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WES, a Robust Expert System for Well Test Analysis

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Publication Date
1989-09-01

UC-403

LBL-27846

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EARTH SCIENCES DIVISION

Presented at the 1988 American Geophysical Union
Fall Meeting, San Francisco, CA, December 5–9, 1988

WES, a Robust Expert System for Well Test Analysis

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September 1989

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

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LBL-27846

WES, A Robust Expert System for Well Test Analysis

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This work was supported by the Manager, Chicago Operations, Repository Technology and Transportation Program, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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1. Introduction

Expert systems have been used successfully for a wide range of problems in the past few years (Hayes-Roth et al., 1983; Jackson, 1986). Examples of applications range from medical diagnosis (Szolovitz, 1981) to the design of computers (McDermott, 1981). WES is an expert system developed for well test analysis which combines data processing and graphic representations with the expertise that can be provided by an expert system. The purpose of this paper is to show the new possibilities offered by an expert system in the field of automatic well test analysis.

1.1. Well Test Analysis

Well tests are generally performed to determine the hydrologic properties of aquifers, petroleum reservoirs and underground waste disposal sites. There are many types of well tests, however, for the purposes of this paper, we consider two of the most common: pressure drawdown tests (production of a well at a constant flow rate) and pressure build-up tests (shut-in of a well after a production period). For both of these tests, the pressure changes in the wellbore are monitored for the duration of the test. The resulting data set consists of pressure versus time values, along with the corresponding flow rate data.

Human experts use this data to identify the nature of the formation, the appropriate model to use for interpreting the data, and, following these two steps, to estimate the transmissivity and storativity of the formation. Additional information relevant to formation heterogeneity may also be obtained from such tests. There are several methods, some of them very recent, that have been developed for interpreting such data. Compilations of these techniques are provided by Matthews and Russell (1967), Earlougher (1977) and Streltsova (1988). Most of them rely on graphical analysis for pattern identification, type-curve matching and parameter estimation. The most common graphical methods include semilog analysis (Miller, Dyes and Hutchinson, 1950; Horner, 1951), log-log type curve analysis (Agarwal et al., 1970), and pressure derivative plots (Bourdet et al, 1983a, b, 1984a).

1.2. Advantages of the Expert System Approach

Expert systems combine two kinds of advantages: those inherent to any computer program, and those specific to expert systems.

Computer systems have several advantages over manual manipulation of the data, including:

- They are much faster than human experts. The analysis of a well test would be completed in a few hours or a few days by an expert, compared to a few minutes by a computer.
- They can provide expertise where it is not always available, that is, in the field at the test site. For example, a real-time data analysis system could propose to stop a test when enough data is collected, or to repeat it if the data is not adequate for a comprehensive analysis (e.g., noise, wellbore storage effects, uncontrolled external effects). This in-field expertise could save a significant amount of time and expense.
- There are presently no real standards in well test analysis, that is, two analysts, each given the same set of data, may provide different interpretations regarding the nature and parameters of a formation. A computer program would help to standardize and document the methods used to data interpretation.

Experts systems also have capabilities not found in classic numerical programs:

- They can easily trace the rules and procedures they use, and therefore explain how they reach their conclusions.
- They are able to handle and manipulate higher-level symbolic representation of the data, and thus are closer to the human reasoning process than numerical algorithms. For example, the shape of the pressure transient curve can be represented as a series of well-defined patterns, such as humps, valleys, and straight lines. In addition, noisy intervals of the test data can be recognized and labeled as such. These are the basic tasks that the human expert performs at the beginning of an analysis.

- They are usually easier to develop and maintain than classic programs, especially when, as for WES, the system tries to mimic the way a human expert is reasoning. For instance, expertise is usually contained in rules written in English-like syntax.

Although there are already some numerical programs performing curve fitting and parameter estimations for well test analysis (McEdwards, 1981), the use of expert system techniques in this field has only begun recently.

2. The System

2.1. General Organization

WES has been developed at the Lawrence Berkeley Laboratory over the past two years. In its present state, the system consists of two modules that interact with each other: a procedural program, written in C, and a rule base system using ART (Automated Reasoning Tool, from Inference Corp.), an expert system shell. The C program performs computations and graphics, and exchanges informations with both the user and ART. Basic inputs for the C program are commands given by the user (i.e. to analyze a well test or to draw a curve) and requests from ART (i.e. to compute a value needed for the analysis). Outputs are graphics and final results (for the user) and results of computations (directed to ART). Both the C program and ART use windows and mouse-clickable icons to interact with the user.

Another interesting feature of the ART expert system shell is its ability to show each fact and rule used to reach a conclusion. This ability can be used at the end of the run to obtain a complete explanation of the reasoning used to reach the results of the analysis.

The following section describes the system and provides an example of a typical analysis.

2.2. Description

WES uses a graphical method for data interpretation, much like most human experts currently perform (Earlougher, 1977; Streltsova, 1988). In its present state, the system can analyze a subset of the general well test analysis problem: it can analyze single-rate pressure drawdown and pressure buildup tests, and identify a limited number of models for the nature of the formation, including homogeneous, infinite reservoirs (Horner, 1951), bounded reservoirs (Bixel, Larkin and Van Poollen, 1963; Gray, 1965) and double-porosity formations (Warren and Root, 1963; Kazemi, 1969).

Three methods are commonly used in well test analysis: the conventional method (Horner, 1951) is based on the semilog plot (plot of the pressure drop versus the log of time), type curve matching (Agarwal et al., 1970) is performed on the log-log plot (plot of the pressure drop versus time on log scales), and a new method (Bourdet et al, 1983a, b, 1984a) that uses the derivative plot (discrete derivative of the pressure drop, taken with respect to the log of time and plotted on log scales). Basically, the latter plot represents the slopes of the curve on semilog scales. Instead of choosing only one of these methods, WES uses a combination of the three of them to analyze the data. Thereby, it benefits from the strengths of each of these methods.

The system goes through four steps to complete the interpretation of a well test. The following sections describe these steps, along with an example showing their application. This example is a drawdown pressure test of a well at Kesterson Reservoir, Merced County, California. It is a 9-hour test, performed in April 1986 (LBL, 1987). The data for this test are shown in Tables 1 and 2.

Table 1: Pressure-time data for the drawdown pressure test

Δt (s)	Δp (psi)	Δt (s)	Δp (psi)	Δt (s)	Δp (psi)	Δt (s)	Δp (psi)	Δt (s)	Δp (psi)
5	0.83	335	2.97	1925	3.39	9905	3.61	25205	3.58
10	1.62	345	2.91	1985	3.40	10205	3.60	25505	3.58
15	2.00	355	2.98	2045	3.42	10505	3.61	25805	3.62
20	2.16	365	2.98	2105	3.45	10805	3.52	26105	3.57
25	2.29	375	3.03	2165	3.43	11105	3.59	26405	3.58
30	2.27	385	3.05	2225	3.44	11405	3.58	26705	3.58
35	2.34	395	3.02	2285	3.43	11705	3.58	27005	3.54
40	2.44	405	3.04	2345	3.46	12005	3.64	27305	3.58
45	2.45	415	3.01	2405	3.49	12305	3.60	27605	3.61
50	2.46	425	3.04	2465	3.39	12605	3.59	27905	3.56
55	2.47	435	3.02	2525	3.44	12905	3.61	28205	3.58
60	2.55	445	3.03	2585	3.42	13205	3.59	28505	3.61
65	2.56	455	3.04	2645	3.46	13505	3.61	28805	3.57
70	2.59	465	3.07	2705	3.45	13805	3.61	29105	3.60
75	2.50	475	3.08	2765	3.44	14105	3.57	29405	3.56
80	2.50	485	3.07	2825	3.48	14405	3.58	29705	3.59
85	2.56	495	3.09	2885	3.44	14705	3.59	30005	3.60
90	2.61	505	3.09	2945	3.51	15005	3.56	30305	3.60
95	2.64	515	3.08	3005	3.48	15305	3.61	30605	3.58
100	2.65	525	3.11	3065	3.48	15605	3.59	30905	3.59
105	2.60	535	3.09	3125	3.52	15905	3.62	31205	3.58
110	2.62	545	3.09	3185	3.51	16205	3.59	31265	3.56
115	2.70	605	3.12	3245	3.41	16505	3.60	31415	3.58
120	2.69	635	3.11	3605	3.55	16805	3.58	31470	3.61
125	2.72	665	3.19	3905	3.51	17105	3.54	31545	3.62
130	2.75	695	3.13	4205	3.53	17405	3.63	31550	3.61
135	2.69	725	3.17	4505	3.55	17705	3.63	31555	3.59
140	2.70	755	3.14	4805	3.49	18005	3.60	31560	3.60
145	2.71	785	3.15	5105	3.54	18305	3.58	31565	3.58
150	2.72	815	3.18	5405	3.54	18605	3.57	31570	3.58
155	2.77	845	3.24	5705	3.58	18905	3.60	31575	3.56
160	2.80	875	3.23	5890	3.58	19205	3.56	31580	3.60
165	2.81	905	3.22	5970	3.55	19505	3.55	31585	3.61
170	2.81	935	3.23	6040	3.54	19805	3.62	31590	3.59
175	2.81	965	3.21	6045	3.56	20105	3.59	31595	3.60
180	2.81	995	3.19	6050	3.58	20405	3.61	31600	3.62
185	2.81	1025	3.25	6055	3.54	20705	3.58	31605	3.63
190	2.79	1055	3.24	6060	3.54	21005	3.55	31610	3.62
195	2.83	1145	3.29	6065	3.57	21305	3.59	31615	3.58
200	2.80	1205	3.33	6070	3.55	21605	3.64	31620	3.60
205	2.85	1265	3.32	6605	3.59	21905	3.57	31625	3.58
210	2.86	1325	3.31	6905	3.59	22205	3.56	31630	3.59
215	2.87	1385	3.35	7205	3.55	22505	3.62	31635	3.59
255	2.88	1445	3.32	7505	3.56	22805	3.57	31640	3.57
265	2.88	1505	3.38	7805	3.62	23105	3.59	31645	3.64
275	2.91	1565	3.34	8105	3.64	23405	3.58	31650	3.59
285	2.90	1625	3.38	8405	3.58	23705	3.65	31655	3.61
295	2.97	1685	3.40	8705	3.57	24005	3.57	31660	3.62
305	2.98	1745	3.37	9005	3.57	24305	3.58	31665	3.55
315	2.96	1805	3.41	9305	3.61	24605	3.63	31670	3.60
325	2.98	1865	3.41	9605	3.59	24905	3.58	31675	3.59

Table 2: Well test data	
Formation thickness h, m	6.0
Flow rate q, m3/s	6.0 10-3
Viscosity μ, Pa.s	1.0 10-3
Wellbore radius rw, in	2.0
Porosity-compressibility Φct, Pa-1	3.5 10-9

2.2.1. Data Processing and Graphics Computation

The system input includes the recordings of pressure versus time and some supplemental data for the well test (shown in Table 2). The number of points for a typical data set ranges from 50 to a few hundreds. International system (SI) units and common oil-field units can be used for input, but all the values are converted to SI units for internal computations.

Once the user has selected a well to analyze, the C program performs four types of computations:

(1) Read the data file and filter the data. Since data sets can be very different in size and may sometimes contain large numbers of points, the system uses filtering to reduce the number of points it has to handle: the time scale is divided in a fixed number of constant intervals (on a log scale, since the abscissa of the three plots used for analysis is the log of time), and each data point of the filtered plot is obtained by averaging the initial data points contained in the corresponding interval. Since pressure data is usually recorded at fairly constant time intervals, the density of points on a log scale increases dramatically with the time. The filtering process thus results often in a large reduction of the number of late data points, whereas the system keeps most of the early ones. It also has a smoothing effect on the last portion of the data.

(2) Compute the discrete derivative. One of the main inconveniences of the pressure derivative approach is that it cannot be measured directly but rather must be computed from discrete data. The algorithm used by the system is the one described by Bourdet et al. (Bourdet et al, 1984b; Clark and Van Golf-Racht, 1985). It computes the weighted average of the slopes between the point under study and a point preceding it, and between the point

under study and a point following it. These two points are not necessarily the points closest to the point of interest, but rather are defined by taking the first point outside of a given interval (I) in each direction. The smoothness of the derivative curve obtained by this method depends on the length of the interval I: increasing the length will result in a smoother derivative data, but may also hide significant patterns. Depending on the noise of the original data, the length of the interval I used by the system ranges from 0.1 to 0.5 log cycles. With the notation of Figure 1, the derivative value is given by:

$$p' = \frac{\frac{\Delta p_1}{\Delta t_1}\Delta t_2 + \frac{\Delta p_2}{\Delta t_2}\Delta t_1}{\Delta t_1 + \Delta t_2}$$

where the time intervals are defined on a natural log scale (since p' is the derivative of the pressure taken with respect to the natural log of time).

(3) Compute the graphic representation of the data: curves and axis, including scales for the graphs. Five curves are computed: initial and filtered data on cartesian plots, semilog, log-log and derivative plots. A combined plot of the log-log and derivative curves is also available.

(4) Compute a new description of the semilog, the log-log and the derivative curves: each curve is represented by a sequence of straight lines. The number of straight lines depends on the shape of the curve and typically 5 to 10 segments are required to adequately describe the curve. These straight lines are computed with a simple least-squares algorithm that gives the best fitting straight line for the data points contained in a given time interval.

At the end of these computations, the three sets of straight lines are sent to ART. The straight line description of the data set has several advantages:

- It reduces and simplifies the amount of data handled by the expert system shell, without a great loss of information.
- The least-squares algorithm used to compute the straight lines has an important smoothing effect.

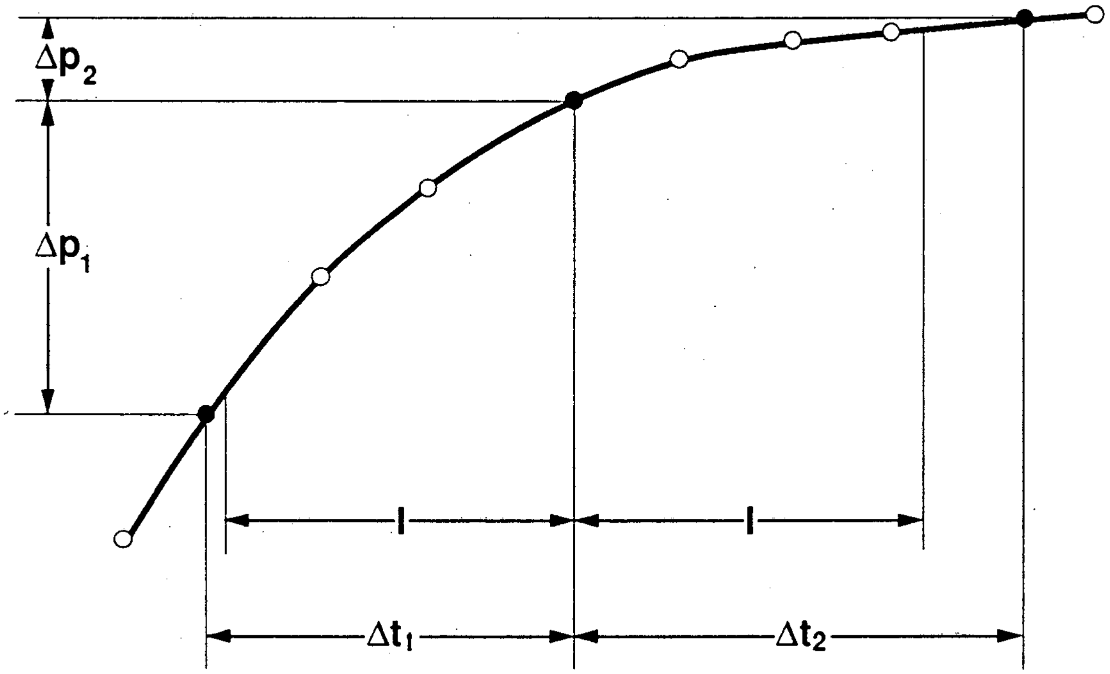

Figure 1. Illustration of the method for computing the discrete pressure derivative.

- It represents a higher-level, symbolic description of the data, and is closer to the global image of the curve that a human expert has. This representation has proved to be very useful to develop the rule base.

In this section and those that follow, an example of each of the steps in the analysis is provided in the italics text, as illustrated below.

Example: Figures 2 to 6 show the curves resulting from the initial computations. Figure 2 is the cartesian plot of the initial data, Figure 3 is the plot of the filtered data, Figure 4 is the semilog plot, Figure 5 the log-log plot and Figure 6 the derivative plot. These curves illustrate some interesting properties: (1) The interval between points on the filtered plot is increasing with the time. A large number of late initial data points have been discarded. These are the results of the filtering process. (2) The level of random noise on the semilog plot is relatively high. This level is typical of the range of random noise encountered in well test analysis. (3) The level of noise on the late part of the derivative plot is much larger. The discrete derivative computation algorithm is very sensitive to the amount of noise present on the data.

Figures 7 and 8 show the semilog, log-log and derivative plots with their straight lines representations. All three curves are described by five or six segments, and the results demonstrate that the straight line computation algorithm is relatively insensitive to random noise: even for the derivative curve, the set of lines obtained is very close to the original curve. However, from our experience, the level of noise present on this example is close to the limit after which the straight line algorithm fails to adequately describe the late part of the derivative curve.

2.2.2. Pattern Identification

Using the simplified linear representation of the data set, the rule base system identifies significant patterns in the shape of the pressure drawdown curve. Significant patterns consist of

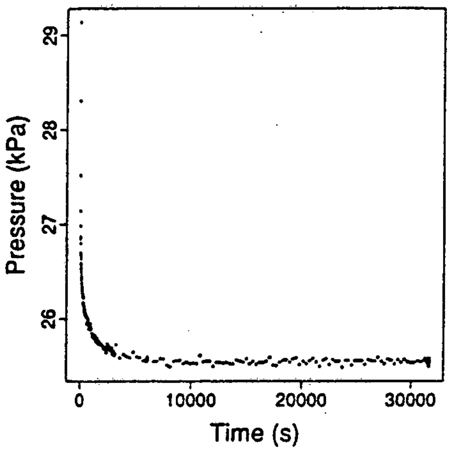

Figure 2. Initial data set for a pressure drawdown test performed at Kesterson site (April 86).

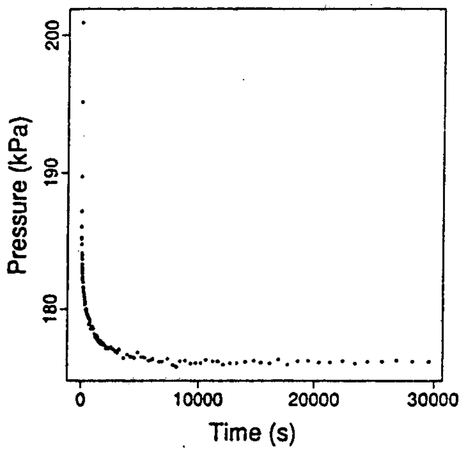

Figure 3. Data set obtained by filtering.

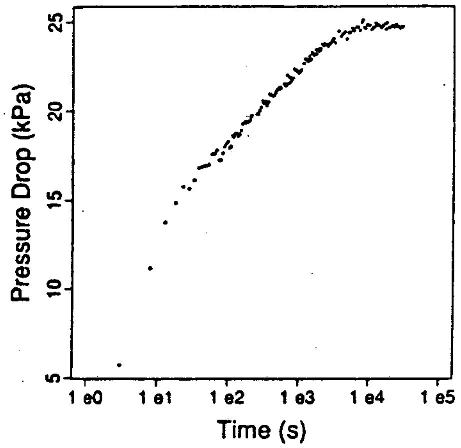

Figure 4. Semilog plot of the pressure drop.

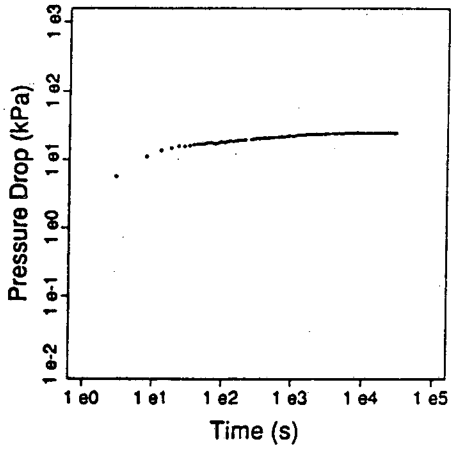

Figure 5. Log-log plot of the pressure drop

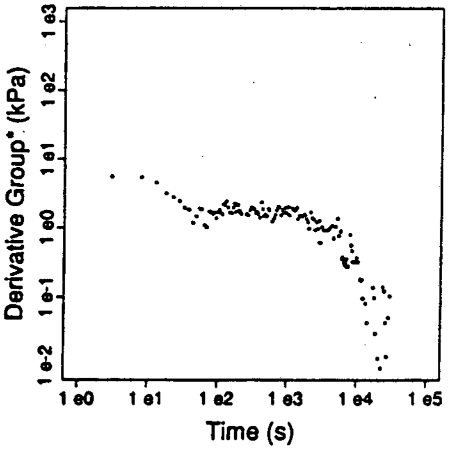

Figure 6. Log-log plot of the pressure derivative.

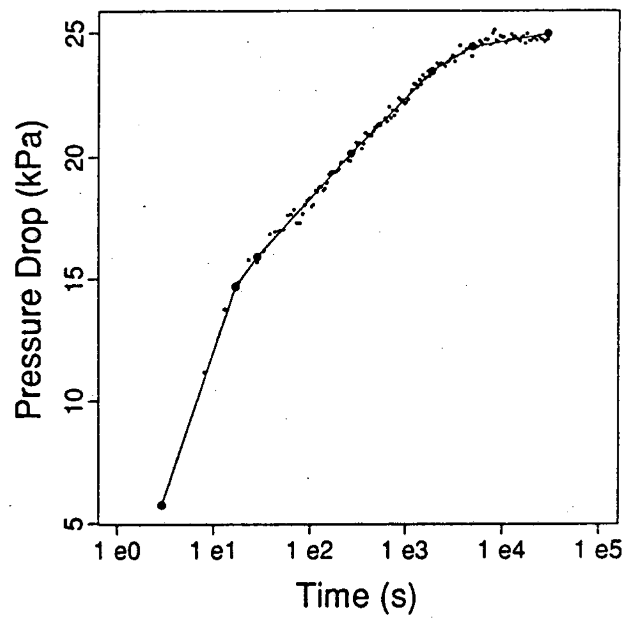

Figure 7. Semilog plot of the pressure drop with its straight line representation.

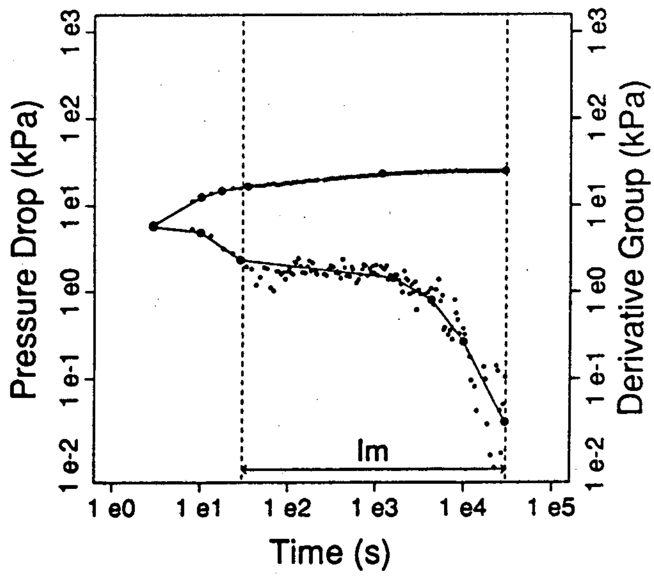

Figure 8. Combined log-log plot of the pressure drop and pressure derivative with their straight line representations.

straight lines with a duration of more than one log cycle on both the semilog and the derivative plots, a hump at the beginning of the derivative curve, and concave or convex curvatures at the end of both the semilog and the derivative curves. Other interesting patterns include unit-slope straight lines at the beginning of the log-log and the derivative plots. Each of those patterns can be ascribed to a property of the well/reservoir system and are described in greater detail below.

WES performs pattern identification in two steps: the first step looks for patterns related to the wellbore storage effect, and the second step for patterns concerning the reservoir model. These are always executed in this order, because the second step uses the results of the first one. They are described in detail in the two following section.

2.2.2.1. Presence of Wellbore Storage

The phenomenon or wellbore storage occurs at the beginning of a well test and masks the response of the reservoir during this period (Agarwal et al., 1970). The major difficulty presented by wellbore storage is that its presence must be recognized so that it is not mistaken for an actual reservoir response. Three time intervals are usually associated with the well test data (Vongvuthipornchai and Raghavan, 1988): early time, where wellbore storage is dominant, and intermediate and late time, where it is negligible. Intermediate time corresponds to the unaffected reservoir response, and late time to the aquifer heterogeneity and the outer boundary effects. WES uses these time interval concepts, but considers the intermediate and late time intervals as a single interval. All three intervals may not be present in a test, and one of the difficulties of well test analysis is to determine precisely the position and duration of these intervals during a test.

The most characteristic pattern of the presence of wellbore storage during a well test is a hump at the beginning of the derivative. Depending on the amount of data available for the beginning of the test, this hump can be either complete or partial: in the second case, only the last part of the hump is present on the derivative curve. When the whole pattern is present, a unit-slope straight line may also appear on both the log-log and the derivative plots. These straight lines are a confirmation of the presence of a wellbore storage effect.

Once it recognizes the hump, the system is able to determine the different time intervals for the test: it first computes precisely the top of the hump (first data point if only the downward portion of the hump is present), and defines the interval ranging from the beginning of the test to half a log cycle before the top of the hump as early time, and the interval beginning one log cycle after the top to the end of the test as intermediate/late time.

Example: Figures 6 and 8 show that only half of the hump appears on the derivative curve. The two first straight lines on the derivative represent a downward, convex pattern that is recognized by the system as the end of a hump. Presence of wellbore storage is inferred from this fact. In this case, there is no unit-slope straight line at the beginning of the test to confirm this interpretation. Since the upward portion of the hump is not present on the curve, the first data point is assumed to be the top of hump. The intermediate/late time interval (Im) begins one log cycle after this point, and the early time interval (Ie) is not defined in this case.

2.2.2.2. Reservoir Pattern

If the intermediate/late time interval is present, the response of the reservoir for this period gives informations about the type of the formation and the outer boundaries. In its present state, the system uses patterns on the semilog curve to recognize the model. The derivative curve also displays characteristic patterns for the different models: the advantage of the derivative method is that patterns are usually more uniquely illustrated on this curve (Clark and Van Golf-Racht, 1985); its drawback is that the derivative curve is sometimes too noisy to be usable. The ideal solution would be to use the derivative method when the data has been recognized to be smooth enough.

WES computes a new set of straight lines to describe the semilog curve on the intermediate/late time interval, determined in the preceding step. One to three straight lines are enough to represent this portion of the curve for tests corresponding to the models currently recognized by the system. Using a new series of lines, computed only on the intermediate/late time interval, provides a better representation of the curve than the original straight line representation. Results of the computation are used by the rule base system to determine the shape of the curve on the intermediate/late time interval. Characteristic shapes include concave, convex and straight portions.

Example: The computation of the new series of straight lines on the semilog curve for the Im interval (Figure 9) returns three lines: a long first one, followed by two shorter segments with decreasing slopes, the last one being almost horizontal. WES describes such a pattern as a long segment followed by a convex portion.

2.2.3. Model Recognition

In its present state, WES is able to identify a limited set of models, including homogeneous and double porosity reservoirs, and two kinds of outer boundaries (no flow and constant pressure boundaries). Typical curves for these models are shown in Figure 10. On the semilog plot (used by WES for the analysis), each model can be associated with a pattern present on the portion of the curve corresponding to the intermediate/late time interval: for instance, an homogeneous well without boundaries is characterized by a long straight line, a double porosity well can be characterized by either a convex portion followed by a concave portion, or only a concave portion when the first pattern is hidden by wellbore storage (Gringarten, 1984).

Some patterns can correspond to more than one model (Gringarten, 1984). In such a case, WES will continue the analysis using each of the different possibilities, or hypotheses, until it is able to resolve the conflict (by the use of geological information, specialized plots, and subdiary information from other wells in the area). The system is designed to generate as many hypotheses compatible with the facts as possible, to ascertain that the correct model is included in the set of hypotheses.

Example: The pattern determined in the preceding step is interpreted by the system

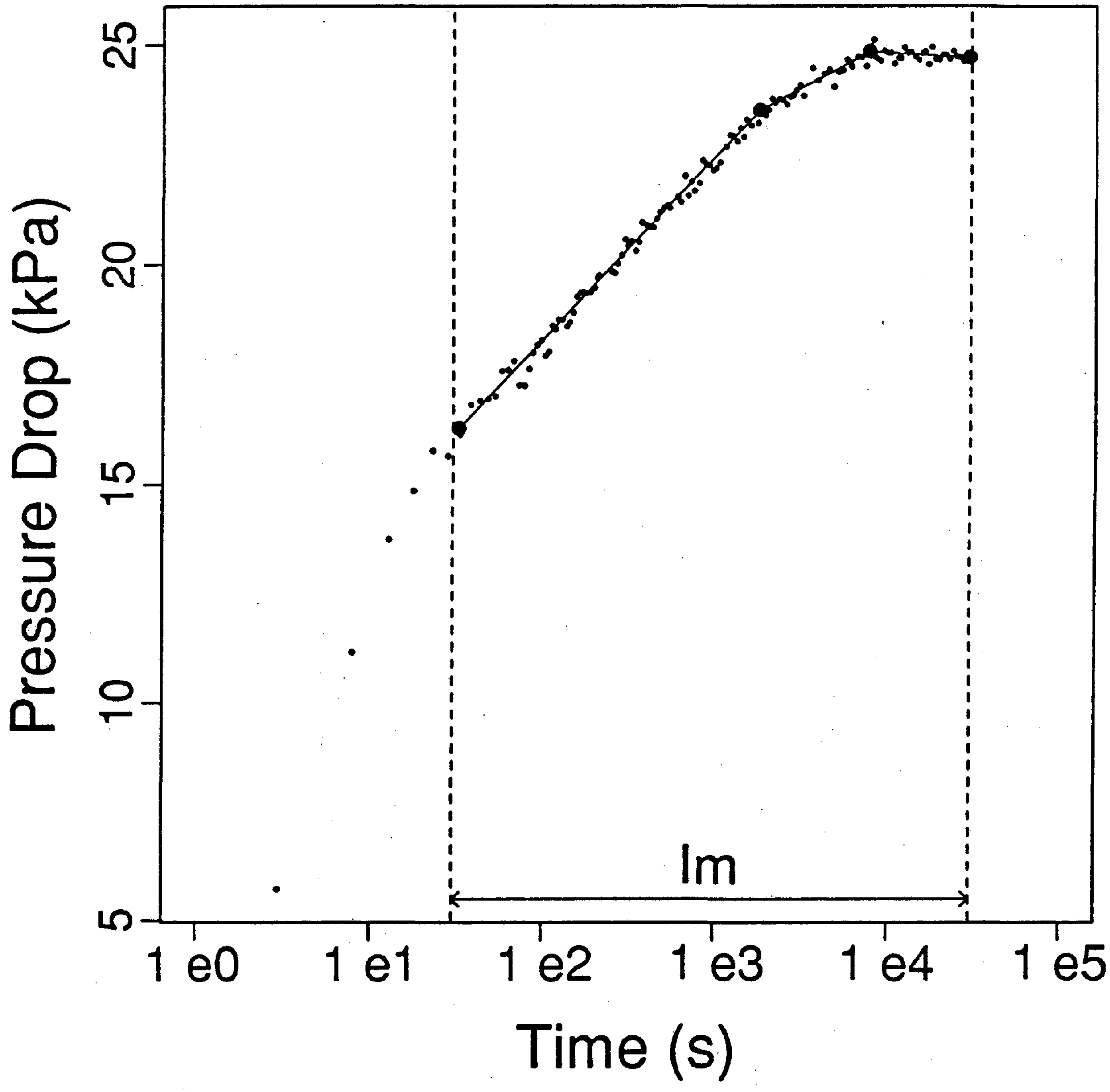

Figure 9. New straight line representations computed on the intermediate/late time interval (Im).

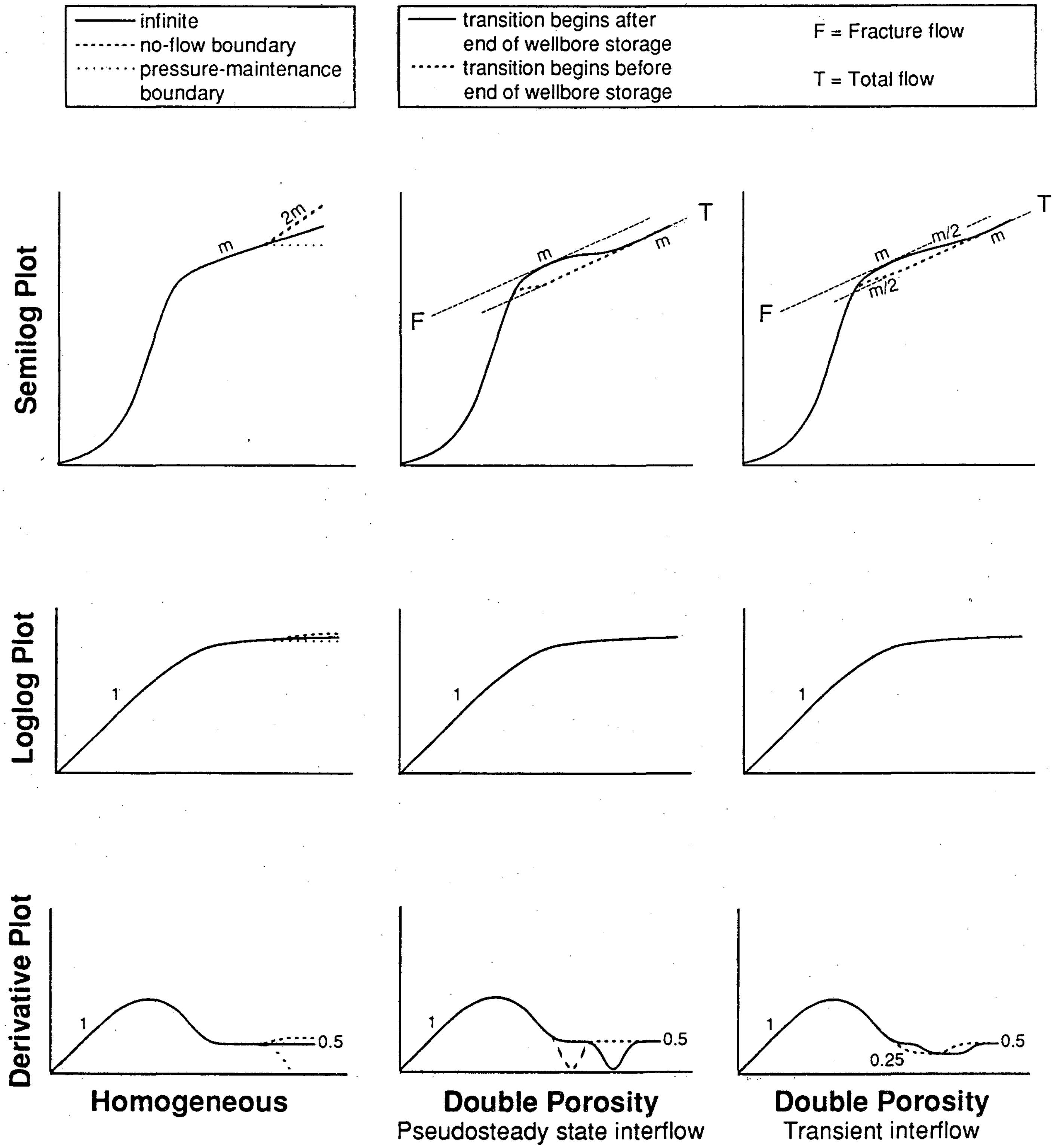

Figure 10. Typical curves for the models currently known by the system.

as characteristic of an homogeneous aquifer with a pressure maintenance boundary. There is only one model corresponding to this pattern in the current knowledge base, therefore only one hypothesis is generated.

2.2.4. Parameters Estimation

Once a model has been selected, the last step of the analysis consists of calculating the properties of the aquifer. The current version of WES uses semilog analysis and an approximate type curve matching procedure to calculate the values of these parameters.

Semilog analysis (Horner, 1951; Earlougher, 1977) consists of measuring the slope and intercept of the straight line corresponding to the radial flow on the semilog plot (this straight line is determined in the preceding steps of the analysis), and computing the values of the permeability k and the skin factor s from the measurements.

$$k = 0.5 \frac{qB\mu}{2\pi h} \times \frac{2.3}{m}$$

$$s = 0.5 \left[\frac{2.3\,\Delta p_1}{m} - \ln \left[\frac{k}{\Phi c_t \mu r_w^2} \right] + 0.80907 \right]$$

where m is the slope of the straight line and Δp_1 the intercept for $t = 1$ (i.e. $\log t = 0$). In these equations, q represents the flow rate, B the formation volume factor, μ the viscosity of the fluid, h the formation thickness, Φ the formation porosity, c_t the total compressibility and r_w the wellbore radius.

The type curve matching procedure (Agarwal et al., 1970; Earlougher, 1977; Bourdet et al, 1983a, b, 1984a; Clark and Van Golf-Racht, 1985) follows two steps: (1) the system computes the ratio between the ordinate of the top of the hump and the ordinate of the horizontal straight line that appear on the derivative plot; this result is compared to values stored in a table to select the appropriate type curve to use; (2) the type curve is adjusted to the real curve by computing the necessary x and y shifts. The values of the permeability k, the wellbore storage constant C and the skin factor s can be derived from the type curve match. Let A be a point with coordinates

(x_c, y_c) on the data plot and (x_t, y_t) on the shifted type curve plot, then

$$k = \frac{qB\mu}{2\pi h} \times \frac{y_t}{y_c}$$

$$C = \frac{2\pi kh}{\mu} \times \frac{x_c}{x_t}$$

$$s = 0.5 \ln \left[\frac{2\pi \Phi c_t h r_w^2}{C} P \right]$$

where P is the characteristic parameter of the type curve selected by the system and the notations are the same as above.

These algorithms give fairly good results for simple models and complete data, but are usually not able to handle models involving numerous parameters and well tests with only partial data sets. More powerful numerical procedures should be added to the system to perform a complete well test analysis.

Example: The chosen model depends on four parameters: the permeability k, the wellbore storage constant C, the skin factor s and the nature of the pressure maintenance boundary. For this particular example, pressure maintenance is created by leakage from an overlying evaporation pond. In its present state, WES cannot estimate the leakage parameters for this type of pressure maintenance boundary. The three other parameters are computed using the two methods described above. These methods yield two values for k and s, and the type curve match also gives a value for C. C can also be estimated independently by computing its geometrical value (that is, the value obtained from the geometrical dimensions of the wellbore, assuming that it is cylindrical). Figure 11 shows the log-log and derivative curves, with the two closest type curves (obtained from a table), and Table 3 gives the numerical values of the parameters. In this case, the early part of the hump is missing, therefore the type curve match may not be very reliable. However, comparison with the results from the semilog analysis indicates that similar values are obtained with both types of *analysis. The advantage of using several methods to compute the parameters is that a good agreement between the different results obtained gives a high degree of confidence in the validity of the analysis.*

Table 3: Results of the parameters estimation.

Method	Results		
	Permeability (k: m2)	Wellbore Storage Constant (C: m3.Pa-1)	Skin Factor (s)
Semilog Analysis	4.53 10-11		-1.73
Type Curve Match	4.60 10-11	1.69 10-6	-1.28
Geometrical Value		8.27 10-7	

2.2.5. Noises and Incomplete Data

Noise and incomplete data (absence of either the early or late time intervals) are problems that are encountered at each step of the process. Noises include random noise (measurement errors and rapid flow rate fluctuations), atmospheric pressure trend, flow rate variations, tidal effects, measurement error of the time origin and external influences (other pumping wells in the area).

Some of the noise can be corrected for. Random noise can be corrected through the use of smoothing techniques and time origin error can be corrected with a simple graphical technique. When correction is impossible, WES is able to recognize the part of the data which is unsuitable for analysis, and the system will proceed to analyze the rest of the data. This could be very useful when using numerical type curve matching procedures as these algorithms are not able to assess the quality of the data and to place more emphasis on the more reliable portions.

Incomplete data is the other major difficulty of well test analysis: some characteristics of a model appear only on a specific portion of the data (for instance, wellbore storage during early time, and boundaries during late time). When this part of the data is missing, the corresponding

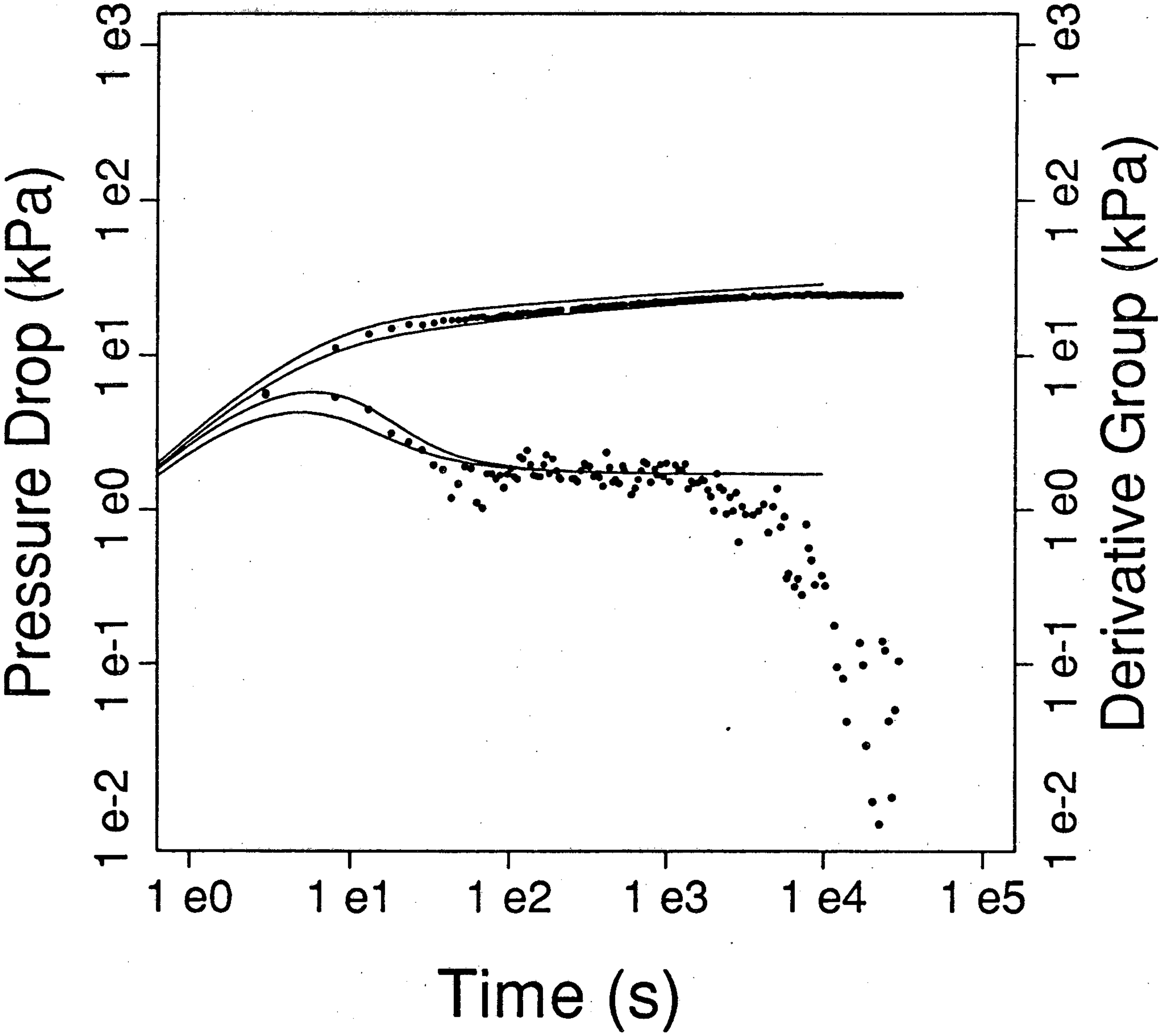

Figure 11. Type curve match of the early part of the data (the pressure maintenance boundary is not taken into account). The curves are obtained from a table.

pattern may be altered or may even disappear. WES is able to identify the different portions of the curves, and adapts its reasoning to the data available.

3. Extensions and Conclusions

In its present state, the system is able to perform the complete analysis of a limited set of well tests, and can deal with some specific types of imperfect data. Several extensions in different domains are needed to improve the capabilities of the system. However, the results obtained so far show that expert systems can be very useful in the field of well test analysis.

3.1. Extensions and Improvements

WES needs extensions in four main domains:

- The system should be able to handle other types of well tests than drawdown and buildup tests with constant flow rate: the capabilities to analyze multiple rate and variable rate tests should be added. WES should also be able to analyze test data from observation wells. In the long term, the system should be able to compare the informations gathered by analyzing a pumping well and several observation wells, to obtain a very robust evaluation of a reservoir.
- More expertise is needed for model recognition: more models for pumping wells; models for observation wells; and use of external informations (for instance, geological data) for conflict resolution, such as when a pattern corresponds to more than one model. One of the advantages of the expert system approach is the modularity of the rule base: each new model is described in a small set of rules, which does not interfere with rules already written. It is therefore fairly easy to add new models to the system.
- The handling of noise could also be improved: in its current state, WES is able to deal with reasonably high levels of random noise, to recognize and correct errors at the time origin, and to recognize imperfect data due to external factors, such as flow rate changes or atmospheric pressure trend. In the future, the system might be able to partially correct these

problems, by using external information (recordings of flow rates or barometric pressures, for instance). Other types of noise, such as tidal effects, should also be considered.

- Parameter estimation is also a domain where extension is needed. Until now, only very simple ways to estimate the formation parameters have been used. The next step consists of including in the system numerical curve fitting and type curve matching algorithms, to improve this estimation.

3.2. Conclusions

Although the system is still in an experimental state, it is already possible to draw some conclusions from its capabilities:

- WES is able to perform a complete and automatic well test analysis for a limited set of models. This is the major difference with the numerical programs that have been developed recently, for which human intervention is requested during the model selection process.
- The system can also recognize, diagnose and sometimes correct some of the most common noises encountered in well test analysis. This could be very useful to automatically adapt numerical estimation algorithms to the case of noisy data (for instance, the algorithm could ignore some meaningless part of the data). It also increases the robustness of the program, that is, its ability to deal with unusual and non-ideal data.
- It is fairly easy to modify and extend the knowledge of the system: the expertise for each model consists of an independent set of rules. Therefore it is possible to add more models without changing the existing system.
- The system can explain its reasoning and model selection process: facts and rules used to reach a conclusion can be traced during or after the analysis. This ability is a common characteristic of all expert systems, and it can be used to check questionable or important results.

All these properties show that expert system techniques could provide computer programs able to perform not only automated type curve matching for parameters estimation, but also a complete automatic well test analysis. However, one of the most difficult problems involved in expert system development has not been really covered in this report: the robustness of the system. The robustness of a rule base depends heavily on the quality of the expertise used to develop it, and on the range and number of examples on which it has been tested. In well test analysis it is always possible to imagine a test for which the system will not find the correct answer. Consequently, an expert system for well test analysis may always be in a dynamic state, where its knowledge is continually expanded to cover a wider range of problems, much as we now require our human experts to keep abreast of the latest developments in this rapidly growing field.

Acknowledgements

This work was supported by the Manager, Chicago Operations, Repository Technology and Transportation Program, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. For their contribution during the early part of the project, we would like to thank Esther Schroeder, Marc Uszinsky and Daniel Billaux. For their review of this paper, we thank Dr. Jane Long and Dr. Kenzi Karasaki.

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