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Pressure Transient Analysis and Sampling in Formation Testing

The formation tester is a well logging instrument with extendable pad nozzles which, when pressed against the borehole sandface, extracts in situ formation fluids for delivery to the surface for chemical examination. This process characterizes its fluid “sampling” function. By-products of this operation are pressure transient histories, which can be interrogated using Darcy math models for fluid and formation properties such as permeability, mobility, anisotropy, compressibility and pore pressure. This is referred to as “pressure transient analysis,” or simply, “PTA.” Both can be conducted as wireline or Measurement While Drilling, or “MWD,” applications, where these operations now represent invaluable elements of the standard well logging suite.

Pressure transient analysis challenges. While collecting and transporting fluids is relatively straightforward, e.g., storing samples in secure vessels that maintain downhole conditions, the PTA process poses a greater design challenge. A well designed tool often begins with a good understanding of the environment, plus physics coupled with sound experience in mathematical modeling. Some ideas are obvious. For example, a single “source” or “sink” probe, serving both pumping and pressure observation functions, will at most provide the “spherical permeability” $k_h^{2/3}k_v^{1/3}$, where k_h and k_v are horizontal and vertical permeabilities. Thus, “single probe” tools, while mechanically simple, will offer fewer logging advantages than “dual probe” or “multiprobe tools” which provide much greater formation evaluation information.

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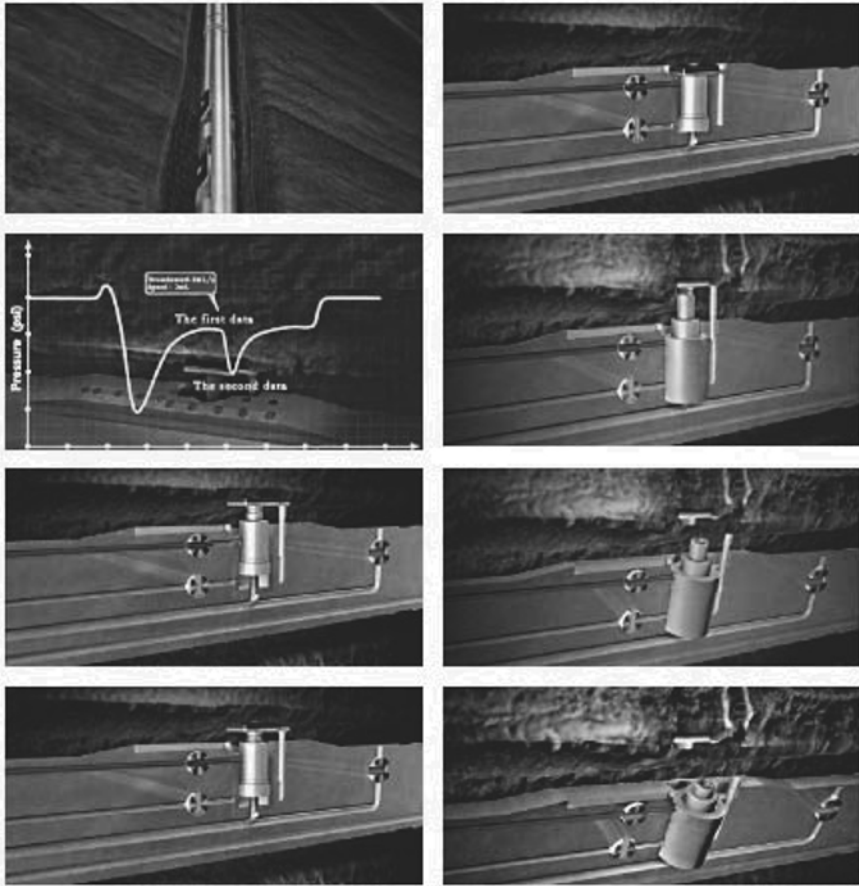


Figure 1.1. Drawdown-buildup pressure response with dynamic pumping action and flowline.

But how are probe arrays configured and placed for optimal effect? Figures 1.1 and 1.2 illustrate the operation of a single probe tool that withdraws fluid and then stops, creating the expected “drawdown and buildup” shown. If a second probe is desired, should it be placed an axial distance apart but along the same azimuth? Or azimuthally apart, at 180° away along the borehole circumference? What about a “drawdown only” pumpout? Or perhaps, have the pump oscillate sinusoidally in place, thus mimicking the AC transmissions of an electromagnetic logging tool? How many probes are best? What are their flow areas? Do answers to these questions depend on fluid and formation properties?

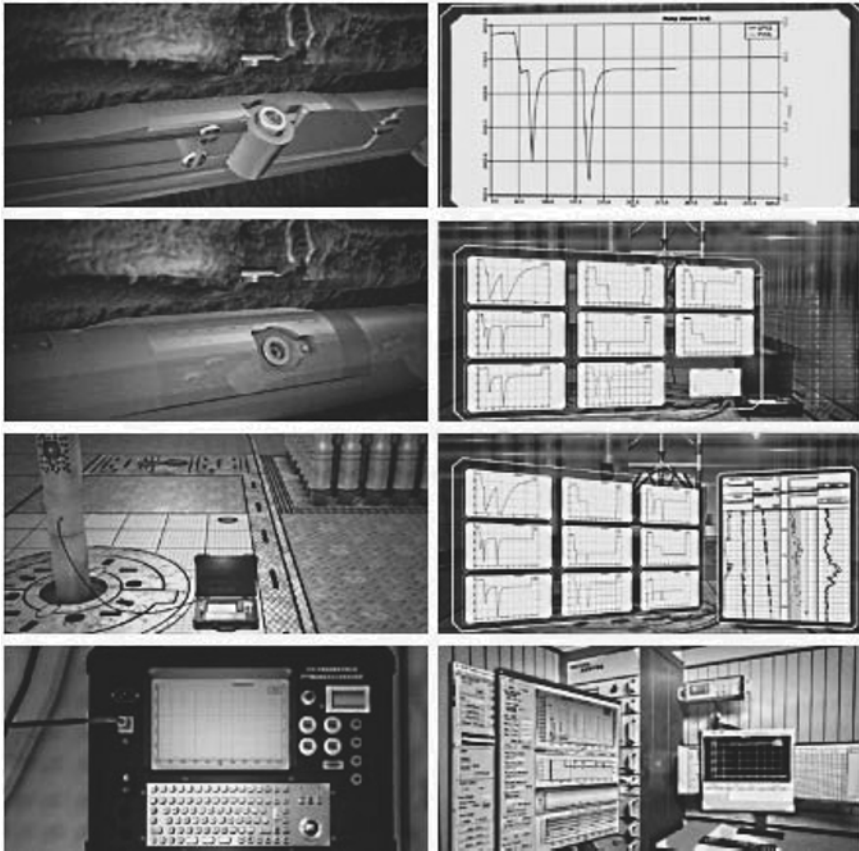


Figure 1.2. Downhole, surface and logging truck operations.

Background development. The present book addresses these questions for “source” or “sink models” of the pumping nozzle, these terms referring to ideal representations of the flow where borehole and pad geometry are described using mathematically small closed surfaces. The recent books due to Chin et al. (2014) or *Formation Testing: Pressure Transient and Contamination Analysis*, Chin et al. (2015) or *Formation Testing: Low Mobility Pressure Transient Analysis*, and Chin (2019) or *Formation Testing: Supercharge, Pressure Testing and Contamination Models*, published by John Wiley & Sons, contain complete math derivations and detailed validations. However, the rapid pace of recent development suggests a separate volume in Wiley’s *Handbook of Petroleum Engineering Series*, focused on the main ideas

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behind the recent works. These ideas are essential as they are also used in the design of newer COSL formation testing tools as well as in interpretation software now available to the petroleum industry. What engineers lack, at present, are job planning and PTA tools both useful at the rigsite and at engineers' desktops. It is our purpose to support this pressing need.

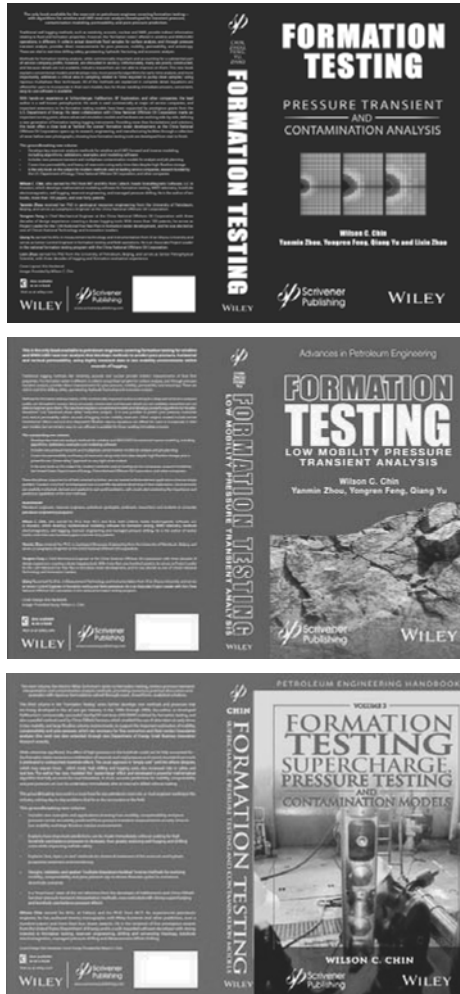


Figure 1.3. Recent formation testing book publications.

1.1 Conventional Formation Testing Concepts.

Formation testing design concepts are rich and varied. A pumping probe, operating as a “sink” or (equivalently) a “source,” or both, also tracks pressure transient responses. Other pressure probes may reside along the tool body, displaced axially, azimuthally or both, which may actively pump or act as passive observers. While the primary formation tester function is fluid sampling, where in-situ reservoir fluids are collected and transported to the surface for analysis, pressure measurements represent critical by-products important to formation evaluation. Examples of testers offered by different manufacturers for wireline and MWD applications are given in Figures 1.4 – 1.7.

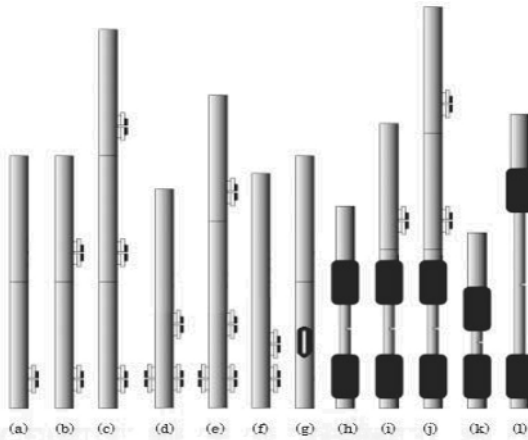


Figure 1.4. Conventional formation tester tool strings.

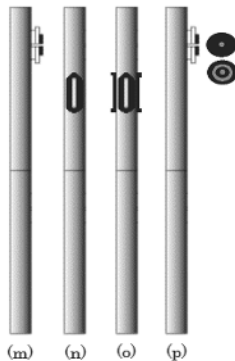


Figure 1.5. Formation testers, additional developments.

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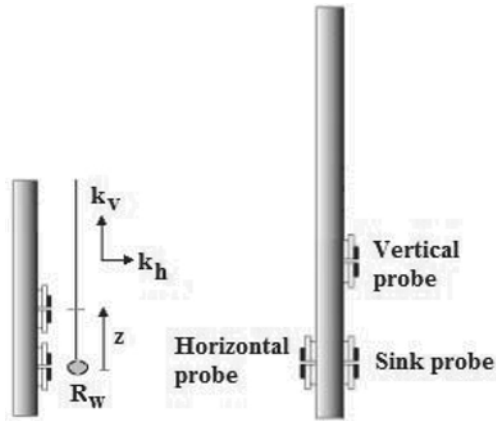


Figure 1.6. Conventional dual and triple probe testers.



Figure 1.7. Dual probe tester with dual packer.

1.2 Prototypes, Tools and Systems.

In a “handbook” such as this, it is important to provide examples of prototypes, commercial tools and systems. The wide ranges in design parameters can be surprising to newcomers in formation testing. For example, the “vertical and sink probes” in Figure 1.6, which are displaced axially but lie along the same azimuth, can range from six or seven inches to as much as 2.3 ft (27.6 in) and 10.3 ft (123.6 in), where the latter two distances are obtained from the manufacturer’s figure in SPE Paper No. 36176. We might, for example, ask, “Just what does the distant observation probe “see” under different mobility backgrounds?” “Will the tool do the job for my formation?” This book attempts to answer the most obvious questions, but it also aims at providing the tools and software for readers to address those pressing questions that invariably arise in any new logging scenario. To provide a flavor of how hardware literature and specifications might appear, we have included discussion of COSL material related to its standard product lines. Note that COSL’s new “triple probe, 120° tool” (as opposed to a conventional 180° tool) is treated separately in our companion 2021 book.

Close-ups of early single and dual probe prototype formation testers are shown in Figure 1.8. These photographs were obtained during field tests. The black pads shown perform an important sealing function, which prevents leakage of fluid through its contact surface with the sandface. However, they are not as “simple” as they appear. For instance, at any given pump rate, the pressure drop, which depends on nozzle diameter, may be excessive and allow the undesired release of dissolved gas – orifice sizes must be chosen judiciously, as suggested by the wide variety of choices shown in Figure 1.9. The shape of the hole or slot is also important; circular or oval shapes may be acceptable for consolidated matrix rock, but slotted models may be required for naturally fractured media or unconsolidated formations. Of course, in supporting PTA interpretation objectives, the size and shape of a formation tester’s pads must be incorporated into the host math model. More often than not, the model must be simple and mathematically tractable in order to obtain useful answers in a reasonable amount of time. This may require the use of idealized source or sink models, or numerical models with limited numbers of grids in the case of finite difference or finite modeling – consequently, questions related to calibration or geometric factors arise, along with test procedures, etc.

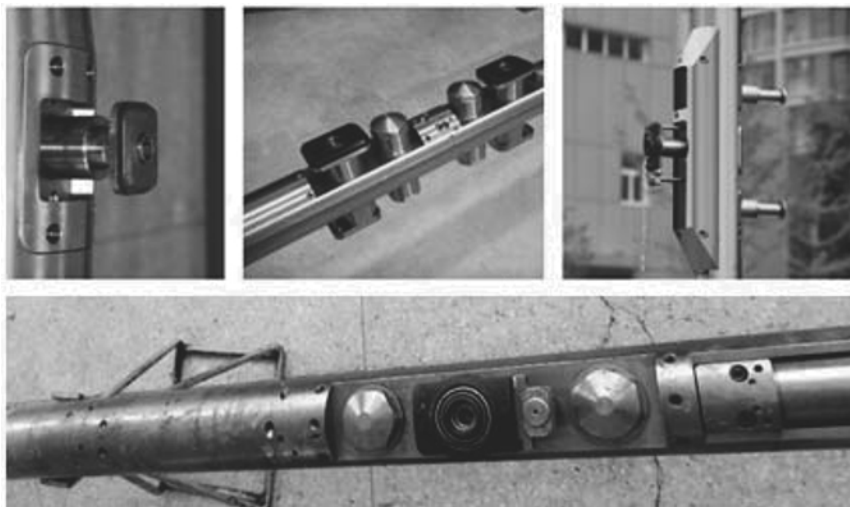


Figure 1.8. Early COSL single and dual probe prototype formation testers (details in 2014 and 2015 books).

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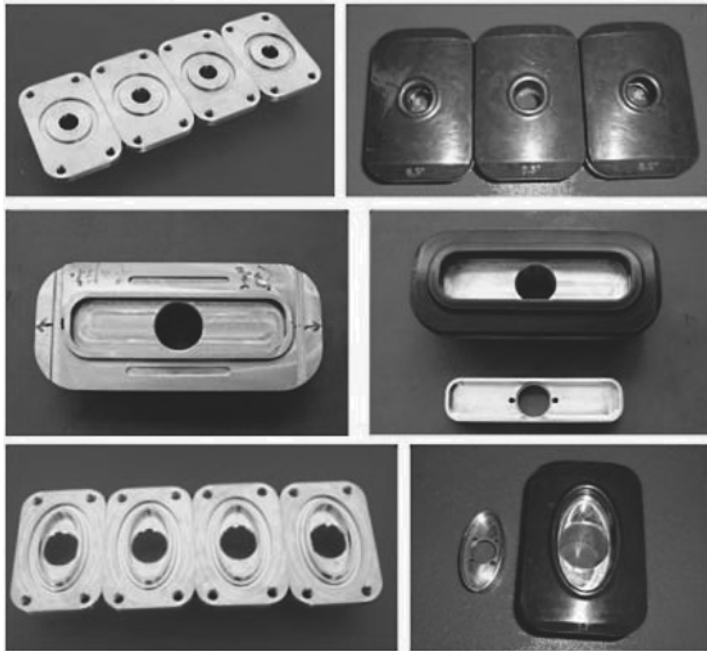


Figure 1.9. COSL pad designs with varied sizes and shapes, for different applications, e.g., firm matrix rock, unconsolidated formations, fractured media, and so on..

Pressures obtained in PTA logging are used for multiple applications. For example, depending on the tool, permeability, anisotropy, compressibility and pore pressure are all possible (the term “mobility,” defined as the ratio of permeability to viscosity, is often interchangeably used, assuming that the viscosity is known). The pore pressure itself is used to identify fluids by their vertical hydrostatic gradients; this is possible because changes in pressure are affected by changes in fluid density. Sudden changes in pressure, for instance, may indicate the presence of barriers. However, the raw measured pressure, unless corrected for the “cushioning” effects associated with flowline volume, will not reflect pore pressures accurately. The correction depends, in turn, on the line volume as well as the compressibility and the mobility of the formation fluid. All said, the physics and math can be challenging, but solutions and analytical highlights are presented in the next chapter for a wide variety of tools and applications. Chapter 2 provides a broad state-of-the-art review for source and sink models.

1.2.1 Enhanced Formation Dynamic Tester (EFDT[®]).

The “Enhanced Formation Dynamic Tester” is an advanced wireline formation testing system that delivers: (1) Multiple, large-volume high-purity formation fluid samples with downhole fluid characterization, (2) Reliable formation pressure testing, and (3) Real-time downhole fluid analyze, and more. Typical tool string configurations and architectures are shown in Figures 1.10 and 1.11. For detailed specifications, the reader is referred to the latest updated manufacturer’s literature.



Figure 1.10. Tool string configurations.

COSL’s EFDT is designed to obtain formation pressures and formation fluid samples at discrete depths within a reservoir. Analyzing pressure buildup profile and the properties of fluid samples helps provide a more complete description of reservoir fluids and behavior. The EFDT service provides key petrophysical information to determine the reservoir volume, producibility of a formation, type and composition of the movable fluids, and to predict reservoir behavior during production.

THE EFDT is a modular formation testing system. It can be customized for the specialized applications. The modularity of EFDT ensures its ability to test and sample fluids in a wide range of geological environments and borehole conditions. For its basic configuration, the string includes a fully controllable Dual Probe Module for fluid in-taking, a Flow Pump Module for variable-volume drawdown and pump out of contaminated fluids, a Fluid Sensor Module for dynamic properties of fluids, a PVT Carrier Module for monophasic sampling, and a Large Sample Carrier Module for large-volume normal sampling. It can also be configured with a Straddle Packer Module, an Optical Analysis Module, a Focused Probe Module and a Multi-PVT Tank Module to meet the requirements of complex reservoir formation tests, such as low permeability rock or natural fractures.

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The EFDT enables up to five properties of fluid and formation to be monitored during testing: fluid conductivity or capacitivity, fluid density, fluid dynamic pressure, fluid optical analysis and formation permeability and anisotropy. The EFDT provides up to four MonoPhase Sampling Tanks (MPST) for one run, which recovers high-quality pressure-compensated reservoir fluid samples during borehole formation testing operations. The new Multi-PVT Module can take up to 24-48 PVT samples in one run (6 X 350 ml per module). The EFDT uses standard EDIB telemetry protocol, is combinable with other EDIB logging tools, and requires the company's ELIS surface acquisition system. Surface control interfaces and user output displays are given in Figures 1.12 and 1.13. Applications, benefits and features are summarized below.

Applications

- Formation pressure measurements and fluid contact identification
- Repeatable formation fluid sampling
- Measurement of formation permeability and anisotropy
- Vertical interference testing
- In-situ downhole fluid analysis

Benefits

- Fast, high-accuracy pressure measurement using Quartz Pressure Gauges (QPG) with temperature compensation
- Conductivity/capacitivity, density, fluid dynamic pressure, NIR optical analysis and formation permeability anisotropy for real-time reservoir evaluation
- Savings of 50% sampling time using focus probe
- Multiple samples in one run, providing high quality PVT samples

Features

- Modularity, offering expanded testing versatility
- Accurate pressure measurement using QPG
- Real time downhole fluid assessment
- PVT quality formation fluid samples

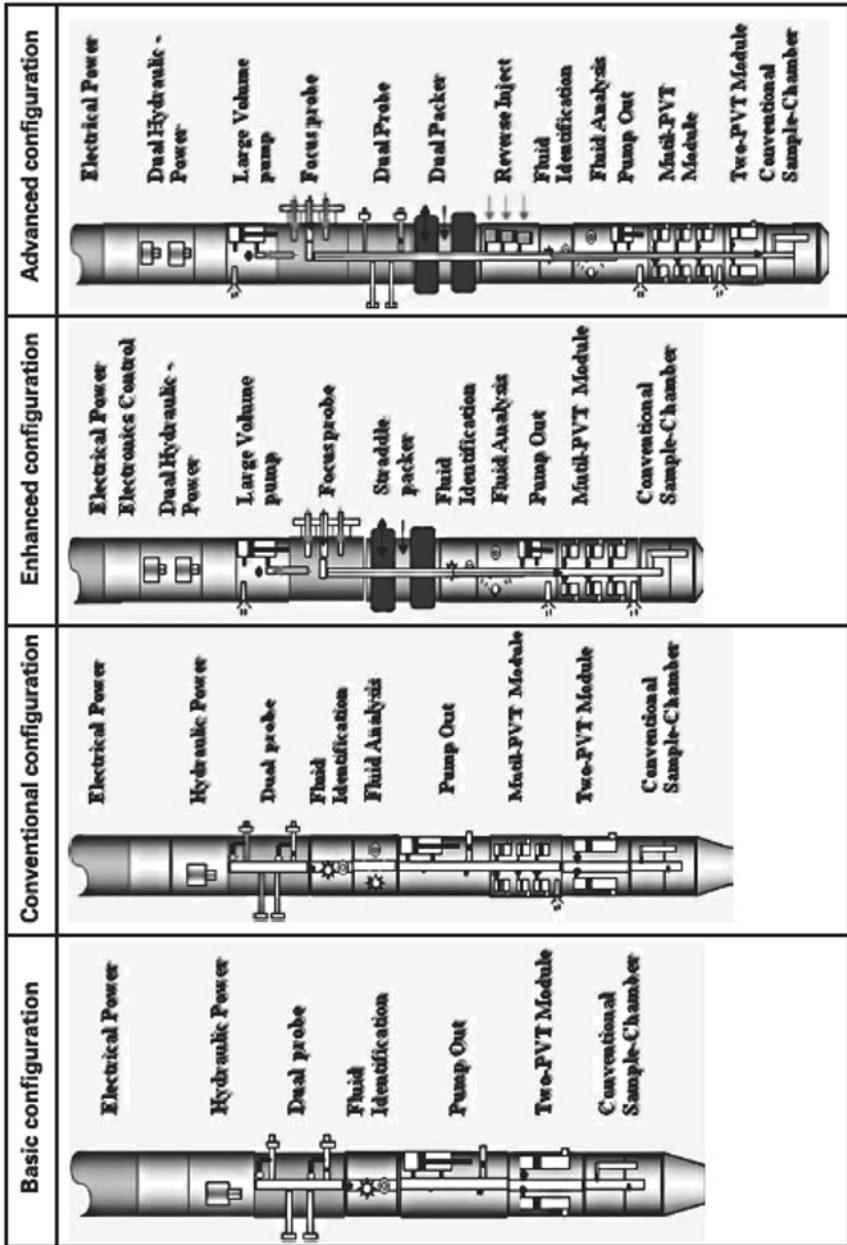


Figure 1.11. Tool architectures.

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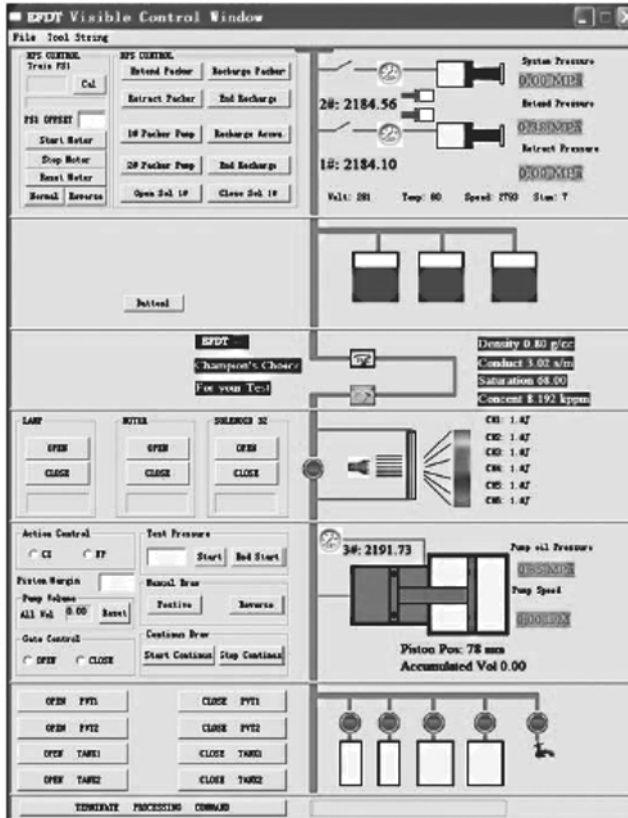


Figure 1.12. Surface control interface.

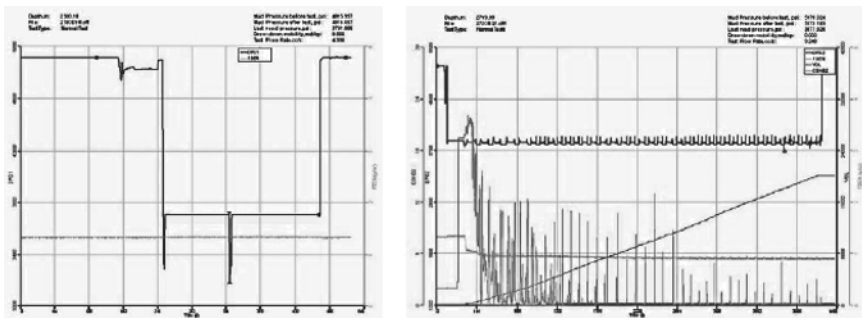


Figure 1.13. Pressure measurement chart (left) and real-time fluid monitoring chart (right).

1.2.2 Basic Reservoir Characteristic Tester (BASIC-RCT™).

COSL's "Basic Reservoir Characteristic Tester" or "BASIC-RCT" is a third generation product of the formation tester family, characterized by its pump through function. BASIC RCT is a compact, convenient, safe and efficient tool. It can replace in part Drill Stem Testing (DST) operations in order to save rig time. BASIC RCT provides economical and reliable solutions to formation evaluation for oilfield exploration and engineering, representing a good means to reduce cost while solving difficult technical problems. BASIC RCT can be run on any service company logging unit, requiring only winch, cable head and depth measurement. All services, telemetry, gamma ray recording, test recording (digital, numerical listing, screen and printer graphics) are provided in real time. Tool configurations are shown in Figure 1.14. For latest specifications, the reader should refer to the manufacturer's updates.

Functions

- Measuring formation pressure accurately
- Taking multi-samples of formation fluids
- Taking large samples
- Pumping through contaminated formation fluids
- Monitoring formation fluid properties in real time.
- Flowing formation fluids at controlled rates
- Pumping through in reverse
- Making quick well site sampler transfer
- Providing real time and reliable data for analyzing permeability and formation damage

Structure

The BASIC RCT is a combination of surface system and downhole tools. The surface system includes the Acquisition and Data Process software, PC and DC control panel, and AC power supply. The downhole tools include the upper electronics section, mechanical/hydraulic section, sensor section, lower electronics section with a standard configuration, and also include the 2 × 520 cc large sampler with optional configuration (see Figures 1.15 and 1.16).



Figure 1.14. Tool string configurations.

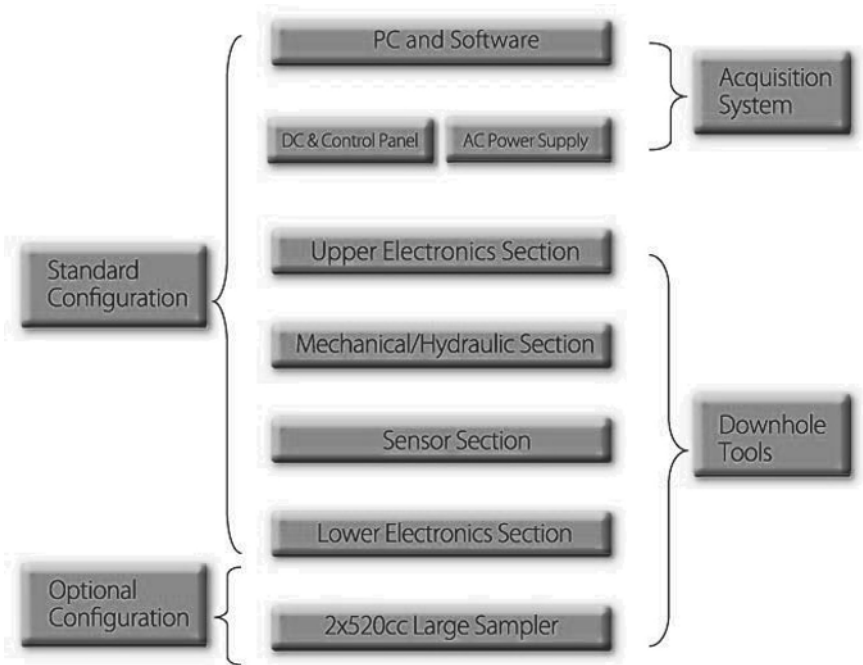


Figure 1.15. Tool architecture.

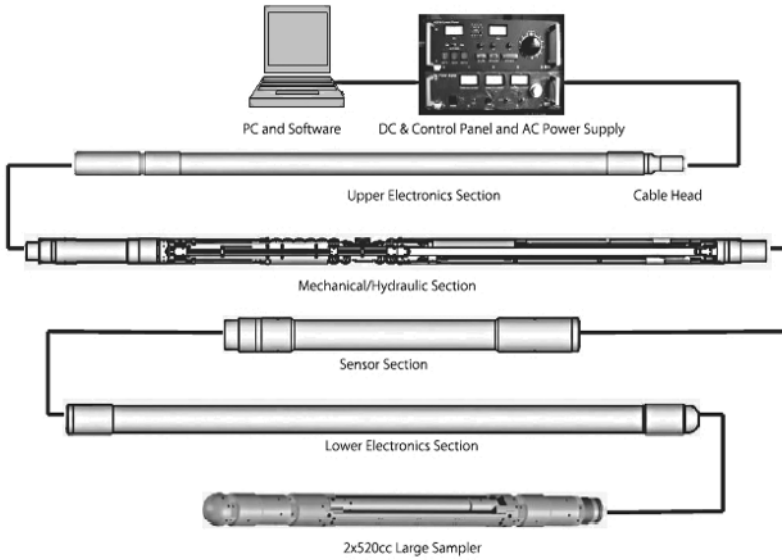


Figure 1.16. Tool and surface system.

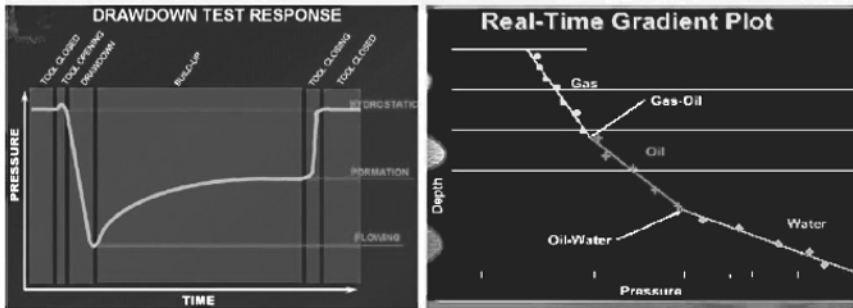


Figure 1.17. Pressure drawdown curve (left) and fluid contact curve (right).

1.2.3 Enhancing and enabling technologies.

While we principally focus on pressure transient analysis in this volume, a number of enabling technologies contribute to the operational success of formation testers in general, and in particular the robustness of the tools mentioned in Sections 1.2.1 and 1.2.2. A critical problem is that associated with “stuck tools,” which results in expensive fishing jobs, lost tools and increased rig costs.

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Stuck tool alleviation. Issues related to stuck pipe are as old as drilling itself. In “Development on Incongruous Pushing and Stuck Releasing Device of EFDT,” by Qin, X., Feng, Y., Song, W., Chu, X. and Wang, L. and appearing in *Journal of China Offshore Oilfield Technology*, Vol. 4, No. 1, April 2016, pp. 70-74, the authors analyze the causes of differential pressure sticking during openhole wireline logging. Their modular IPSRD releasing device, designed for EFDT formation tester applications, could be seamlessly assembled to the tool. “Stuck Release Arms” (SRA) are driven by hydraulic forces that free the dual probe tool from adhesive forces. In Chapters 4 and 5, we show how mudcake thicknesses can be accurately modeled and predicted – small values to reduce chances for tool loss are needed, while larger thicknesses are required to seal tester pads to the sandface – at the same time, providing excellent descriptions for supercharge pressure effects.

The authors importantly point out that while measuring pressure and sampling, even at a single point in the well, duration times may last several hours or even tens of hours. In particular, for higher mud densities, the possibility of differential sticking – and the likelihood of expensive fishing jobs – is high. In extreme cases, loss of the tool downhole and well abandonment are possible. Figure 1.18 explains the conceptual ideas behind IPSRD. The left diagram illustrates the differential sticking process, with the following nomenclature: 1- Wellbore fluid, 2-Backup, 3-EFDT, 4-Mudcake, 5-Probe, 6-Protector and 7-Formation. The right side outlines the tool architecture. Upper Stuck and Lower Stuck release modules USRM and LSRM are found at the top and bottom, with the Dual Probe Module (DPM) residing between the two. The “stuck release arms” (SRA) for each releasing module are designed in opposite directions for pushing separately. The paper describes several field applications and savings in logging costs.

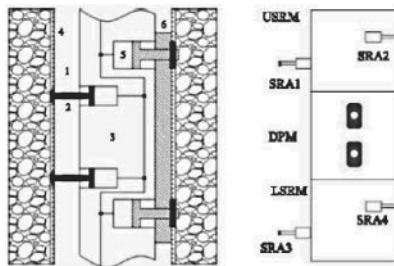


Figure 1.18. IPSRD stuck tool release mechanism.

Field facilities. Finally, we offer some snapshots of COSL logging trucks and rigsite facilities from which formation testing jobs are run. The photographs are self-explanatory.



Figure 1.19. Rigsite facilities.

1.3 Recent Formation Testing Developments.

Conventional formation tester tools with single and dual probes are shown in Figures 1.8 and 1.9, noting that different testers may be outfitted with different pad designs depending on the application. For instance, small round nozzles may be used with firm matrix rock; in low permeability formations, larger nozzles may be preferable in order to prevent excessive pressure drawdowns that result in the undesired release of dissolved gas or increased mechanical demands. Larger slot nozzles are ideal when formations are lower in permeability or naturally fractured and higher pump rates are desired.

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The right-side diagram in Figure 1.6 shows an active pumping “sink probe” mounted on the mandrel, with a passive “horizontal” observation probe located 180° circumferentially away around the borehole. A “vertical probe” is also shown displaced axially from the sink probe and lying along the same azimuth. This conventional 1990s designed “triple probe” tool has seen wide application since its introduction. However, in low mobility formations, questions related to weak pressure signal detection and large diffusion arise.

These have motivated the design of a new and different type of “triple probe” tester, where three independently operated, closer probes are located about the borehole at 120° separations, all residing in the same axial plane and supporting pumping and pressure measurement. Axially displaced “vertical probes” also augment the new triple probe design. The new COSL tool offers advantages over conventional instruments and these are described in a companion 2021 book *Formation Testing – Multiprobe Design and Pressure Analysis* by Lu, Zhou, Feng, Yang and Chin (John Wiley & Sons). Because of the three-dimensional nature of the physics, the complementary volume develops new analysis and interpretation methods that account for borehole size and shape, and without invoking symmetry assumptions, since the probes may differ during any logging run and pump with different flow rate schedules. Figures 1.20 – 1.22 show example graphics from the book.



Figure 1.20. New triple probe formation tester. Pads with “small round nozzle and slot probe” (top) and “all long slot nozzles” (bottom).



Figure 1.21. New COSL triple probe tester, perspective view.

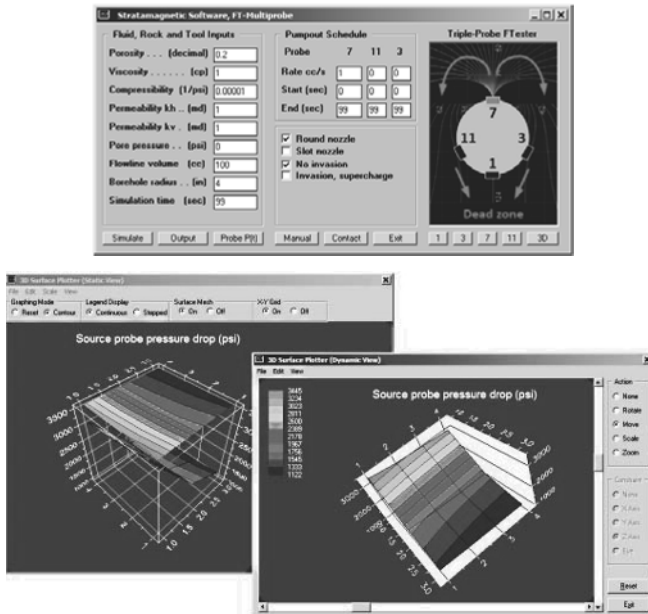


Figure 1.22. Simulator menu for Probes 3, 7 and 11 (top), sink Probe 7 pressure drop versus kh and kv at fixed rate (bottom).

1.4 References.

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