SKIN ANALYSIS PROGRAM BOOSTS MATRIX STIMULATION RESULTS

D. Zhu and A. D. Hill
Center for Petroleum and Geosystems Engineering
The University of Texas at Austin

INTRODUCTION

Matrix stimulation treatments (most commonly using acid as a solvent) are aimed at overcoming the effect of near wellbore damage by dissolving solids and, hence, increasing permeability. The skin factor, a parameter to account for altered flow conditions in the near wellbore vicinity, is often used as a quantitative indicator of the level of damage. In the absence of other effects, such as partial completion or poor perforations, a high positive skin factor indicates severe damage; a zero skin factor results for an undamaged well, and a negative skin factor is due to higher effective permeability in the near-wellbore region[1]. Thus, determining the evolution of the skin factor during a matrix stimulation treatment is a means of measuring the effectiveness of the acid or other solvent in overcoming formation damage.

Based on the theory of pressure behavior in transient flow, the skin factor can be calculated from the bottomhole injection pressure and the injection rate during a treatment. However, the bottomhole pressure is seldom measured during an acidizing treatment and the injection rate is usually variable, complicating the determination of the skin factor. In a typical matrix stimulation treatment, only the surface pressure and injection rate are measured and multiple rate changes occur during the course of the treatment. These effects must be considered to properly calculate the evolving skin factor.

We have developed a computer program, UTRTM (University of Texas Real-Time Monitoring), that calculates and displays the skin factor during a matrix stimulation treatment from the measured surface injection conditions. The program can be used in real-time to monitor the progress of a stimulation treatment or after completion of a treatment to analyze its effectiveness. We have used this program for a wide variety of acid treatments and found it to be extremely valuable. We present examples in this paper that illustrate how the skin analysis program can be used to optimize a particular treatment on the fly, to evaluate the effectiveness of acidizing methods applied in an area, and to quantify secondary effects, such as diversion.

SKIN FACTOR ANALYSIS

We calculate the evolving skin factor from the surface injection rate and pressure, and then diagnose the well response to acid injection from the skin factor behavior. The equations used to calculate skin factor will be discussed in this section and are listed in Table 1.

A transient inflow equation is applied to calculate the skin factor. For constant rate or constant pressure injection, the approximate solution for infinite-acting radial flow for a slightly compressible fluid[2] (Equation 1) can be rearranged to show that inverse injectivity ($\Delta p/q$) is a linear function of log(t) (Equation *2)*, with a slope and intercept given by Equations 3 and 4. Since the injection rate is usually changing during an acid treatment, we use superposition theory to account for the effect of changing injection rate. For this case, log(t) is replaced by a superposition time function (Equations 5 and 6). By monitoring inverse injectivity versus time, the intercept b can be calculated at any time, with the constant slope m calculated before the treatment by Equation **3.** Then, skin factor is calculated by Equation 7[3].

When surface pressure is measured, we convert surface pressure to bottomhole pressure first. If stages of different fluids are injected, each stage is tracked down the injection tubing to correctly calculate the bottomhole pressure[4] (Equations 8 and 9). If an annulus pressure is monitored instead of the tubing injection pressure, the bottomhole injection pressure is obtained simply by adding the hydrostatic head of the annulus fluid column to the surface annulus pressure (Equation 10).

For gas reservoirs, the transient inflow relationship is given by Equation 11 and the slope m is now as shown in Equation 12[5]. The intercept b is the same as for slightly compressible reservoirs (Equation 4) and skin factor is again calculated by Equation 7.

For horizontal wells, transient pressure behavior is still described by Equation 5, but the slope m, the intercept b, and the superposition time Δt_{sup} in the equation are different. Two of the several transient flow theories for horizontal wells, the early-time linear flow model and the semi-infinite slab model, have been implemented in UTRTM[6]. Equations **13** - 15 are the definitions for the slope, the intercept and superposition time function for the early-time linear model, while

Equations 16 - 18 comprise the semi-infinite slab model. For either horizontal well model, the skin factor is calculated from the intercept b, as for vertical wells.

When the viscosity of the injected fluid is different from that of the reservoir tluid, there will be a viscous effect that alters the skin factors. The viscous skin can be calculated by Equations 19-21, and the true damage skin for this case is calculated by Equation 22.

UTRTM PROGRAM

Program UTRTM[7] was designed to monitor the skin factor evolving during a matrix acidizing treatment, thereby allowing the operator to optimize the stimulation job during the treatment. The program includes a vertical well model and a horizontal well model. Since the bottomhole pressure is required to calculate skin factor, the program converts surface pressure or annular pressure to bottomhole pressure when bottomhole pressure is not directly measured. The program consists of three parts, pre-treatment test, real-time monitoring, and post-treatment study.

Pre-Treatment Test. This section estimates permeability and initial skin by a simple injectivity test. The pre-treatment test can be conducted during injection of an inert fluid, but before any reactive fluid injection. The pressure from the test has to be bottomhole pressure. **A** pretreatment test is always recommended even when initial skin and permeability arc known from other sources. An example of such a test by UTRTM is shown in Fig. 1. The calculated permeability will be used automatically in the following calculations unless overwritten by the user.

Real-Time Monitoring. This section processes the real-time field data, and calculates the skin factor at each selected time increment. The options for monitoring skin factor in UTRTM include well type (vertical well or horizontal well), pressure measured (surface pressure, annulus pressure or bottomhole pressure), formation fluid type (oil or gas) and the input time format. Fig. 2 shows the Options panel. The injection schedule table on Fig. *2* gathers the injection fluid data for converting surface pressure to bottomhole pressure. When monitoring in real-time, the injection schedule input is only an estimate and will be overwritten by the actual data acquired; for post-treatment study, the injection schedule must be accurate in order to correctly track each injection sequence.

The information about the reservoir, fluid, and wellbore required in the calculation of pressure drop in the tubing and also skin factor are listed in the Reservoir/Wellbore Information panel of the program **(Fig.** 3). In this list, permeability and initial skin factor can be estimated from a pre-treatment test. The most sensitive parameter in the skin calculation procedure is the reservoir pressure. Since the value of reservoir pressure obtained often has some error, it can always be adjusted during the skin calculation until a reasonable result is obtained.

The main section for real-time monitoring in UTRTM is shown in Fig. **4.** The main panel has a spreadsheet that contains the treatment data and the calculated skin factor, and **4** graphics boxes for plots of inverse injectivity vs. superposition time function (Dt_{sup}), the skin evolution, flow rate vs. time, and bottomhole pressure vs. time. At each time step, a set of time, flow rate and pressure data can be either typed in, or input through an automatic data acquisition section, to the spreadsheet. The bottomhole pressure (in case it is not measured) and the skin factor will be calculated by the theory presented before. During the monitoring calculation, only one plot, the skin evolution, will be displayed with the most recent 50 data points. The range of the time-axis changes as time progresses. The other plots can be viewed at any time by selecting a built-in function.

During a treatment, the trend of skin factor change is more important than the actual value of skin factor calculated. In general, a decreasing skin factor indicates a positive response to stimulation. An increasing skin could be caused by either a positive response to diversion or additional damage caused by injection of the treatment fluids into the formation. A leveled-out skin trend means that stimulation has approached its limit and injection of acid should be terminated.

Post-Treatment Study. Post-treatment study is designed to review an acidizing treatment after it is completed. **A** previously saved file containing time, injection rate, and pressure data from an acidization treatment can be opened, and the analysis of the skin factor for the entire treatment can be re-performed. The conclusions drawn from post-treatment study can be used to improve subsequent treatment design. This feature of UTRTM has proven very useful for studying acidizing performance for a field or a region.

Data Acquisition. An automatic data acquisition system has been built into the program to transfer data on-site from a service company data acquisition system to a computer. The data format used in the program is compatible with the output data provided by the major service companies.

FIELD EXAMPLES

Successful sandstone acidizing treatment. The first example illustrates an almost ideal response to acidizing in a sandstone reservoir'. The example well was a water-disposal injection well and was treated with a 30 bbl preflush of 15 wt% HCI, followed by 60 bbl of 3 wt% HF, 12 wt% HCI, displaced with a 2 wt% NH_4Cl solution. No diversion methods were used.

Figure 5 is the rate/pressure record for this treatment, and Fig. 6 shows the skin factor response generated by UTRTM. The initial skin factor for this well was about 110 and remained constant while the normal injection water was displaced from the tubing by the HCI preflush. The skin factor then decreased gradually in response to the HCI preflush, with the decrease beginning after about 12 bbl of HCI should have reached the formation. The response to the HF/HCl stage was more pronounced, but, again, with a delay from when HF first reached the formation. Skin factor became constant at near zero at the end of the treatment when the NH_4Cl solution had displaced the mud acid from the near wellbore vicinity.

This treatment showed an obvious, pronounced decrease in skin factor in response to both the HCI preflush and the HF/HCI mud acid stages. The final skin factor of near zero showed that the designed acid volume, which was only 7 gal/ft of mud acid, was sufficient to regain the natural conductivity of the undamaged reservoir (skin = 0) with a matrix acidizing treatment.

Excessive HF/HCl injection in sandstones. Sometimes, excessive acid not only increases the cost of stimulation, but also results in additional damage to sandstone formations. Either precipitation of reaction products or unconsolidation of the formation can cause decreased near-wellbore permeability when acidizing a sandstone formation. Fig. 7 shows the skin response of an acid treatment for such a case[4]. After the acid entered the formation, the skin factor decreased rapidly from 15 to around 2. Continued injection increased the skin gradually from 2 to 5, possibly due to the precipitation of reaction products. This could be prevented if the injection was stopped when the skin response became flat.

In more extreme cases, excess acid could cause severe damage to the formation, and greatly increase the skin effect. Fig. 8 shows the skin plot for a failed acid treatment. The formation responded to the acid injection at the beginning of the treatment. The skin factor decreased from 5 to close to zero. The next 30 minutes of injection did not add any significant benefit to the stimulation, as indicated by the skin factor remaining constant at near zero. Then, the skin factor increased gradually for the next 20 minutes, almost reaching the initial skin. At 80 minutes of injection, severe damage apparently occurred, as the skin factor increased abruptly. The treatment was stopped because of a high bottomhole pressure, which also indicated possible damage to the formation. In this well, what could have been a successful stimulation treatment became a failure because of excessive acid injection. Such failures can be prevented by monitoring the skin evolution in real-time and stopping acid injection when a skin increase is observed.

Evaluation of diversion. Multiple diversion stages are designed in multi-layer formations to extend the acid coverage to every layer of the formation. This is an example of multi-stage diversion used in a Gulf of Mexico oil producer'. The treatment consisted of four stages of acidizing, with stages of diversion between each acid injection. The spacer used was NH_4Cl, and the diverter was HEC w/#650 sand. The initial skin was about 32. The formation is relatively thick (98 ft).

Effective diversion is indicated during injection by an increase in the apparent skin factor, because the diverter must generate additional pressure drop to divert fluids to other parts of the formation. Fig. 9 is the skin plot during the treatment for this example. It shows that the first acid stage reduced the skin effectively. The well responded to each diversion stage positively, especially the first diversion. Each acid stage after diversion further treated the well, including the last acid stage, which brought the skin factor down from 40 to about 30. Even though the final skin was not much lower than the initial skin, since most of the final skin was contributed by the first diversion, it is expected that back flushing will reduce the final skin to a lower number (close to zero).

Acidizing response of a gas well. The next example illustrates the viscous skin effect that occurs when acid is injected into a gas well. The well was located offshore Brazil and was producing 187,000 m^3/d of gas before the acid treatment with a damage skin factor of 12. Since the viscosity of acid is much higher than that of gas, a viscous skin factor will develop as the bank of relatively viscous acid moves into the formation'. When acidizing gas wells, this viscous skin can obscure the changes in the damage skin factor, and should be subtracted from the apparent total skin factor. Figure 10 shows the total skin factor measured with UTRTM for this well. The actual damage skin is obtained by subtracting the viscous skin factor from the total skin (Equation 22). Without considering the viscous skin effect, the total skin response suggests that the acid damaged the formation, as indicated by the increase from 12 to over 25. However, when the viscous skin factor is subtracted, the true damage skin is revealed to have decreased from 12 to near zero. In fact, this response was confirmed by the post-treatment production rate of 731,000 m^3/d.

CONCLUSIONS

A PC program, UTRTM, has been developed to monitor the skin factor evolution during a matrix acidizing treatment or to evaluate a treatment that has already been performed. The program has proven extremely valuable in optimizing acid treatments.

Monitoring the skin response in real-time allows the operator to prevent deleterious effects of over-treating the formation, to evaluate diversion, and to plan future treatments in the area more effectively.

NOMENCLATURE

b = intercept
B = formation volume factor
c_t = total compressibility
D = tubing diameter
f_f = friction factor
g = acceleration of gravity
g_c = gravitational constant
h = reservoir thickness
h_s = coordinate of wellbore location in z-direction for horizontal model
h_x = length of the flow field for horizontal model
h_z = height of the flow field for horizontal model
k = permeability
k_x = permeability in x-direction
k_y = permeability in y-direction
k_z = permeability in z-direction
L = length of tubing
L_j = length of tubing occupied by fluid j
L_w = length of horizontal well
L_{xd} = left coordinate of wellbore in x-direction for horizontal model
L_{xl} = right coordinate of wellbore in x-direction for horizontal model
m = slope
p_i = initial reservoir pressure
p_{ti} = surface tubing injection pressure
p_{wi} = bottomhole injection pressure
p_{sc} = standard pressure
q = flow rate
r_{acid} = radial penetration of acid
r_w = wellbore radius
r_w' = equivalent wellbore radius
s = skin factor
s_{app} = apparent skin factor
s_d = damage skin factor
s_{vis} = viscous skin factor
t = time
t_D = dimensionless time

T = temperature
T_{sc} = standard tempeature
V_{acid} = acid volume
z_1 = gas compressibility factor
a = well inclination from vertical
Dp = tubing pressure drop
Dt_{sup} = superposition time
f = porosity
m = fluid viscosity
m_{gi} = gas viscosity at initial pressure
m_{acid} = acid viscosity
m_g = gas viscosity
r_j = density of fluid j

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$$p_{wi} - p_i = \frac{162.6qB\mu}{kh}\left(\log(t)+\log\left(\frac{k}{\phi\mu cr_w^2}\right)-3.23+0.87s\right) \qquad (1)$$

$$\frac{p_{wi}-p_i}{4} = m\,log(\,t\,)+b \qquad (2)$$

$$m = \frac{162.6B\mu}{kh} \qquad (3)$$

$$b = m\left(\log\left(\frac{k}{\varphi\mu c_t r_w^2}\right)-3.23+0.87s\right) \qquad (4)$$

$$\frac{p_{wi}-p_i}{q} = m\Delta t_{sup} + b \qquad (5)$$

$$\Delta t_{sup} = \sum_{j=1}^{N}\frac{q_j - q_{j-1}}{q_N}\log\left(t_N - t_{j-1}\right)$$

$$p_{wi} - p_i = \frac{162.6qB\mu}{kh}\left(\log(t)+\log\left(\frac{k}{\phi\mu cr_w^2}\right)-3.23+0.87s\right) \qquad (6)$$

$$s = \frac{1}{0.87}\left[\frac{b}{m} - log\left(\frac{k}{\phi\mu c_t r_w^2}\right)+3.23\right] \qquad (7)$$

$$p_{wi} = p_{ti} + \Delta p \qquad (8)$$

$$\Delta p = \frac{g\sin\alpha}{g_c}\sum_i \rho_j L_j + \frac{32q^2}{g_c\pi^2 D^5}\sum_j \left(f_f\right)_j \rho_j L_j \qquad (9)$$

$$p_{wi} = p_{ann} + \frac{g}{g_c}\rho_{ann} L\sin\alpha \qquad (10)$$

$$\frac{p_{wi}-p_i}{q} = 50300\frac{z_i\mu_{gi}}{2p_i}\frac{p_{sc}}{T_{sc}}\frac{T}{kh}\left(log\left(\frac{tk}{\phi\mu c_t r_w^2}\right) - 3.23 + 0.87s \right| \quad (11)$$

$$m = 50300\frac{z_i\mu_{gi}}{2p_i}\frac{p_{sc}}{T_{sc}}\frac{T}{kh} \quad (12)$$

$$rn = \frac{8.128B\mu}{Lh\sqrt{\phi\mu c_t k_y}} \quad (13)$$

$$b = \frac{141.2qB\mu}{L\sqrt{k_v k_y}}s \quad (14)$$

$$\Delta t_{\sup} = \sum_{j=1}^{i}\frac{q_j - q_{j-1}}{q_N}\sqrt{t_N - t_{j-1}} \quad (15)$$

$$m = \frac{282.4\mu B r_w'}{h_x h_z k_y} \quad (16)$$

$$b = m\frac{h_x^2}{\pi^2 v_x}\sum_{j=1}^{N}\frac{q_j - q_{j-1}}{q_N}\sum_{n=1}^{\infty}\left[\frac{1}{n}erf\left(v_x\pi n\sqrt{t_D - t_{D,j-1}}\right)\Xi_n^2\right]$$

$$+ m\frac{hxh_z}{L_w v_z \pi}\sum_{j=1}^{N}\frac{q_j - q_{j-1}}{q_N}\sum_{l=1}^{\infty}\left[\frac{1}{m}erf\left(v_z\pi l\sqrt{t_D - t_{D,j-1}}\right)\Xi_l\cos(l\pi z_e)\right] \quad (17)$$

$$+\frac{141.2B\mu}{\sqrt{k_y k_z}L_w}s$$

$$\Delta t_{\sup} = \sum_{j=1}^{i}\frac{q_j - q_{j-1}}{q_N}\sqrt{\pi\left(t_{D,N} - t_{D,j-1}\right)} \quad (18)$$

$$s_{vis} = \left(\frac{\mu_{acid}}{\mu_g} - 1\right)\ln\frac{r_{acid}}{r_w} \quad (19)$$

$$r_{acid} = \sqrt{r_w^2 + \frac{V_{acid}}{\pi \phi h}} \quad (20)$$

$$s_{vis} = \frac{1}{2}\left(\frac{\mu_{acid}}{\mu_g} - 1\right)\ln\left(1 + \frac{V_{acid}}{\pi \phi h r_w^2}\right) \quad (21)$$

$$s_d = s_{app} - s_{vis} \quad (22)$$

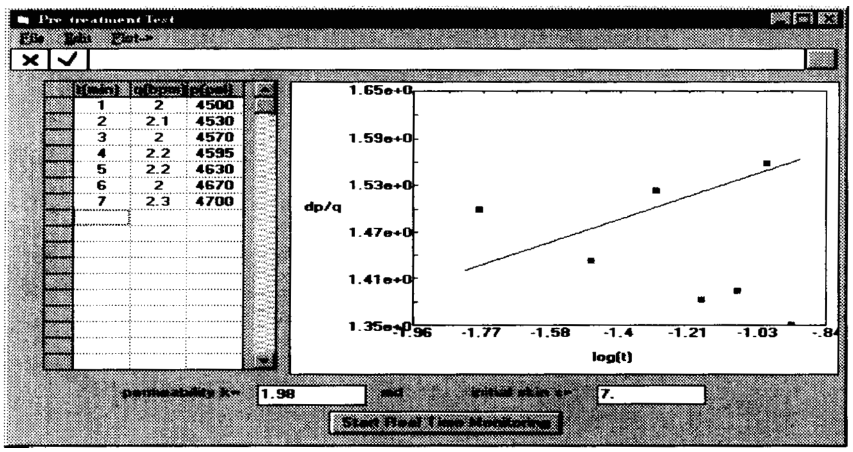


Figure 1 - Pretreatment-test Conducted **by** UTRTM

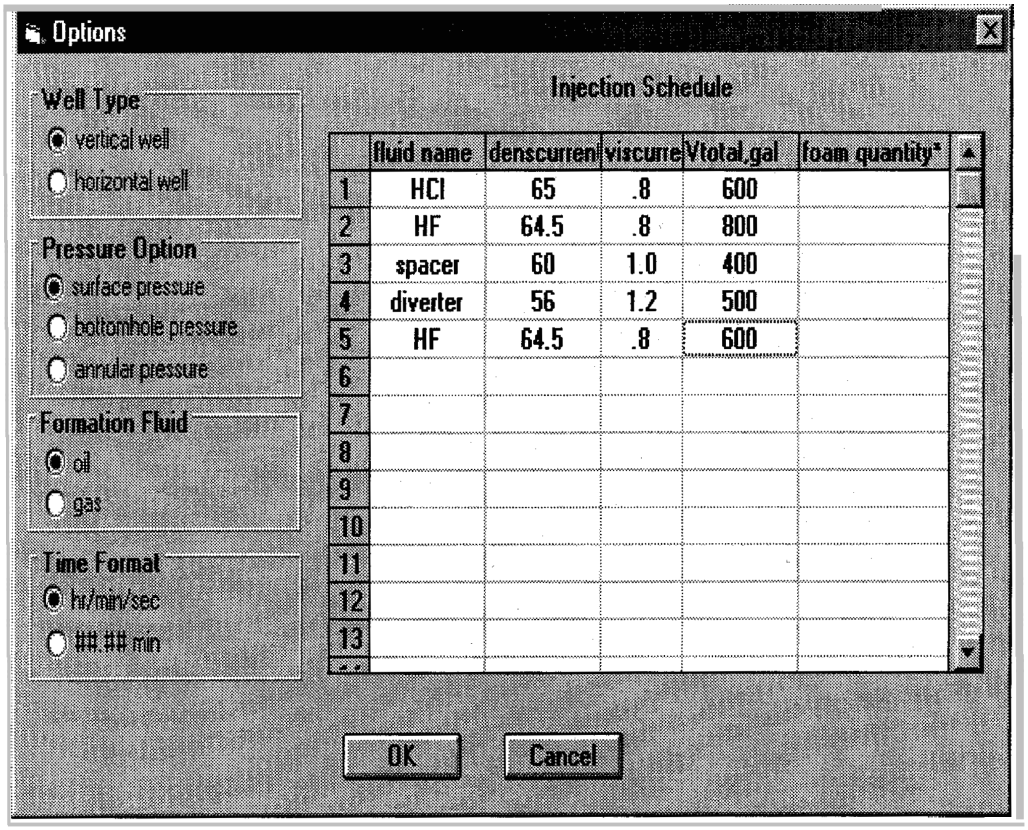


Figure 2 - The Option Panel

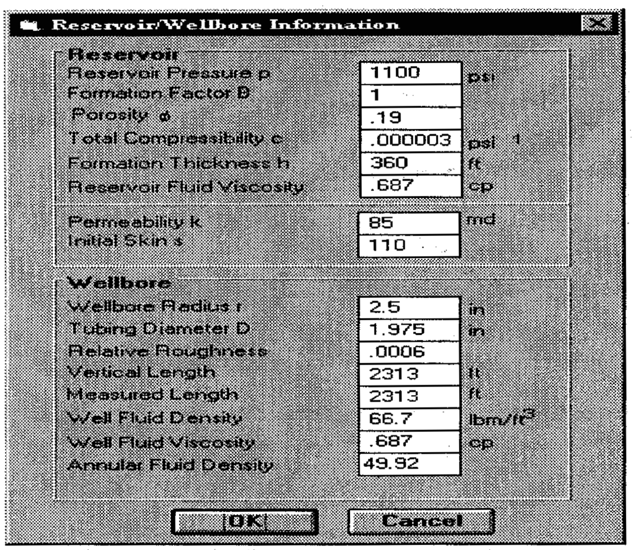
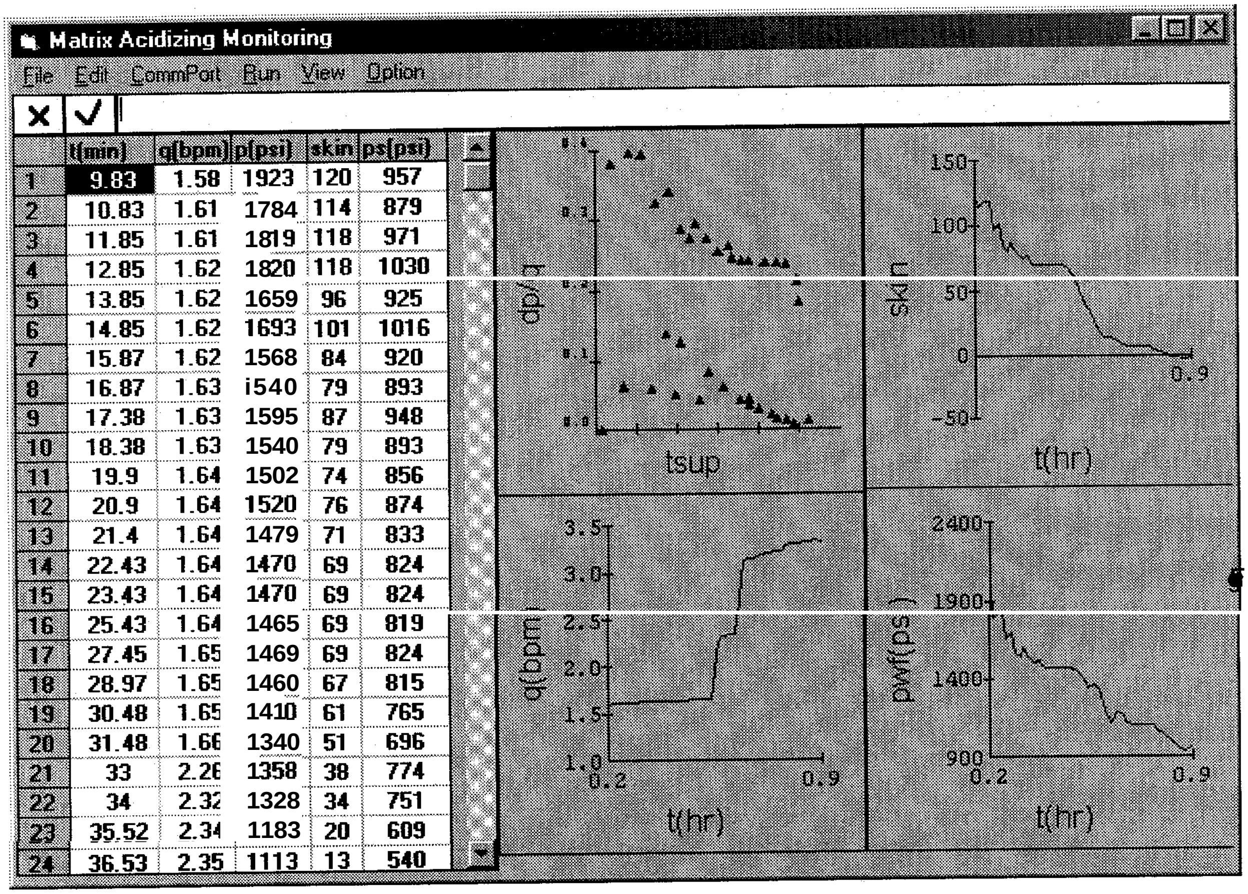


Figure 3 - The Reservoir/Wellbore Information Panel for Vertical Well



4 - The Main Panel of the UTRTM Program

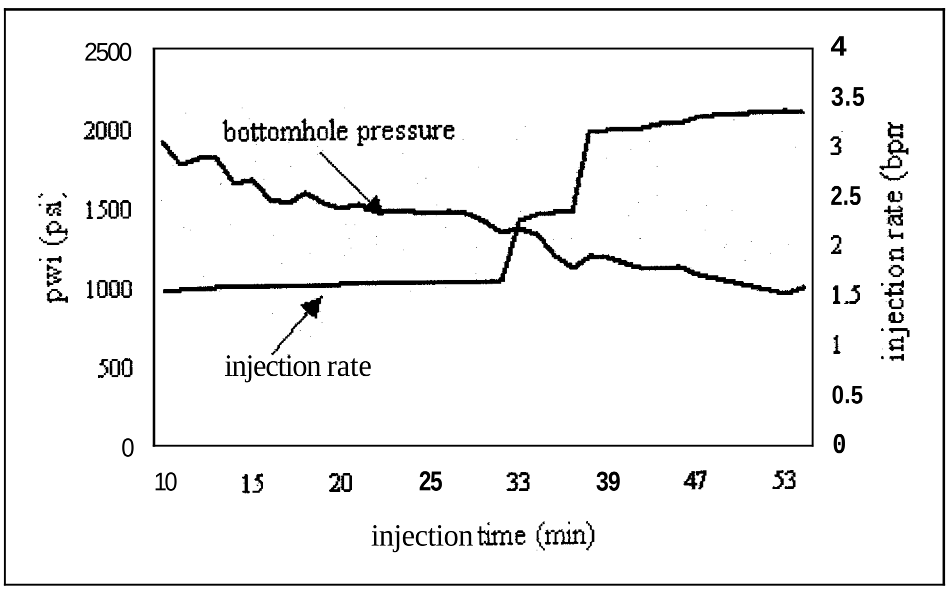


Figure *5* - **Flow** Rate and Bottomhole Pressure for Sandstone Acidizing Treatment

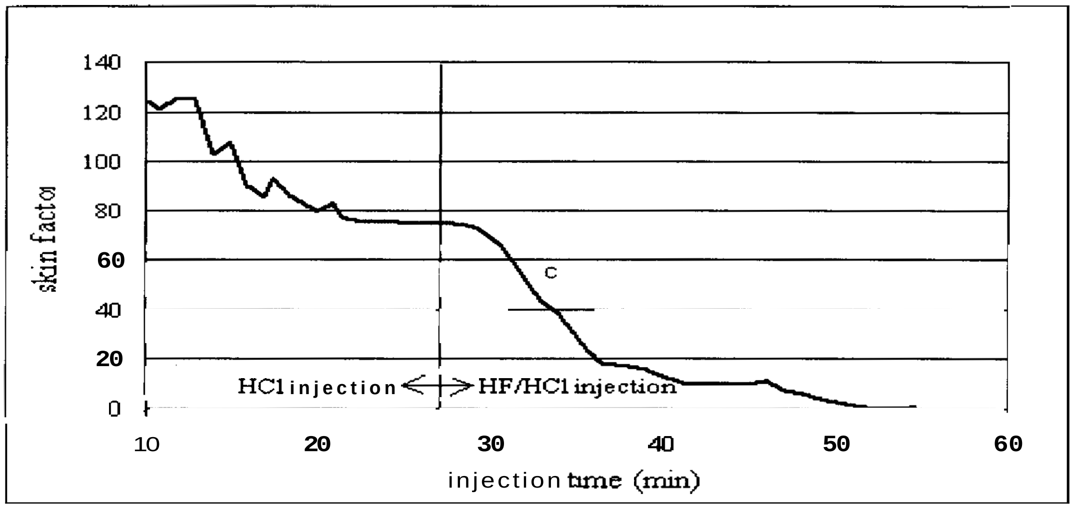


Figure 6 - Skin Response for a Successful Matrix Acidizing Treatment

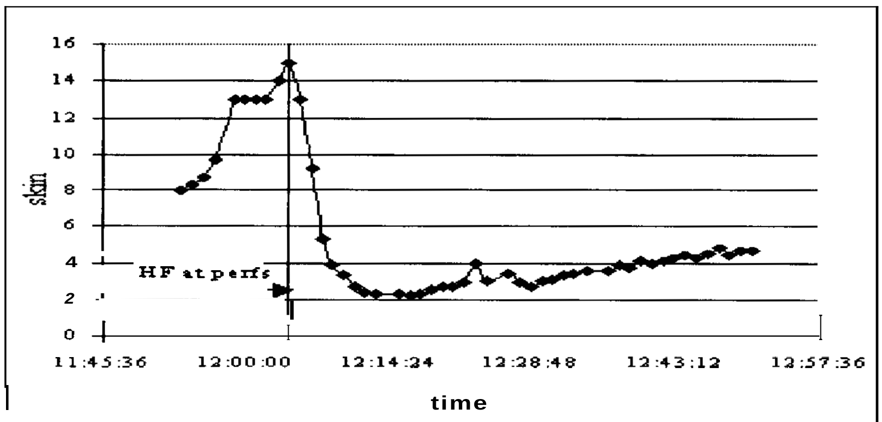


Figure 7 - Gradual Damage Caused by Excessive Acid Injection

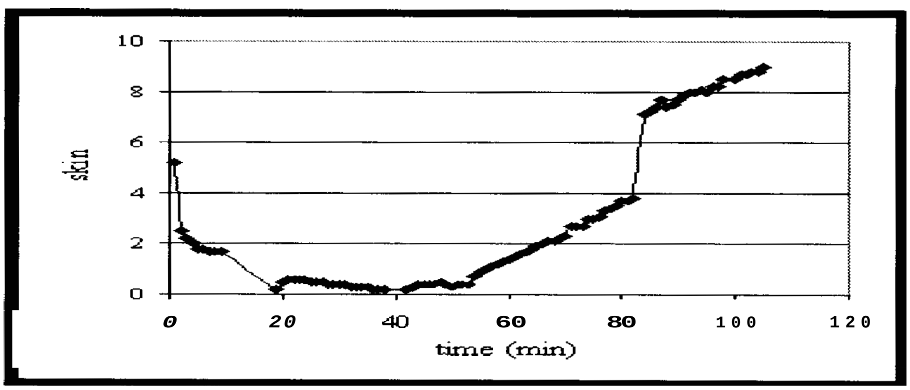


Figure 8 - Severe Damage Caused by Excessive Acid Injection

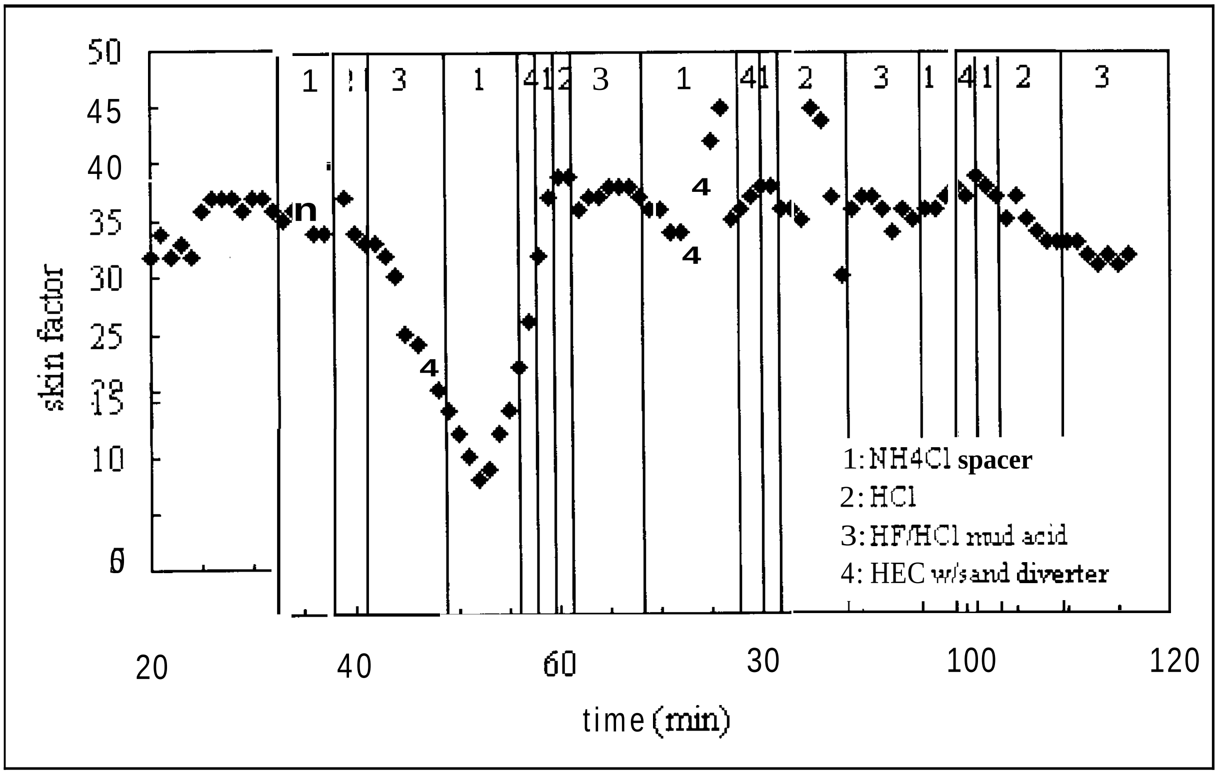


Figure 9 - Skin Response to Diverter

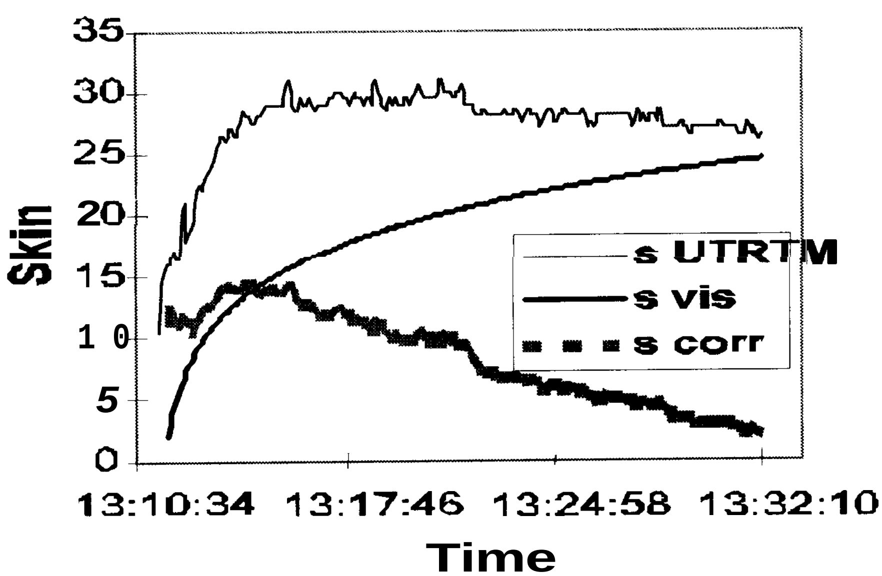


Figure 10 - Skin Factor Response of a Gas Well Illustrating Viscous Skin Effect