work [95]. A rise in measured pressure can have several explanations, including a changed reservoir level or an instrument problem. The diagnostic comparison should include the expected response to loading, earlier behavior, and direct inspection. Large numbers of sensors do not compensate for poor placement relative to a possible failure mechanism.

27. Embedded, fiber-optic, and wireless sensing

Embedded sensing made some observations possible without repeated access to the same location. Strain, temperature, acceleration, displacement, and environmental measurements could be collected inside structures or from remote equipment. The 1978 report of photosensitivity in optical fibers was an important foundation for fiber Bragg grating sensors [96]. Later systems could place several sensing locations along a fiber and compare their responses. This created opportunities for distributed observation while making installation and interpretation part of the design.

Wireless networks reduced cabling requirements and connected sensing with local computation. Lynch and Loh's 2006 review describes the development of these systems for structural monitoring [97]. Processing at the sensor node can reduce the amount of transmitted data. However, the selected feature then depends on software, local timing, and configuration as well as the physical measurement. Communication loss and power limitations also affect which events reach the analyst.

The sensor installation becomes an object of diagnosis in its own right. Debonding, moisture, drift, temperature sensitivity, installation strain, clock errors, or missing data can imitate a structural change. Redundancy helps only when we understand the shared failure possibilities. A reference sensor, independent modality, environmental measurement, or periodic inspection may answer a question that another identical sensor cannot. We must also distinguish a healthy reading from absence of a reading. A silent network provides no assurance by itself.

28. Offshore structures and wind turbines

Offshore structures operate under cyclic loads, corrosion, waves, wind, and seabed interaction, often with difficult access. Divers and remotely operated vehicles examine members, welds, coatings, marine growth, and scour. Machinery and process systems add vibration, lubricant, electrical, thermal, and operating evidence. Remote monitoring is useful, but the environment can produce changes larger than those associated with early damage. We need enough context to separate an altered operating condition from deterioration.

A wind turbine combines a flexible structure with blades, a rotating drivetrain, electrical equipment, and control systems. Blade examination may use visual images, ultrasonics, thermography, shearography, and acoustic methods. Drivetrain monitoring follows bearings, gears, lubrication, and generator behavior. ISO 16079-2 describes condition monitoring of wind-turbine drivetrains [98]. These different observations should remain associated with their physical locations and the operating conditions under which they were collected.

Consider a change in a tower's natural frequency. Possible explanations include structural damage, soil stiffness, temperature, rotor speed, and control state. A gearbox alarm may similarly follow a torque transient rather than a progressive fault. Synchronized structural, mechanical, meteorological, and control records help distinguish the alternatives. Maintenance, curtailment, sensor changes, and uncertainty are also part of the record. The remote analyst needs the circumstances of an observation, not only the value that crossed a threshold.

29. Manufacturing and process monitoring

Manufacturing has two related diagnostic objects: the process and the resulting product. Final inspection examines the part, while process monitoring examines the activity that produced it. Dimensional gauges, sampling, nondestructive examination, and destructive coupons provided different forms of product evidence. Statistical process control used variation to identify changes in production. Later systems added force, power, temperature, vibration, images, and machine state to the manufacturing record.

Additive manufacturing makes the relationship especially visible. Images and thermal measurements can record behavior during a build, while CT, microscopy, ultrasonics, and mechanical tests examine the resulting material. NIST IR 8538 reviews monitoring and nondestructive evaluation for metal additive manufacturing and the remaining measurement and qualification problems [99]. A process feature may help locate a region for further examination, but the connection with a material discontinuity must be demonstrated.

For example, an unusual bright region, spatter event, or recoater interruption is initially evidence about the process. It does not establish by itself that the part contains a rejectable flaw. We need registration between the process observation and the finished geometry, together with machine, material, and parameter histories. Post-build examination and selected destructive tests can then test the proposed relationship. The digital thread is useful when these connections are preserved and can be followed in both directions.

30. Qualification and diagnostic decisions

An examination method needs demonstrated performance for the actual target, material, geometry, procedure, equipment, and personnel. MIL-HDBK-1823A describes assessment of nondestructive-examination reliability using probability of detection [100]. Instead of assuming that all flaws above a nominal size will be found, we estimate detection probability and its uncertainty. These estimates belong to a defined inspection system. They should not be transferred to another access condition or flaw population without justification.

Personnel and laboratory competence also affect the result. ISO 9712 describes qualification and certification for industrial NDT personnel [101]. ISO/IEC 17025 addresses the competence and consistent operation of testing and calibration laboratories [102]. Procedures, representative specimens, equipment checks, calibration, and environmental controls establish the conditions under which results can be trusted. A certificate does not remove the need to check whether a particular method and setup answer the question in the investigation.

A detection threshold changes both misses and false calls. Their consequences depend on the application: a missed crack may lead to failure, while unnecessary rejection or rework can introduce additional cost and damage. We need to report coverage, sizing error, reproducibility, and blind regions as well as detection performance. Evidence supporting a method should describe the conditions under which it was demonstrated and the limits on transferring that result.

Probability of detection and confidence in its estimate are different quantities. A commonly reported size corresponds to 90 percent detection probability at a 95 percent lower confidence bound [100]. This does not mean that an individual negative examination has established a 95 percent probability of no damage. That interpretation would also require information about the prior flaw population and the examination conditions. Keeping these questions separate prevents a qualification statistic from becoming an unsupported assurance claim.

Conformity assessment adds a decision rule when a measured value is compared with an acceptance limit. JCGM 106 explains the role of measurement uncertainty in that decision [103]. Consider a thickness measurement close to the minimum permitted value. Repeating the displayed number without its uncertainty hides the possibility of an incorrect acceptance or rejection. The governing procedure should state how uncertainty enters the decision. Measurement, detection, and acceptance remain distinct even when one instrument supports all three.

PART VI

Models, prediction, and cultural heritage

31. Technical examination in the arts and cultural heritage

The handbook includes technical examination of works of art and cultural objects within the same field [1]. Here the purpose may be to understand construction, identify changes, investigate deterioration, or select a conservation treatment. A painting or archaeological object also contains evidence accumulated over time. Examination must preserve that evidence while distinguishing the original material from later additions, repairs, and environmental effects.

Conservation laboratories combine visual examination with microscopy, ultraviolet fluorescence, infrared imaging, radiography, X-ray fluorescence, spectroscopy, and other methods. The Smithsonian describes infrared and ultraviolet imaging in conservation work [104]. The Metropolitan Museum's examination of Madame X illustrates the use of scanning XRF to map pigment-related elements and investigate alterations [105]. Registered observations allow features in one image to be compared with the same locations in another.

Interpretation still requires material and historical knowledge. An elemental map does not uniquely identify every pigment. An underdrawing need not establish a different artist, and a crack pattern may reflect the support, ground, paint, climate, or treatment. We can first use broader, less invasive observations to identify where a more specific examination would be useful. If sampling is necessary, its location and relation to the intact object must remain documented.

32. Signal processing and model-based diagnosis

Digital processing made it easier to obtain spectra, envelopes, orders, coherence, wavelets, modal estimates, and image features from measurements. The FFT was an important computational development [35]. However, every processing operation also selects or transforms information. Filtering may remove an event; averaging may conceal intermittent behavior; resampling may change a spectral feature. We should retain the parameters and, where practicable, the original measurements so that the result can be reproduced and compared with another interpretation.

Observability has a precise meaning in control theory: internal state can be reconstructed from available outputs under the stated system model and input conditions. Kalman's 1960 work formalized observability and controllability [106], while his filtering paper developed recursive estimation [107]. Elsewhere in this history, we also use observability in the broader practical sense of making condition accessible to examination. More sensors or logs do not by themselves prove observability in the mathematical sense. The model and the distinctions it permits remain essential.

Model-based diagnosis compares observations with expected behavior. Isermann's 1984 survey describes fault detection through modeling and estimation, with examples involving pumps and pipelines [108]. Residuals can reveal disagreement, but model error, disturbance, sensor error, and a component fault may produce similar residuals. Detection asks whether a relevant departure occurred. Isolation asks which fault explanations can be distinguished. Reiter's 1987 theory formalized another approach through conflicts between observations and assumptions about component behavior [109].

Data fusion combines observations at the signal, feature, or decision level. ISO 13379 provides guidance on interpretation and machine diagnosis [110]. Vibration and debris can describe different effects of contact damage; load and temperature can help explain a strain change. We should also examine dependencies among the evidence. Two features calculated from the same sensor are not two independent confirmations. Disagreement should remain visible because it may reveal a sensor fault, registration problem, or an operating condition omitted from the model.

A controlled test can help when passive observations leave several explanations possible. For example, a permitted change in operating point may produce different expected responses under two fault hypotheses. The test should be selected for that difference, with its physical limits established beforehand. This is one connection between diagnosis and debugging: intervention acquires discriminating evidence. Repeating an uncontrolled disturbance without preserving its conditions may produce more data without resolving the ambiguity.

33. Prognostics, digital twins, and AI-assisted diagnosis

Prognostics estimates future condition relative to a specified failure or intervention threshold. NASA's Prognostics Center of Excellence made degradation datasets available for research [111]. The C-MAPSS simulated turbofan data became a widely used resource for remaining-useful-life studies [112]. The first edition of ISO 13381-1 appeared in 2004 [113]. Its 2025 successor gives general guidelines and requirements for prognosis [114]. These developments supported comparison of methods. They also made it necessary to distinguish performance on a benchmark from performance on equipment with different operating histories and maintenance practices.

A digital twin associates models and observations with a particular asset. NASA's 2012 formulation described probabilistic, multiscale simulation informed by the as-built vehicle or system [115]. NIST addresses verification, validation, uncertainty quantification, and reference architectures for manufacturing twins [116], and ISO 23247 provides a manufacturing framework [117]. For diagnosis, the association must survive configuration changes, repairs, sensor changes, and data delays. A model of the nominal design may remain useful, but it is not sufficient to describe every installed asset.

Machine-learning methods extended automatic feature extraction and classification. Zhao and colleagues and Lei and colleagues review developments in machine-health monitoring and fault diagnosis [118,119]. The training data still determine which conditions the model has encountered. Rare faults, uncertain labels, changing environments, and maintenance-selected samples can limit generalization. NIST's AI Risk

Management Framework addresses the management of risks in such use [120]. A model output should remain connected with its supporting observations, uncertainty, and conditions of validation.

The evaluation must reflect the intended deployment. Randomly distributing neighboring windows from one run between training and test data can let a model recognize that run instead of a transferable fault relationship. Holding out complete assets, operating campaigns, or later time periods provides a more demanding comparison when those are the expected sources of change. Reliability analysis distinguishes observed failure times from censored lifetimes [121]. Consider a component replaced before the failure endpoint of interest. We know how long it remained in service, but not when it would have reached that endpoint. The record should preserve the observed service time and the reason observation ended. We should not silently treat it as a complete run-to-failure history.

Remaining useful life is conditional on future use, environment, and the chosen endpoint. A change in load or an intervention may invalidate an earlier forecast [114]. We should distinguish uncertainty in the measurements, uncertainty in the model, and uncertainty about future operation. An AI assistant may help retrieve records or propose comparisons, but an explanation must be checked against those records. Unsupported details introduced into a diagnostic narrative would contaminate the evidence used by subsequent analysis.

PART VII

Case studies, synthesis, and future directions

34. Diagnostic lessons from consequential technical failures

The wartime welded-ship investigations brought together material behavior, welding, geometry, stress concentration, and crack arrest. The Board of Investigation's final report examined the design and construction of welded steel merchant vessels [122]. A later metallurgical study of surviving Liberty-ship material provided another opportunity to investigate that history [123]. The Comet inquiries similarly combined wreckage with full-scale testing and analysis [80]. These examples show why a successful proof test and an adequate explanation of service failure are different achievements.

Bridge and railway failures also expose limits in what an inspection program is designed to find. The Silver Bridge's critical eyebar detail was difficult to examine [88]. I-35W involved a capacity deficiency and actual loading beyond what routine condition inspection addressed [89]. At Hatfield, knowledge of deteriorating rail did not produce a timely effective intervention [84]. We need to examine access, analytical assumptions, reporting, and completion of corrective work as parts of the same investigation.

Apollo 13 provides an example of interpreting telemetry during an unfolding failure and using it to support recovery [124]. Challenger illustrates the treatment and communication of evidence about O-ring damage [125]. Fukushima exposed limits of instrumentation and situational awareness during an extreme event [126]. Deepwater Horizon included misinterpretation of negative-pressure-test results [127]. Aloha 243 connected physical deterioration with inspection assumptions [81]. These cases have different mechanisms. Their comparison is useful when we identify the particular point at which evidence was unavailable, misunderstood, or insufficiently acted upon.

We should also resist reading an investigation backward as though the outcome had been obvious from the first sign. The analyst after a failure may have recovered parts, combined records, and test results that were unavailable to the operator. A useful historical reconstruction distinguishes what could have been known at each stage from what was established later. This makes the account more informative for diagnostic design: which additional observation, interpretation, or decision process could have changed the available options?

35. Recurring principles and pattern-oriented analysis

Across these developments, we repeatedly move between an object, its diagnostic artifacts, and possible explanations. We first need to know which object and operating conditions the artifacts describe. Detection, localization, characterization, mechanism analysis, consequence assessment, and prognosis then add different claims. Keeping these claims separate helps identify what further evidence is required. A detailed image can support localization while leaving the mechanism unresolved.

Our pattern-oriented software diagnostics provides a related way to organize this reasoning. In Theoretical Software Diagnostics, we distinguish artifacts, diagnostic patterns, and mechanisms, and make the investigation iterative [128]. We can use the distinction here as an interpretive framework without claiming that technical-diagnostics methods historically originated from software analysis. A vibration spectrum, fracture surface, thermal image, and maintenance record are different artifacts. Their patterns help formulate hypotheses, while physical mechanisms explain the relationships among the observed features.

Consider a hypothetical pump investigation. We find increasing vibration, elevated bearing temperature, and metallic particles in a lubricant sample. These are related diagnostic indicators, but they do not uniquely establish the initiating mechanism. We compare operating load, alignment, lubricant supply, and the condition of the contact surfaces. New findings may require another sample or a different examination. After intervention, we retain both the actions taken and the measured response. The diagnostic explanation is then a revisable account of how the evidence fits together, rather than a list of alarm names.

The same approach makes the observation system part of the investigation. We can examine missing measurements, inconsistent timestamps, sensor changes, and processing steps as potential sources of misleading patterns. Independent methods and controlled tests help resolve the ambiguity. Inspection intervals should reflect degradation behavior and demonstrated detection capability. The FAA's damage-tolerance guidance connects inspection scheduling with crack growth and the ability to detect damage [129]. Qualification and laboratory competence support repeatable evidence [101,102]. Findings should return to design, manufacture, inspection access, maintenance, and training.

Robotic examination, distributed sensing, digital twins, and AI-assisted analysis can extend coverage and reduce some manual work. They also introduce additional transformations between the physical object and the reported conclusion. We should preserve those transformations and test their behavior outside familiar conditions [120]. The useful direction of development is a diagnostic system in which a person can follow a finding back to the observations, compare alternative mechanisms, and decide what further investigation is needed.

Conclusion

Here we have followed several threads that together form technical diagnostics. Inspection made physical signs available for comparison. Mechanics and materials science provided explanations of stress, damage, and failure. Metrology qualified the measurements. Nondestructive methods extended access to internal condition, while laboratory analysis examined the traces left by particular mechanisms. Monitoring and prognostics added time, operating history, and possible future states to the investigation.

The methods remain complementary. A calibrated sensor may miss an uninstrumented region. A model may omit a relevant load, and an anomaly may have several possible explanations. We therefore return to the object and its artifacts as the analysis develops. Each comparison can refine the next examination, and each intervention can provide new evidence if its conditions and effects are preserved.

The scope brought together in the Handbook of Technical Diagnostics provides a useful basis for understanding these relationships [1]. Structures, machines, plants, and cultural objects differ in their materials and purposes, but all require careful interpretation of incomplete evidence. For pattern-oriented diagnostic analysis, the history offers concrete examples of how recurrent signs become useful through context and knowledge of mechanisms. It also shows why the analysis process must remain open to revision when new artifacts or better explanations become available.

Appendix A. Selected chronology

Table 3. Selected milestones with supporting references; dates do not imply universal adoption.

PERIOD	DEVELOPMENT	DIAGNOSTIC SIGNIFICANCE
1638	Galileo publishes Two New Sciences [2]	Beam strength and fracture become subjects of mathematical mechanics.
1796	Watt's steam-engine indicator is documented [3]	Cylinder pressure is recorded against piston travel, making performance losses visible.
1800	Herschel identifies infrared radiation [57]	Invisible thermal radiation enters experimental science.
1820s–1850s	Elasticity and strength theories mature [5]	Stress, strain, and deflection become calculable diagnostic expectations.
1858–1870	Wöhler conducts railway-axle fatigue tests [11]	Repeated-load failure is organized into stress–life evidence.
1862	Richards introduces an improved steam-engine indicator [4]	Reduced piston travel limits inertia-related distortion of the pressure diagram.
1875	Metre Convention is signed [6]	International measurement traceability gains a durable institution.
1879	Hughes demonstrates material effects on induction coils [54]	A foundation for practical eddy-current testing is established.
1890s	Oil-and-whiting crack detection used in railway shops [42]	Surface-breaking defects are revealed by penetrant action.
1895	Röntgen discovers X-rays [46]	Internal structure becomes observable through radiographic projection.
1911	ASME begins work on a uniform boiler code [9]	Failure experience is converted into common construction and inspection rules.
1914–1915	First ASME Boiler Code edition appears [9]	Pressure-equipment assurance becomes institutional and repeatable.
1921	Griffith publishes energy theory of fracture [12]	Flaw size and fracture energy explain strength below theoretical cohesion.
1922	Hoke receives a magnetic-particle defect-detection patent [45]	A magnetic field and finely divided magnetic material reveal discontinuities.
1931	Coker and Filon publish Treatise on Photo-Elasticity [32]	Whole-field stress patterns become a mature experimental method.
1931–1933	Ruska and Knoll build early electron microscopes; Ruska surpasses optical resolution [65]	Microstructure and fracture morphology gain far higher resolution.
1938	Bonded resistance strain gauges are developed [29]	Local strain becomes practical to instrument on real structures.
1940s	Liberty-ship fractures intensify materials investigations [122]	Brittle transition, welding detail, and crack arrest reshape fracture practice.
1941	American Industrial Radium and X-Ray Society is founded [39]	A predecessor of ASNT professionalizes industrial NDE.
1942	Firestone pulse-echo flaw-detector patent is granted [49]	Reflected ultrasound becomes an internal inspection method.
1943	NACE is founded [19]	Pipeline corrosion knowledge becomes an organized profession.

PERIOD	DEVELOPMENT	DIAGNOSTIC SIGNIFICANCE
1945	Miner publishes cumulative-fatigue rule [13]	Variable-amplitude histories gain a simple engineering damage measure.
1950	Kaiser documents acoustic emission during tensile tests [55]	Loading history is connected with the onset of renewed emission.
1951	Weibull publishes wide-applicability strength distribution [16]	Population variability and weakest-link reasoning become practical.
1952	Larson–Miller parameter is published [17]	Creep-rupture behavior is organized across time and temperature.
1953	Archard publishes sliding-wear relation [18]	Tribological degradation gains a compact quantitative model.
1954–1955	Comet losses and inquiry drive full-scale fatigue investigation [80]	Wreckage, pressure testing, and stress concentration reshape aircraft assurance.
1957	Irwin formalizes stress intensity [14]	Crack-tip fields support quantitative fracture assessment.
1960	Kalman formulates state observability [106]	Internal state inference becomes a formal systems question.
1963	Paris and Erdogan publish crack-growth law [15]	Fatigue crack propagation can be related to stress-intensity range.
1965	Cooley and Tukey publish the FFT algorithm [35]	Routine digital spectral analysis becomes computationally feasible.
1967	Silver Bridge collapses [88]	Inaccessible critical details and nonredundancy transform bridge inspection policy.
1968–1971	U.S. national bridge inspection system is established [87]	Periodic inventory and condition assessment become national infrastructure.
late 1970s	FFT analyzers replace time-compression analyzers [36]	Digital spectral analysis gains smaller and lighter instruments.
1978	Photosensitivity in optical fiber is reported [96]	The foundation for fiber Bragg grating sensing is established.
1978	Nowlan and Heap publish Reliability-Centered Maintenance [26]	Maintenance tasks are related to functions, failure modes, and consequences.
1980	MIL-STD-1629A consolidates FMECA procedures [23]	Failure modes, effects, and criticality are systematically enumerated.
1980s	Industrial computed tomography expands [60]	Radiographic projections support internal material analysis and nondestructive testing.
1982–1984	Route-based portable vibration data collectors are introduced [36]	Repeated measurements connect machine locations with condition trends.
1984	Isermann surveys model-based process fault detection [108]	Modeling and estimation connect pump and pipeline observations with fault hypotheses.
1987	Reiter publishes a theory of model-based diagnosis [109]	Conflicts between expected and observed behavior support systematic hypotheses.
1988–1989	Aloha Airlines Flight 243 accident and investigation report [81]	Aging-aircraft inspection confronts multiple-site fatigue and corrosion.
1990s	Portable phased-array ultrasonic instruments enter industrial use [52]	Battery-powered instruments bring beam steering and focusing to field examination.

PERIOD	DEVELOPMENT	DIAGNOSTIC SIGNIFICANCE
2000	Hatfield derailment [83,84]	Rolling-contact fatigue and failures in inspection, maintenance, and renewal are investigated.
2003	ISO 13374-1 organizes condition-monitoring data processing [72]	Acquisition, manipulation, state detection, health assessment, prognostic assessment, and advisory generation share an architecture.
2004	First edition of ISO 13381-1 gives prognostics guidance [113]	Prognosis processes gain common concepts and guidelines.
2006–2007	Wireless and statistical SHM syntheses appear [90,92,97]	Distributed sensing and pattern recognition frame asset-scale diagnosis.
2007	I-35W bridge collapses [89]	Design capacity, load history, and inspection scope are shown to be distinct evidence problems.
2008	PHM08 data challenge uses NASA C-MAPSS data [112]	Reusable run-to-failure benchmarks accelerate data-driven prognosis.
2008	GUM is issued as JCGM 100:2008 [7]	A common framework describes measurement uncertainty; this continues earlier GUM editions.
2009	MIL-HDBK-1823A updates POD guidance [100]	Inspection reliability is expressed with target-size curves and confidence.
2009–2010	FAA AC 20-107B and Change 1 address composite structures [82]	Design, production, inspection, and maintenance are considered together.
2012	NASA presents the digital-twin paradigm [115]	As-built identity, live data, physics, and uncertainty are joined in one model concept.
2012	JCGM 200:2012 publishes the corrected third-edition VIM [8]	Metrological traceability and related measurement concepts receive shared definitions.
2012	JCGM 106 addresses uncertainty in conformity assessment [103]	Measurement results are connected with explicit acceptance decisions.
2013	Handbook of Technical Diagnostics is published [1]	The field is synthesized across methods, machinery, structures, systems, and heritage.
2014	Reclamation publishes revised embankment-dam monitoring guidance [95]	Instrumentation is organized around dam behavior and potential failure modes.
2021	ISO 23247 digital-twin framework is published [117]	Manufacturing twins gain shared concepts, architecture, attributes, and exchange requirements.
2024	NIST publishes a review of metal-AM monitoring and NDE [99]	Process signatures, material state, and qualification are treated as one measurement chain.

Appendix B. Glossary

Working definitions used in this history. Standards and individual fields may define some terms more narrowly.

Acceptance criterion. A rule or limit used to decide whether a measured or characterized condition is acceptable for a stated purpose.

Acoustic emission (AE). Transient elastic waves generated by active processes such as crack growth, friction, leakage, or fiber breakage.

Alarm. A configured notification that a monitored variable or feature crossed a rule; it is not, by itself, a diagnosis.

Analysis pattern. A reusable method of examining artifacts for a recurrent diagnostic problem in a specified context.

Anomaly. A departure from an expected baseline, distribution, model, or peer population.

Asset genealogy. The identity, material, manufacture, installation, repair, configuration, and service history of a physical item.

Baseline. A qualified reference condition against which later observations are compared.

Calibration. Under specified conditions, establishing a relation between reference values and instrument indications, with their uncertainties, and then using that relation to obtain measurement results. Calibration is distinct from adjustment.

Causal isolation. Testing or analysis that discriminates among competing mechanisms capable of producing similar symptoms.

Censoring. Incomplete observation of an event time; for example, replacement before the component reaches the failure endpoint of interest.

Computed radiography (CR). Digital radiography using a reusable imaging plate that is scanned after exposure.

Computed tomography (CT). Reconstruction of cross-sectional or volumetric attenuation information from multiple projections.

Condition monitoring. Acquisition of data that indicate the condition of an item over time; diagnostic interpretation is a related activity.

Confidence bound. A statistical bound expressing uncertainty in an estimated quantity or performance curve.

Conformity assessment. Evaluation of whether stated requirements are fulfilled, using an appropriate decision rule when measurements are involved.

Consequence assessment. Evaluation of what an identified condition could do to function, safety, environment, cost, or mission.

Coverage. The portion of a target volume, surface, state space, or failure-mode set that an observation system can examine.

Crack-growth law. A relation used to estimate crack extension under a specified loading and environmental history.

Damage tolerance. An assurance approach that assumes flaws may exist and controls risk through analysis, inspectability, and timely detection.

Data fusion. Combination of signals, features, models, or decisions from multiple evidence sources.

Data provenance. The origin, identity, acquisition conditions, and transformation history of a record or dataset.

Defect. A discontinuity or condition that fails a stated acceptance requirement; not every discontinuity is a defect.

Degradation mechanism. A physical or chemical process by which condition changes, such as fatigue, corrosion, creep, or wear.

Diagnostic coverage. Here, the set or proportion of relevant faults or damage states that a diagnostic system can detect or isolate under stated conditions. This broad usage is distinct from the dangerous-failure detection fraction used in functional safety.

Diagnostic pattern. A recurrent arrangement of signs or features that helps characterize a problem and guide further analysis.

DICONDE. Digital Imaging and Communication in Nondestructive Evaluation, a standard practice for interoperable images and metadata.

Digital image correlation (DIC). Optical estimation of displacement and strain fields by tracking image texture.

Digital thread. Linked lifecycle information that preserves identity and relationships across design, manufacture, operation, inspection, and maintenance.

Digital twin. A maintained digital representation of an identified physical counterpart, updated with data for a defined use such as diagnosis or prediction.

Discontinuity. An intentional or unintentional interruption of physical continuity or cohesion in material; its acceptability requires separate evaluation.

Dissolved-gas analysis (DGA). Examination of gases in insulating liquid to support interpretation of electrical-equipment condition.

Domain shift. A change between development and use conditions that alters the statistical or physical relation between data and state.

Eddy-current testing (ET). Electromagnetic inspection based on changes in induced current flow and probe impedance.

Effectivity. The exact serial-number, build, modification, or configuration population to which information applies.

Environmental normalization. Accounting for environmental influences on observations before attributing a change to damage; operating-load effects also require explicit treatment.

False call. A reported relevant condition when the target condition is absent or not supported.

Fault. Here, an abnormal state or causal condition capable of impairing required function, using the broad machine-diagnostics sense rather than requiring an already failed state.

Fault isolation. Discrimination among candidate fault locations or types using the available observations and model.

Fault tree. A deductive model that decomposes an undesired event into logical combinations of contributing events.

Feature. A quantity extracted from raw observations for comparison, classification, estimation, or diagnosis.

Fitness for service. Engineering assessment of whether equipment containing a flaw or degradation can continue operating under defined conditions.

Flaw. An imperfection or discontinuity that may be detectable by examination; it is not necessarily rejectable under the applicable acceptance requirements.

Focused ion beam (FIB). A localized ion-beam technique used for imaging, milling, or specimen preparation, including selected subsurface sections.

Fractography. Examination and interpretation of fracture surfaces to identify origin, propagation, loading, and mechanism.

Full-matrix capture (FMC). Ultrasonic acquisition in which each array element transmits in turn and all elements receive for later reconstruction.

Health indicator. A scalar or vector intended to track progression from a reference condition toward functional failure.

Indication. An instrument or examination response that may require interpretation; it is not automatically a flaw.

Infrared thermography. Imaging and analysis of infrared radiation to infer surface temperature or heat-flow behavior.

Inspection interval. Time, usage, or cycles between examinations, ideally set from degradation rate, consequence, and detection reliability.

Intervention test. A controlled change in load, configuration, boundary condition, or component used to discriminate causal hypotheses.

Leak testing. Examination for fluid passage through a boundary under specified test conditions, with detection, location, or rate measurement as possible objectives.

Leakage field. Magnetic flux emerging from a ferromagnetic surface because a discontinuity perturbs the magnetic path.

Lift-off. Separation between an electromagnetic probe and the test surface, often a major confounding variable.

Load path. The route by which applied forces and moments are transmitted through a structure or assembly.

Localization. Estimation of the spatial position or source region of an indication or anomaly.

Maintenance-induced fault. Damage, misassembly, contamination, or configuration error introduced during maintenance.

Metrological traceability. A measurement result’s documented relationship to a reference through an unbroken calibration chain whose steps contribute uncertainty.

Modal assurance criterion (MAC). A measure of similarity between two mode-shape vectors.

Modal testing. Experimental identification of natural frequencies, mode shapes, and damping from measured dynamic response.

Model residual. Difference between an observed quantity and the value predicted by a model under stated inputs and assumptions.

NDE / NDT. Nondestructive evaluation or testing: examination of materials or components without impairing their intended future use.

Noise floor. Background response below which relevant signals cannot be reliably distinguished.

Observability. In control theory, the ability to infer internal state from outputs under a specified model and inputs. Broader diagnostic usage concerns practical access to condition.

Operating regime. A bounded state such as speed, load, temperature, process recipe, or control mode that conditions expected behavior.

Order tracking. Analysis of vibration or sound relative to rotational speed so features remain aligned with shaft orders during speed change.

Out-of-plane motion. Motion normal to an image plane that can bias apparent in-plane displacement in optical measurements.

Phased-array ultrasonics (PAUT). Ultrasonic testing using controlled timing across array elements to steer or focus beams.

Physics of failure. Use of material, load, environment, and mechanism models to explain or predict degradation.

Probability of detection (POD). The probability that a defined inspection system reports a target as a function of target size or other parameter.

Process signature. Measured behavior of a manufacturing or operating process that may correlate with resulting condition.

Prognosis. Prediction of future condition, failure probability, or remaining useful life under stated assumptions.

Proof test. Application of a specified load or pressure to demonstrate minimum capacity or expose certain weaknesses.

Qualification. Demonstration that a procedure, equipment, personnel, and conditions can meet stated performance requirements.

Radiographic testing (RT). Inspection using penetrating ionizing radiation and a detector to form attenuation images.

Reference block. A specimen with controlled material, geometry, and reflectors or discontinuities used to set or check inspection response.

Reliability-centered maintenance (RCM). Selection of maintenance actions by the functions, failure modes, and consequences relevant to an asset in its operating context.

Remaining useful life (RUL). Estimated time or usage until a defined functional or safety threshold is reached.

Repeatability. Measurement precision under specified conditions kept substantially the same over a short interval.

Reproducibility. Measurement precision under specified changed conditions, such as laboratories, operators, or measuring systems.

Residual stress. Stress retained in a body without external load, often created by welding, forming, heat treatment, or assembly.

Risk-based inspection (RBI). Planning that prioritizes inspection using estimated likelihood and consequence of failure.

Sensitivity. Change in instrument response per change in the quantity or target characteristic of interest.

Sensor drift. Gradual change in sensor output unrelated to the measurand.

Sizing. Estimation of discontinuity dimensions, distinct from detection and localization.

Spall. Material detached from a surface, often through contact fatigue, corrosion, impact, or thermal damage.

Spectral sideband. Frequency component offset from a carrier or order, often produced by modulation from a fault or process.

State estimation. Inference of internal system variables from measurements and a dynamical model.

Strain gauge. A transducer whose electrical or optical response changes with deformation.

Stress concentration. Localized amplification of stress caused by geometry, discontinuity, contact, or material change.

Structural integrity. Ability of a structure or component to perform its required load-bearing function with acceptable risk.

Structural-health monitoring (SHM). Persistent or repeated sensing and inference used to detect, locate, characterize, or assess structural change.

Technical diagnostics. Evidence-based identification and explanation of faults, degradation, or integrity states in physical structures and systems.

Thermal excitation. Controlled heating or cooling used to make subsurface differences visible through transient heat flow.

Threshold. A decision boundary applied to a measurement, feature, probability, or risk estimate.

Time-of-flight. Travel time of a signal used to estimate propagation distance or locate a reflector or source; for example, in ultrasonic examination.

Traceability. A context-dependent term. Distinguish metrological traceability of a result from the provenance of a specimen, record, or digital artifact.

Trend. Ordered series of comparable observations used to estimate change over time or usage.

Tribology. Science and engineering of friction, lubrication, wear, and interacting surfaces in relative motion.

Ultrasonic testing (UT). Inspection using high-frequency mechanical waves and their transmission or reflection.

Uncertainty. Here, incomplete knowledge about a measurement, model, inference, or future condition. Measurement uncertainty specifically characterizes the dispersion of values attributed to the measured quantity.

Uncertainty budget. An organized account of contributions to the uncertainty of a measurement result.

Validation. Evidence that a method or model is adequate for its intended real-world use.

Vibration envelope. Demodulated amplitude history or spectrum used to reveal repetitive impacts and bearing-related modulation.

Voxel. A volumetric picture element in a reconstructed three-dimensional data set.

Wear debris. Particles generated by interacting surfaces and carried in lubricant, filters, or deposits.

Witness mark. Physical mark that records relative motion, contact, alignment, or prior position.

Appendix C. Evidence taxonomy

Table 4. Evidence families, useful questions, limitations, and the records needed to interpret them.

Evidence family	Useful questions	Main limitations	Records needed
Sensory and visual	Surface damage, leakage, motion, or changed appearance	Access, lighting, observer variation; hidden damage	Location, scale, orientation, lighting, as-found photographs
Dimensions and geometry	Clearance, alignment, profile, deformation, or settlement	Datum choice, temperature, setup, uncertainty	Datums, units, calibration, geometry, measurement conditions
Operating and process	Relationship between condition, function, and exposure	Changing regimes, sensor drift, incomplete context	Time, load, speed, pressure, configuration, sensor identity
Strain and displacement	Local response and the assumed load path	Bonding, thermal effects, limited spatial coverage	Sensor position, coordinates, load, temperature, calibration
Vibration and modal	Dynamic changes and possible rotating-machine faults	Non-unique responses; environmental and operating variation	Waveforms, speed, phase, directions, timing, processing
Ultrasonic and acoustic	Internal reflectors or sources of active damage	Orientation, coupling, attenuation, noise, dead zones	Scan plan, positions, calibration, coupling, retained signals
Electromagnetic	Discontinuities or changes in material and geometry	Lift-off, permeability, conductivity, geometric effects	Probe, frequency, direction, references, material, position
Thermal	Heating patterns and changes in heat flow	Emissivity, reflections, excitation, environment	Radiometric data, load, timing, surface and ambient conditions
Radiographic and tomographic	Internal geometry and discontinuities	Projection overlap, artifacts, energy, detectability	Object identity, geometry, exposure, calibration, reconstruction
Leak testing	Whether a fluid crosses a boundary and where	Test-medium effects, temperature, stabilization, sensitivity	Medium, pressure difference, time, temperature, method, leak reference
Material and microstructure	Composition, phases, fracture features, and mechanisms	Sampling and preparation may alter or miss relevant evidence	Sample location, orientation, preparation, scale, analytical conditions
Fluid and gas analysis	Wear products, contamination, lubricant or insulation condition	Transport, sampling, filtration, fluid replacement	Sampling point, method, time, fluid type, operating and maintenance history
History and provenance	Exposure, sequence, repairs, and earlier indications	Missing records, terminology changes, survivor bias	Asset identity, dates, versions, source records, interventions
Models and probabilities	Expected behavior, residuals, detection, and future condition	Model assumptions, parameter uncertainty, domain shift	Model version, inputs, validation conditions, dependencies, uncertainty
Intervention and retest	Which explanation predicts the response to a controlled change	Confounding changes; evidence may be altered	As-found condition, individual actions, limits, before-and-after observations

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