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A Cost Effective and User Friendly Approach to Design Wireline Formation Tests

[1]Clara Bertolini, [2]Giuseppe Tripaldi, [2]Elena Manassero, [2]Enzo Beretta,
[3]Francesca Verga and [3]Dario Viberti
[1]Department of R & D Management,
[2]Department of Reservoir Management,
E & P Division, eni, Via Emilia 1, 20097 San Donato Mil., Italy
[3]Department DITAG, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

Abstract: Problem statement: Wireline formation testing (also named Mini-DSTs) are gaining more and more popularity as a possible alternative to conventional well testing especially where there are major environmental and economical constraints. The increased offshore exploration activity, which often implies highly risky and huge operational costs, makes the conventional well testing less attractive in favor of other technologies that can provide some of the key dynamic information about the well-reservoir system through relatively quick and less expensive operations. The design phase is recognized to be one of the most critical aspects in order to guarantee an acceptable value of information in exploration scenarios where very limited data is available. The success of any mini-DST operation can be significantly compromised if two major issues are not addressed in the design phase: possibility to clearly identify the radial flow behavior and avoidance of noise in the pressure response due to the gauge resolution. **Approach:** The study consisted in the development of a new tool for mini-DST design to easily identify whether this technology can be successfully applied. The tool comprises dimensionless and dimensional charts, which are of general validity because they can be applied to any lithological environment and for any type of hydrocarbon. **Results:** Field applications proved the reliability of the charts: First of all the test durations were optimized to collect interpretable bottomhole pressures and to obtain valid reservoir characterizations. Besides, a cost saving effectiveness was achieved avoiding the acquisition of useless extra-data affected by noise due to gauge resolution. **Conclusion/Recommendations:** The use of the charts is strongly suggested at the early stage of decision making for new exploration/appraisal operations; they are a user-friendly tool for assessing the feasibility of a mini-DST test. Additionally, the charts are more versatile with respect to available commercial software in managing uncertainties of the major input parameters.

Key words: Charts, unconventional well testing, wireline formation test

INTRODUCTION

The wireline formation test technology consists in producing the reservoir fluid directly in the wellbore using a downhole pump so as to avoid hydrocarbons flow at the surface. After this short production period, a pressure build-up occurs. Pressure is monitored during the production and subsequent shut-in period. The result is a sort of mini test of the formation, hence named mini-DST, for reservoir dynamic characterization.

Depending on the reservoir and fluid properties, the volume of produced fluid can induce a pressure transient that extends to a rather long distance from the wellbore. When the pressure transient travels beyond the damaged zone and intercepts the upper and lower boundaries of the formation, a radial flow develops and the analysis of the pressure derivative can provide the average effective permeability of the reservoir.

Frimann-Dahl *et al*.[1] presented one of the first studies to apply the advanced well test analysis technique to wireline formation test data. After that, advanced transient analysis was applied extensively to wireline formation test acquired with single, dual probe and dual packer configurations[2-4].

Whittle *et al*.[3] and Daungkaew *et al*.[4] underlined the main critical issues that can make a mini-DST test completely ineffective to obtain valid reservoir information. Besides operational problems connected to the tool positioning as poor packer seal, tool stuck and

Corresponding Author: Clara Bertolini, Department of R & D Management, E & P Division, eni, Via Emilia 1, 20097 San Donato Mil., Italy

wellbore instability, there are two main causes that might compromise the success of a mini-DST: build-up duration too short to reach radial flow conditions and invalid test data due to insufficient draw-down and/or gauge resolution.

Therefore, the main question to be answered in order to assess the feasibility of a mini-DST in a given reservoir scenario is whether it is possible to collect interpretable bottomhole pressure data. In case of a positive answer, the following step is to design the test sequence so that the build-up is long enough to obtain the horizontal permeability value and at the same time to meet the cost/time saving targets.

In exploration/appraisal wells the design phase could be complicated by the presence of some degree of uncertainty associated to the available data, such as the fluid mobility, λ, the net pay (formation thickness), h, the anisotropy ratio, α, (given by the ratio between the vertical permeability, k_V, and horizontal permeability, k_H) and the storativity (given by the product of porosity, ϕ, by total compressibility, c_t).

Dedicated well testing software could be used to verify the mini-DST feasibility, but software must be licensed, skilled personnel is required for their use and time to run sensitivities should be allocated-all requisites typically missing when a mini-DST needs to be designed.

The design charts presented in this study were conceived to provide a user-friendly tool to quickly establish the feasibility of a test and to properly estimate the draw-down and build-up durations. eni copyrighted and published them with an exhaustive user guide. Besides, the charts equations were implemented as a standalone IT tool to ease their use.

In the following the basic idea from which the charts were developed is first introduced, then the equation needed to plot them are examined.

MATERIALS AND METHODS

Theoretical background: The diagnostic log-log plot for a synthetic build-up response simulated with the input data summarized in Table 1 is presented in Fig. 1. Three characteristic zones can be recognized.

In the first zone (time up to Δt_{min}, which represents the minimum build-up duration) the negative half slope of the pressure derivative in the diagnostic plot indicates spherical flow due to limited entry effects. Such effects are enhanced by low h_W/h, where h_w is the producing interval, and low anisotropy ratio, α. Being Δt_{min} inversely proportional to the fluid mobility, λ, in gas reservoirs limited entry effects usually disappear very rapidly (few minutes or less). Sometimes, the build-up duration of a mini-DST does not last enough to reach radial flow conditions, making it difficult to obtain the horizontal permeability value, k_H[3].

In the interval corresponding to times from Δt_{min} to Δt_{max}, which represents the maximum build-up duration, the pressure derivative exhibits a horizontal stabilization typical of radial flow in homogenous reservoirs and provides the average formation $k_H h$.

When time is greater than Δt_{max}, a sever scatter of the pressure derivative could prevent any interpretation if the pressure draw-down is too small. The noise in the pressure data and thus in the pressure derivative is strongly influenced by the resolution of the pressure gauge[3,4]. Parallel segments in the pressure derivative are a typical evidence of poor gauge resolution. Being the pressure draw-down inversely proportional to the fluid mobility, λ, data scattering is more likely to occur in gas/gas and condensate reservoirs and in high permeability sands.

Therefore, the evaluation of Δt_{min} and Δt_{max} for a given test scenario makes it simple to verify whether it is possible to perform a reliable test interpretation and thus to select a proper build-up duration. The decision criteria are summarized here below:

- If Δt_{min} is so long that it exceeds the build-up duration constraints due to cost/time saving targets or to tool operational limits, the test is not feasible

Table 1: Input data for mini-DST simulated build-up

Net pay, h (ft)	16.40
Perforated interval, h_w (ft)	3.28
Permeability, k_H (mD)	20.00
Porosity, ϕ (%)	0.10
Oil viscosity, μ_o (cP)	1.00
Oil FVF, B_o (rb/stb)	1.00
Total compressibility, c_t (psi^{-1})	10^{-5}
Anisotropy ratio, α (-)	0.02
Gauge resolution, δ (psi)	0.01
Draw-down duration, t_p (h)	1.00
Pumping rate, Q (stb day^{-1})	20.00

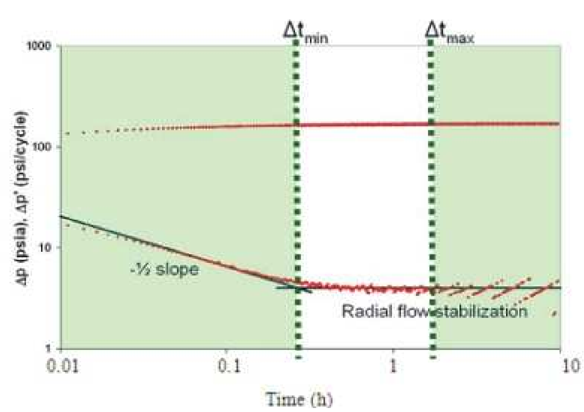

Fig. 1: Log-log plot for simulated mini-DST build-up

- If Δt_{max} is very short (minutes), the test is not feasible
- If the difference between Δt_{min} and Δt_{max} is small (tens of minutes), the test is not feasible

In all the other cases, the test is feasible and the pressure build-up duration has to be selected in the range Δt_{min} and Δt_{max}, termed "build-up working area". Build-up shorter than the minimum time cannot be interpreted and the test is to be discarded. On the other hand, if the build-up is longer than the maximum time, useless data is collected wasting time and money.

The recommendation is that the duration of the mini-DST build up approximates Δt_{max} in order to achieve a radius of investigation as large as possible.

The equations that govern the limited entry effects and the data scattering due to the gauge resolution will be discussed in the following. All the equations as well as the charts are expressed in oilfield units (Table 2).

The minimum build-up time Δt_{min} is related to the input data according to Eq. 1. Such equation can be easily derived by calculating the intersection between the spherical and radial flow trend-lines[3,5,6]. Equation 1 also includes a factor of two as a safety margin; it was introduced in order to avoid wrong decisions when the minimum and the maximum build-up durations are very close:

$$\Delta t_{min} = \frac{h^2}{2\pi\alpha}\frac{\phi c_t}{0.0002637\lambda} \qquad (1)$$

A corresponding dimensionless minimum build-up time $\Delta t_{min,D}$ is given by Eq. 2:

$$\Delta t_{min,D} = \frac{1}{2\pi\alpha}\left(\frac{h}{h_w}\right)^2 \qquad (2)$$

Hence:

$$\Delta t_{min} = \frac{\phi c_t h_w^2}{0.0002637\lambda}\Delta t_{min,D} \qquad (3)$$

Table 2: SI metric conversion factors

bbl × 1.589873	10^{-1} = m^3
cP × 1.0*	1 = mPa s
ft × 3.048*	10^{-1} = m
h × 2.777778	10^{-4} = s
in × 2.54*	1 = cm
mD × 9.869233	10^{-4} = μm^2
psi × 6.894757	1 = kPa
cf × 2.831685	10^{-2} = m^3

*: Conversion factor is exact

Equation 4 shows that the dimensionless maximum build-up time $\Delta t_{max,D}$ is a function of the parameter ΔP_D, a dimensionless expression of the gauge resolution (δ) given by Eq. 5, where β is a conversion factor depending on the fluid type (equal to 54.2 for oil, and to 9652 for gas). The shape of $\Delta t_{max,D}$ was obtained developing an in-house numerical algorithm. The conversion from dimensionless to dimensional maximum build-up time is obtained multiplying the dimensionless maximum build-up time by the draw-down duration t_p (Eq. 6):

$$\Delta t_{max,D} = \Delta t_{max,D}\left(\Delta P_D\right) \qquad (4)$$

$$\Delta P_D = \delta\frac{\lambda h}{\beta Q} \qquad (5)$$

$$\Delta t_{max} = t_p \Delta t_{max,D} \qquad (6)$$

The dimensionless chart, unique for both oil and gas reservoirs, is presented in Fig. 2. It was plotted using Eq. 2 and 4.

For sake of convenience of use, it was preferred to plot a family of curves for the minimum build-up duration (in red) corresponding to different anisotropy ratio instead of one curve only. Its use is quite simple; the step-by-step sequence is as follows:

- Evaluate $\Delta t_{min,D}$ corresponding to h/h_W (use the 'red' curve corresponding to the appropriate anisotropy ratio)
- Calculate the dimensionless resolution parameter ΔP_D according to Eq. 5
- Evaluate $\Delta t_{max,D}$ corresponding to ΔP_D
- Convert $\Delta t_{min,D}$ and $\Delta t_{max,D}$ in dimensional times Δt_{min} and Δt_{max} using Eq. 3 and 6

RESULTS AND DISCUSSION

Design charts: As dimensionless quantities do not provide immediate indications and require additional computations, the dimensionless chart was re-arranged as dimensional charts. Examples for oil and gas bearing formations are presented in Fig. 3 and 4, respectively.

The dimensional charts consist of a family of curves (in red) that provide Δt_{min} as a function of mobility, λ, according to Eq. 1 and a family of curves (in black) that provide Δt_{max} as a function of mobility, λ, according to Eq. 4-6. Each curve is plotted for a different net pay.

The curves on each chart are plotted for a given anisotropy ratio and based on the default parameters in Table 3.

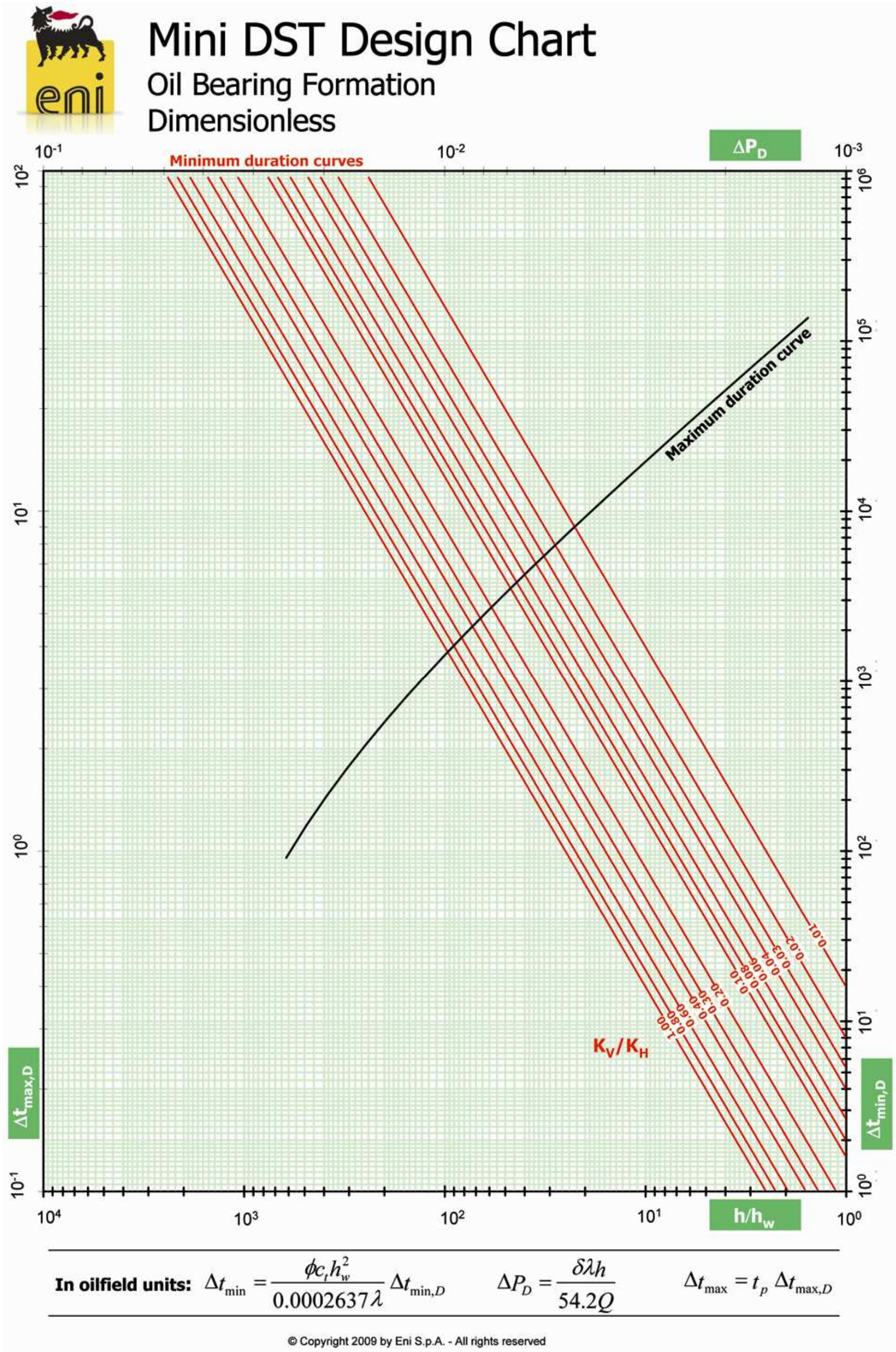

Fig. 2: Dimensionless design chart

Table 3: Default values for the dimensional charts

	Oil	Gas
Gauge resolution (psi)	0.01	0.01
Draw-down duration (h)	1.00	1.00
Storativity (psi^{-1})	10^{-6}	10^{-5}
Pumping rate (lpm)	3 (27 stb day^{-1})	1 (51 cf day^{-1})
Tool position	Centered	Centered

Even if the charts were developed for a given set of parameters, this does not imply a loss of generality and any sort of limitation in their use. How to manage any arbitrary value in the input data (storativity, anisotropy ratio, pumping rate, and gauge resolution) will be discussed in the following.

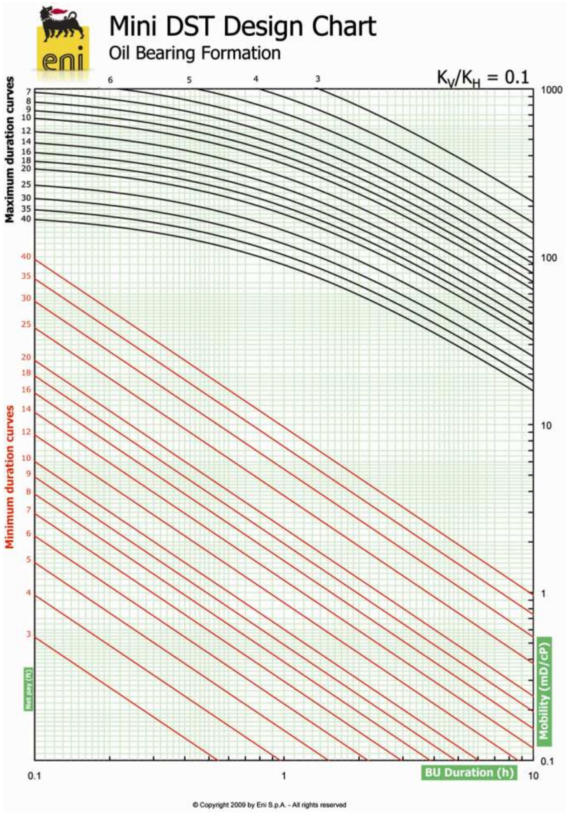

Fig. 3: Example of a chart for oil formation

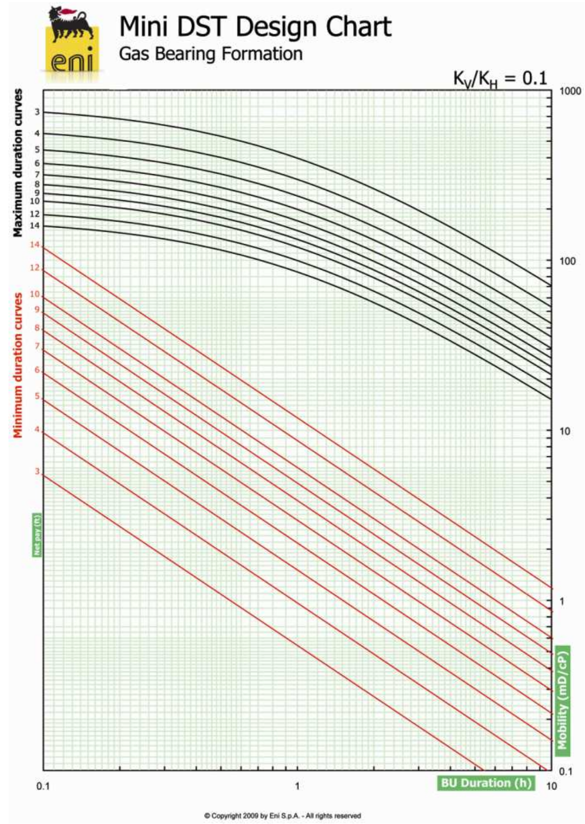

Fig. 4: Example of a chart for gas formation

The basic use of a dimensional chart is illustrated in Fig. 5.

Let's consider a design scenario for an oil reservoir with some uncertainty in fluid mobility, ranging from 10-30 mD/cP and assume that all other petrophysical and tool parameters are well known: 80 ft net pay and all the other parameters equal to the default values in Table 3. The build-up working area can be simply assessed in two steps. First, the minimum duration curve for the given net pay is identified and the Δt_{min} corresponding to the lower mobility is obtained. Then, the appropriate maximum duration curve is identified, and Δt_{max} as a function of the higher mobility is evaluated.

The powerfulness of the charts is that they allow handling uncertainty in any of the petrophysical parameters (net pay, storativity and anisotropy ratio). The simplest way to describe such uncertainties is to define a "most likely" range of variation for one or more parameters. Therefore, the problem can be solved by computing the build-up working area for each combination of the range extreme values and then evaluate the final build-up working area as the interval defined by the maximum Δt_{min} and the minimum Δt_{max}.

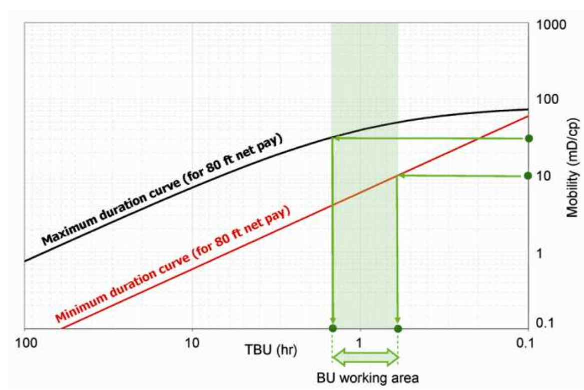

Fig. 5: Draft of a dimensional design chart

There are also very simple rules that can be easily derived from the physical background and equations previously discussed, and that can help in identifying the correct build-up working area:

* Net pay: only the thicker pay should be considered. In fact, when the net pay increases, Δt_{min} increases too (Eq. 1) whereas Δt_{max} decreases because the

pressure draw-down is reduced and the data scattering occurs at a shorter time

- Storativity: only the highest value should be considered. The storativity affects the limited entry behavior, so Δt_{min} increases for increasing storativity values (Eq. 1)
- Anisotropy ratio: only the lowest value should be considered. Similarly to the storativity, the anisotropy ratio impacts on the limited entry effects only, but it appears at the denominator of Eq. 1

It is worth pointing out that some care must be taken when setting-up the design scenario. Increasing the uncertainty, i.e., widening the ranges or increasing the number of uncertain parameters, could result in determining the non-feasibility of a mini-DST and thus could induce to improperly reject its application. It is strongly recommended to be cautious in being cautious.

Generalization of the charts: When one or more of the design parameters differ from the default values used to plot the chart and summarized in Table 3, the charts can be utilized by simply correcting the calculated minimum and maximum build-up time.

For the storativity and the anisotropy ratio that control Δt_{min} first the $\Delta t_{min,default}$ should be calculated as described above and the corrections as in Eq. 7 and 8 should be applied:

$$\Delta t_{min,corrected} = \frac{(\phi\ c_t)_{actual}}{(\phi\ c_t)_{default}} \Delta t_{min,default} \tag{7}$$

$$\Delta t_{min,corrected} = \frac{\alpha_{default}}{\alpha_{actual}} \Delta t_{min,default} \tag{8}$$

A similar procedure should be followed for the draw-down duration that affects Δt_{max} (Eq. 6):

$$\Delta t_{max,corrected} = \frac{t_{p,actual}}{t_{p,default}} \Delta t_{max,default} \tag{9}$$

The default tool position is assumed to be centered with respect to the formation net pay. In the case the tool position is close to the top/bottom of the tested layer (as a rule of thumb, a distance less than h/3 to the top or the bottom of the formation should be set) the hemispherical flow approximation has to be considered. The correction is given by Eq. 10:

$$\Delta t_{min,corrected} = 4\Delta t_{min,default} \tag{10}$$

The pumping rate and the gauge resolution affect Δt_{max} only. In order to account for differences from the default values, first an equivalent mobility should be calculated according to Eq. 11 and 12, then the equivalent mobility should be used to obtain the maximum build-up duration from the chart.

Note: Δt_{min} must be estimated using the original mobility:

$$\lambda_{eq} = \frac{Q_{default}}{Q} \lambda_{fluid} \tag{11}$$

$$\lambda_{eq} = \frac{\delta}{\delta_{default}} \lambda_{fluid} \tag{12}$$

Field example: The reservoir is an almost symmetric anticline located on-shore Iran. Currently, the field is producing oil through more than 20 wells, from the deep carbonate sequence of Fm. 1 (lower cretaceous).

Above Fm. 1, other carbonate and clastic reservoir units were identified from logs, indicated as shallow reservoirs (Fm. 2 and 3). A well was perforated in order to estimate the productivity potential of these shallow formations, performing a well test in the thicker layer and a mini-DST test in the thinner one.

The presented field example was a dual packer mini-DST performed in Fm. 3 unit to sample the formation fluids and to estimate the reservoir permeability.

The well log interpretation along the tested interval is shown in Fig. 6. The expected reservoir fluid is a medium-oil of about 27°API.

The mini-DST design was carried out assuming the input data summarized in Table 4.

In particular, the uncertainty in the fluid mobility and in the formation permeability anisotropy was accounted for. Hemispherical flow conditions had to be taken into account because the tool position was close to the bottom of the tested layer. The uncertainty in the anisotropy ratio was managed just considering the minimum value of the given range (here equal to 0.3).

Table 4: Input data for mini-DST design

Net pay (ft)	30.00
Storativity (psi^{-1})	10^{-6}
Oil gravity (°API)	27.00
Oil viscosity (cP)	1.87
Gauge resolution (psi)	0.01
Draw-down duration (h)	1.00
Pumping rate (STB/D)	27.00
Distance tool center-bottom fm. (ft)	6.00
Expected mobility (mD/cP)	10-100
Expected anisotropy ratio	0.3-1

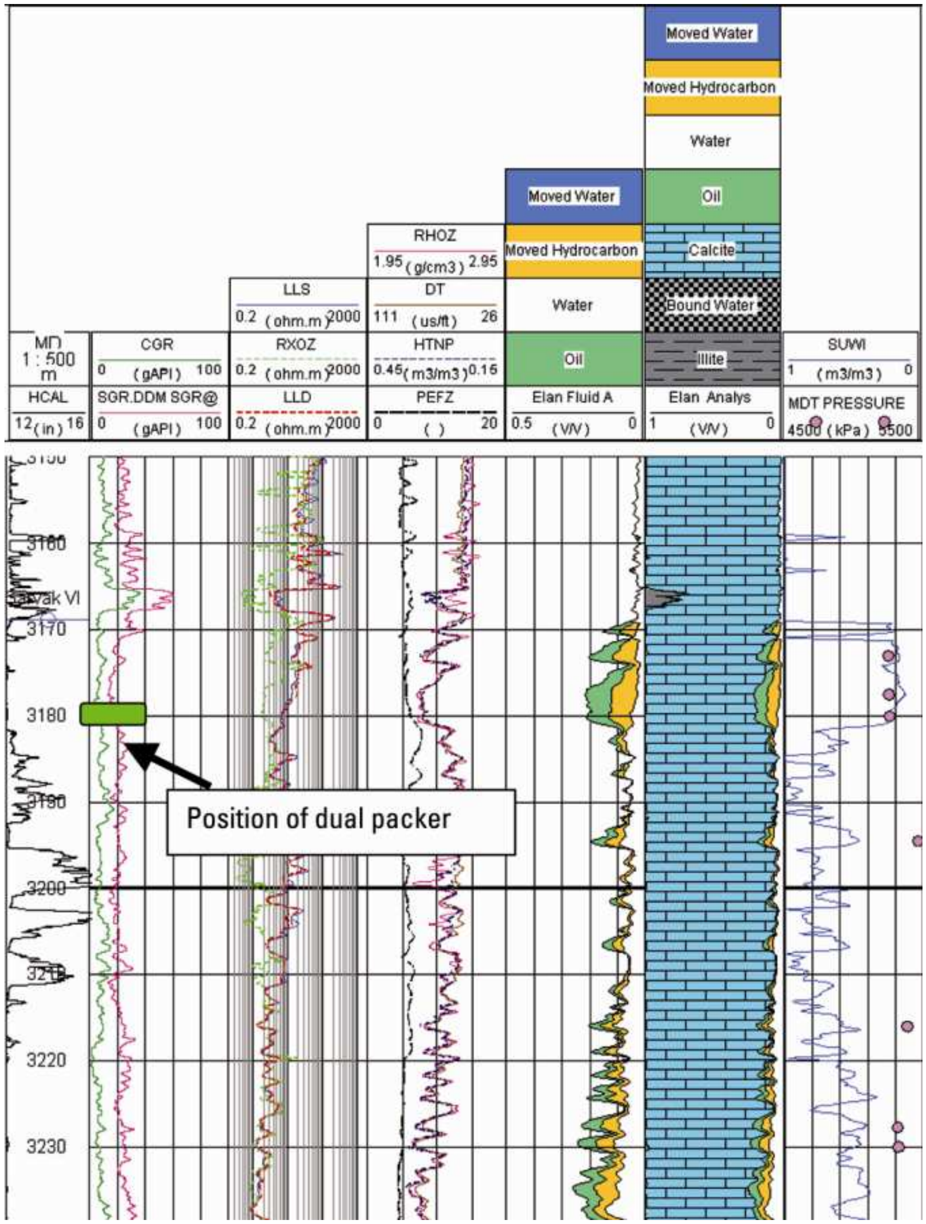

Fig. 6: CPI and input data for the discussed field example

The minimum and maximum values of mobility ratio (10-100 mD/cP) were used to obtain Δt_{min} and Δt_{max} through the use of the reference chart (Fig. 7) and assess the "build-up working area".

Using the minimum mobility, and selecting the corresponding net pay, a Δt_{min} of 0.55 h was obtained.

The next step consisted in applying the correction for hemispherical flow (Eq. 10) and anisotropy ratio (Eq. 8). The overall correction factor is 1.3 so the corrected Δt_{min} resulted to be about 0.7 h.

Finally, the chart was entered with the highest mobility and the Δt_{max} from the maximum duration curve corresponding to the given net pay was obtained; the result was about 1.2 h.

Therefore, the mini-DST resulted to be feasible, with a build-up working area ranging between 0.7 and 1.2 h (Fig. 7).

The operations comprised fluid sampling after significant mud filtrate pumping and discharge so that contamination reached the maximum tolerable level.

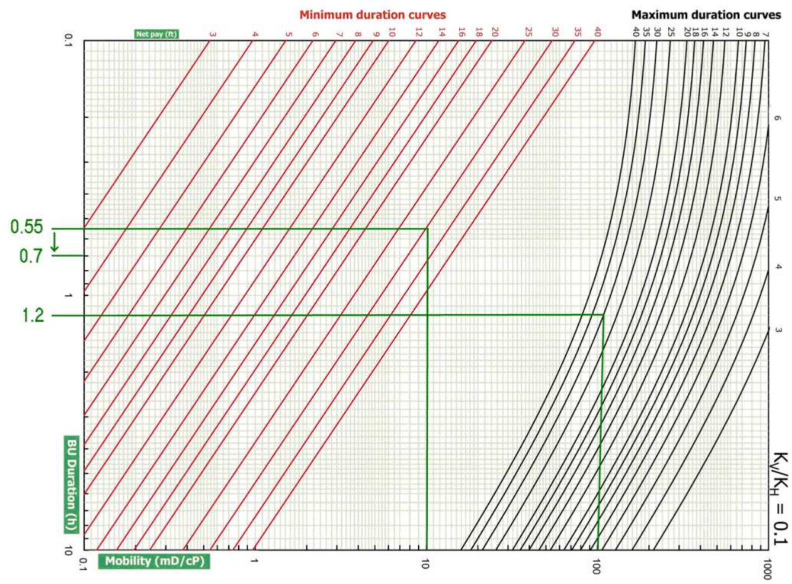

Fig. 7: Design chart for field example (oil reservoir)

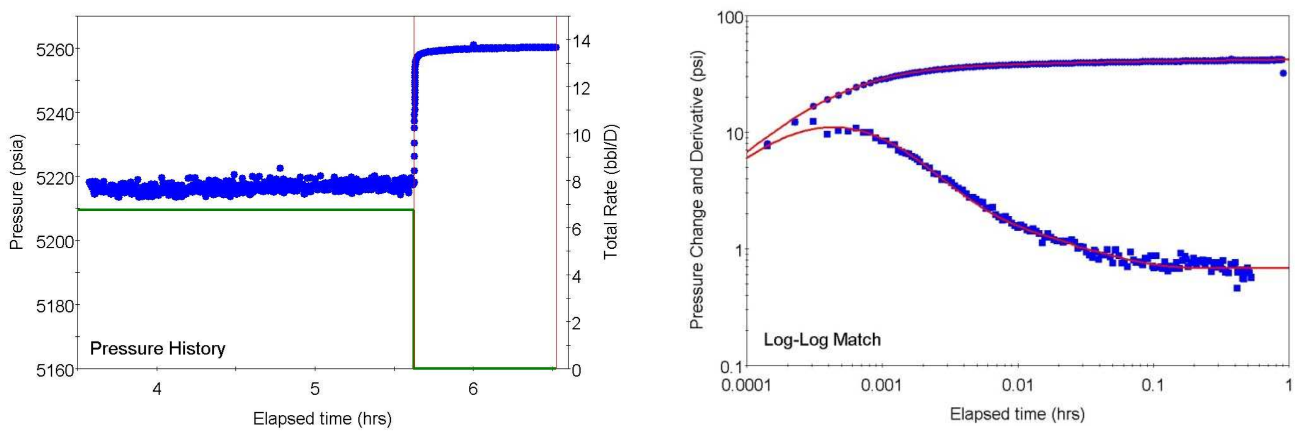

Fig. 8: Mini-DST pressure history and interpretation plots

Table 5: Mini-DST main output parameters

Reservoir press at gauge depth (psia)	5262
Flowing pressure (psia)	5218
kh (mD ft)	1290
Radial permeability (mD)	43
Vertical permeability (mD)	19
Anisotropy ratio	0.44
Wellbore storage coeff. (bbl psi^{-1})	3.7×10^{-6}
Total skin	25
Radius of investigation (ft)	130

Afterwards a pressure draw-down and build-up were performed.

The bottomhole pressure data were interpreted as usual by means of analytical commercial software; the analysis of the build-up provided the results shown in Fig. 8 and Table 5.

CONCLUSION

A wireline formation test could be a cost-effective alternative to conventional well testing, when a standard well test is not feasible for time/cost or safety/environmental constraints. In such cases, it is extremely important to evaluate whether the mini-DST can guarantee an acceptable value of information, thus minimizing the risk of collecting useless data with a waste of time and money and provide the possibility to obtain a reservoir dynamic characterization, although around the wellbore.

The new mini-DST design approach based on dimensionless and dimensional charts allows the user to easily evaluate the feasibility of the test, through the identification of the "build up working area", delimited on one extreme by the minimum time, controlled by limited entry effects and on the other extreme by the maximum time, controlled by gauge resolution.

The field example showed how quickly and straightforward this procedure can be applied.

The charts are valid in any lithological environment and for any type of hydrocarbons. In addition to that, even if the dimensional charts were developed for a given set of parameters, this does not imply any limitations in their use or any loss of generality because any arbitrary value of the input data can be managed.

The charts also proved to be powerful in managing uncertainties of the input parameters; however, it is strongly recommend to be careful in the selection of the expected ranges because the wider the uncertainty the higher the risk to improperly consider a mini-DST as not feasible.

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