

# **WELL CONTROL MODEL (WELCON2)**

**THEORY AND USER'S MANUAL**

**DEA 67  
PHASE I**

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**WELL CONTROL MODEL  
(WELCON2)**

**Theory and User's Manual**

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# 1. Introduction

Well control is one of the most important aspects of drilling operations. Improper handling of kicks can result in blowouts with potential loss of life and equipment. To help prevent such disasters, Maurer Engineering Inc. has developed a well control windows application, **WELCON2**, as part of the DEA-44 Project to "Develop and Evaluate Horizontal Well Technology" and the DEA-67 Project to "Develop and Evaluate Slim-Hole and Coiled-Tubing Technology." This program is written in Visual Basic 1.0 for use with IBM compatible computers. Program **WELCON2** runs in Windows 3.0 or later versions. **WELCON2** will run with 80286 or higher processors (with math co-processors), but run times may be long with 80286 processors due to the large number of calculations (see Table 3-1).

The program describes the complex multiphase flow as a gas influx is circulated out of the well. The mathematical model consists of differential equations that are solved using finite difference methods. The model is suitable for 3D wellbores (vertical and horizontal) for inland and offshore applications. It handles both Driller's and Engineer's methods and uses Bingham plastic and power-law fluid models for frictional pressure calculations. The program allows the user to select either a single-bubble model (water-based mud only) or one of three two-phase flow correlations for handling gas migration in the wellbore. It takes into account the effect of gas solubility when oil-based mud is used.

The program calculates kill-mud weight and drill-pipe pressure schedule. It predicts pressure changes and equivalent circulating densities (ECD) at the choke, casing shoe, wellhead, at the end of the well, and at any other one point the user specifies (e.g., entrance to horizontal section). The maximum ECD along the wellbore is also calculated and compared with the pore pressure gradient and fracture pressure gradient. These results are useful for determining equipment adequacy and kick tolerance.

Every effort has been made to ensure that **WELCON2** will converge to a meaningful solution over the expected range of input variables. However, it is conceivable that the mathematical system may exhibit instability for one or more combinations of input variables. Should this occur, we would appreciate being advised of the circumstances leading to the failure of **WELCON2** and the nature of the output generated.

## 1.1 MODEL FEATURES OF WELCON2

The key features of **WELCON2** are its ability to:

1. Handle both water-based and oil-based muds.
2. Deal with 3D wellbores.
3. Select either single-bubble or one of three flow correlations.
4. Handle inland and offshore drilling rigs.
5. Handle both Driller's and Engineer's method.

6. Handle fifteen (15) sections of drill string and ten (10) well intervals.
7. Use Bingham Plastic or Power-Law models.
8. Use two-unit system: English and metric.

The output window is a compilation of child windows of text reports and graphs, which include:

1. Summary report.
2. Tabulated results.
3. Pressure or ECD at choke, drill pipe, bottom hole, casing shoe, wellhead, and user-specified point.
4. Pit gain and gas flow rate.
5. Maximum ECD along wellbore compared with pore pressure gradient and fracture pressure gradient.

## **1.2 WHAT IS NEW IN WELCON2**

1. Oil-based mud is added to the model. The effect of gas solubility in the oil-based mud is taken into account.
2. In **WELCON1**, user is required to input the gas distribution along the wellbore. In **WELCON2**, a gas kick-in model is used to calculate the distribution.
3. **WELCON2** allows user either to include gas kick-in period in the report or exclude it by selecting time origin.
4. The **TEXT REPORT** is taken out. It is consolidated into the **SUMMARY REPORT** in **WELCON2**.
5. Different curves of the same kind can be plotted on one page for easy comparison. User decides what to plot.
6. User can print or plot pit gain and gas flow rate as a function of time.

## **1.3 REQUIRED INPUT DATA**

There are four data files associated with **WELCON2**:

1. Survey data file (**.SDI**).
  - a. Directional survey data for the well. Survey must start with zero depth, zero azimuth, and zero inclination.
2. Tubular data file (**.WT1**).
  - a. Bit depth.
  - b. Casing set depth.
  - c. Pump data.
  - d. Drilling bit data.



- e. Lengths, ID and OD of drill string.
  - f. Positions and IDs of choke line, casing and open hole.
3. Parameter data file (.WP1).
- a. Shut-in data.
  - b. Gas influx data.
  - c. Original drilling mud data.
  - d. Kill-mud data.
  - e. Temperature distribution along wellbore.
  - f. Pore pressure gradient and fracture pressure gradient.
4. Project data file with the extension name (.PJT).
- The project file only stores names of three files mentioned above.

All input data saved on the disk or in memory are in the English system of units.

#### 1.4 **DISCLAIMER**

No warranty or representation is expressed or implied with respect to these programs or documentation including their quality, performance, merchantability, or fitness for a particular purpose.

#### 1.5 **COPYRIGHT**

Participants in DEA-44/67 can provide data output from this copyrighted program to their affiliates and can duplicate the program and manual for their in-house use, but this data is not to be disclosed to other parties.



## 2. Theory and Equations

### 2.1 APPROACH

Figure 2-1 illustrates the conceptual approach used to model the areas of interest in the well system. The drilling fluid, referred to as the liquid phase, is pumped into the drill pipe, flows through the bit, up the annulus, and exits through the choke. After drilling into an overpressured gas sand, the gas (kick fluid) enters the wellbore creating a two-phase mixture region. If oil-based mud is used, some of the gas will be dissolved in the mud. The rest of the gas remains as free gas if pressure is smaller than the saturation pressure. The objective of the well control is to circulate the gas out of the annulus through the choke while maintaining the bottom-hole pressure (BHP) at the formation pressure to prevent further gas influx. The gas circulation can be initiated by pumping either original drilling mud (Driller's method) or heavier kill mud (Engineer's method).

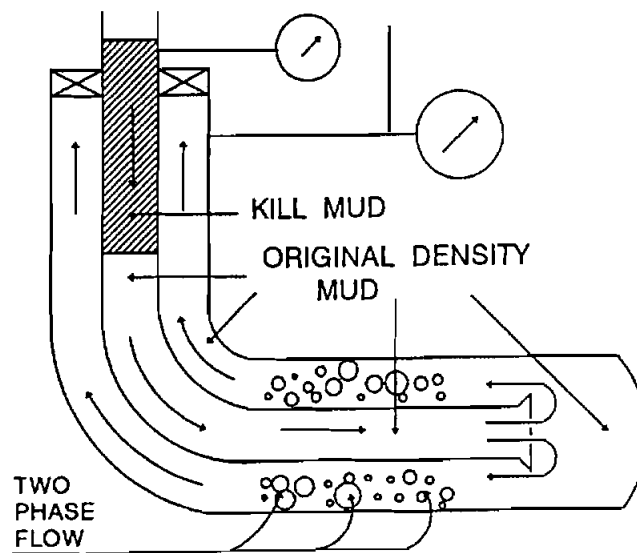


Figure 2-1. Well-Control Flow Pattern

After a gas influx (kick) has been recognized and the well is shut in, two quantities should be determined:

1. Shut-in drill-pipe pressure, (SIDPP).
2. Influx volume (pit gain).

Influx volume can be easily determined from a pit gain recording.

The formation pressure is calculated from the following equation:

$$P_i = \text{SIDPP} + 0.052 \cdot \rho_{\text{ODM}} \cdot \text{TVD}, (\text{psi}) \quad (2-1)$$

The kill-mud weight is determined by:

$$\rho_k = \frac{P_{bh}}{0.052 \cdot \text{TVD}} (\text{ppg}) \quad (2-2)$$

The bottom-hole pressure is maintained by adjusting the choke such that the drill pipe pressure follows a precalculated schedule.

A two-step procedure is used to simulate the kick behavior in the annulus. The first-step uses a kick-in model to simulate the gas kick-in process. This step ends when either pit gain reaches the specified value or the well is producing free gas before the specified pit gain is reached. The final result from this step is the gas distribution in the annulus which will be used in the next step: the kill model. In reality, there is a shut-in period between the kick-in period and the kill period. However, the shut-in period is not modeled in this program.

The kick-in model assumes that the choke is wide-open. The bottom-hole pressure is then determined by calculating the hydrostatic and frictional pressure loss in the annulus. If the calculated bottom-hole pressure is smaller than the formation pressure, gas kicks in. The gas influx rate is determined from the reservoir model. The bottom-hole pressure may increase or decrease due to the gas influx. This change in pressure will affect the influx rate. all these changes are reflected in the reservoir model.

The kill model assumes that the bottom-hole pressure is always maintained at formation pressure. There is no additional gas influx during the kill process. When kill mud fills most of the annulus, the bottom-hole pressure may have to be raised above the formation pressure to overcome the increased frictional pressure loss. The kill model consists of two parts. One is for calculating the drill pipe pressure schedule (Drill Pipe Model), another is for calculating pressure behavior in the annulus (Annulus Model). These two models will be discussed in greater detail in sections following.

## 2.2 RESERVOIR MODEL (Nickens, 1987)

During the kick-in process, the drilling continues at the rate of penetration (ROP). An increasing portion of the formation is exposed to the gas flow. To model this dynamic flow process, the formation is divided into a series of segments of thickness  $h_i$  equal to the ROP times the time step during which that segment was first exposed to the wellbore. Each time step for which the ROP is non-zero generates a

new  $h_i$ . Each segment generated is updated after each time step so that the total time of exposure of each segment is constantly increasing as the kick progresses.

Each segment is assumed to flow independently of the others for the purpose of calculating the total gas influx rate. The flow rate from the  $i$ th component is calculated from the radial flow equation:

$$q_{gi} = \frac{kh_i (P_i^2 - P_{wf}^2)}{50.35 \mu P_D P_{wf}} \quad (2-3)$$

where:

$$P_D = 0.5 [\ln(t_D) + 0.81]$$

$$t_D = 7.324 \times 10^{-8} \frac{kt_i}{\phi C_p \mu r_w^2}$$

The total gas influx rate is then

$$q_g = \sum_{i=0}^{N(t)} q_{gi} \quad (2-4)$$

where

$N(t)$	=	Total number of segments at time $t$
$k$	=	Permeability, md
$t_i$	=	Exposed time of $i$ th segments, second
$\phi$	=	Porosity, fraction
$C_p$	=	Compressibility, 1/psi
$\mu$	=	Gas viscosity, cp
$r_w$	=	Wellbore radius, ft
$P_i$	=	Formation pressure, psi
$P_{wf}$	=	Bottom-hole pressure, psi
$q_g$	=	Gas influx rate, Rcf/day

### 2.3 DRILL-PIPE MODEL

The drill string is defined here as the flow path from the mud pump (excluded) to the bit (included). It may consist of many sections of different cross-sectional areas.

The calculation of drill-pipe pressure schedule is straightforward. The following equations can be derived by referring to Figure 2-2, assuming that no gas enters the drill pipe.

$$P_{dp} = P_{bh} - \Delta P_{bit} - \Delta(P_{f,ODM} + P_{h,ODM}) - \Delta(P_{f,k} + P_{h,k}) \quad (2-5)$$

During the kick-in period,  $P_{bh}$  is calculated assuming the choke is wide-open. During the kill period,  $P_{bh}$  equals the formation pressure.

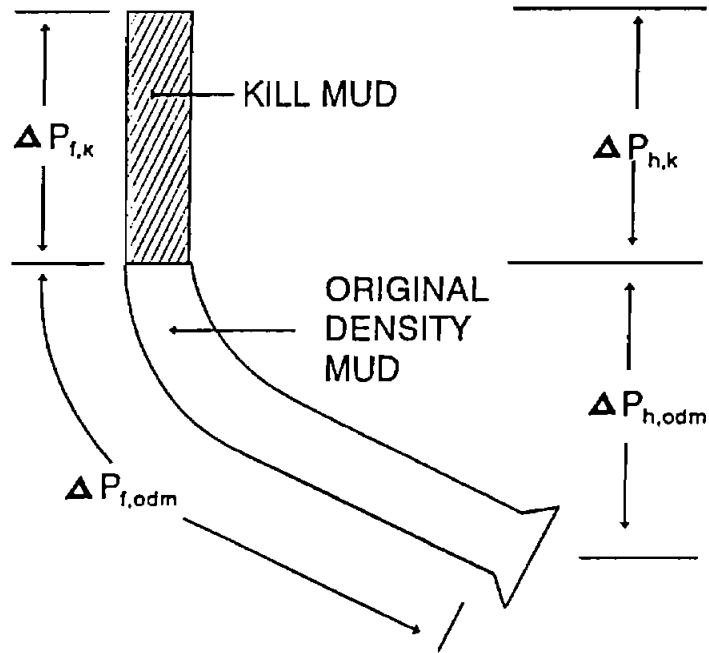


Figure 2-2. Drill-Pipe Model

The pressure loss across the bit is determined as:

$$\Delta P_{bit} = \frac{\rho q^2}{10859 \cdot A_{bit}^2} \quad (2-6)$$

The frictional pressure loss inside drill pipe and annulus is calculated using either Bingham plastic or power-law models. These two models are documented in Section 2.9.

## 2.4 ANNULUS MODEL

The annulus is defined as the flow path from the bit to the surface, which consists of 1) the annular region between the drill pipe and the casing or formation, and 2) the choke line, which is a circular pipe. As with the drill string, the annulus may have as many sections of different cross-sectional areas as desired. However, in the program, the number of sections is limited to ten.

During the course of gas circulation, there could be as many as four sections of fluids in the annulus as shown in Figure 2-3.

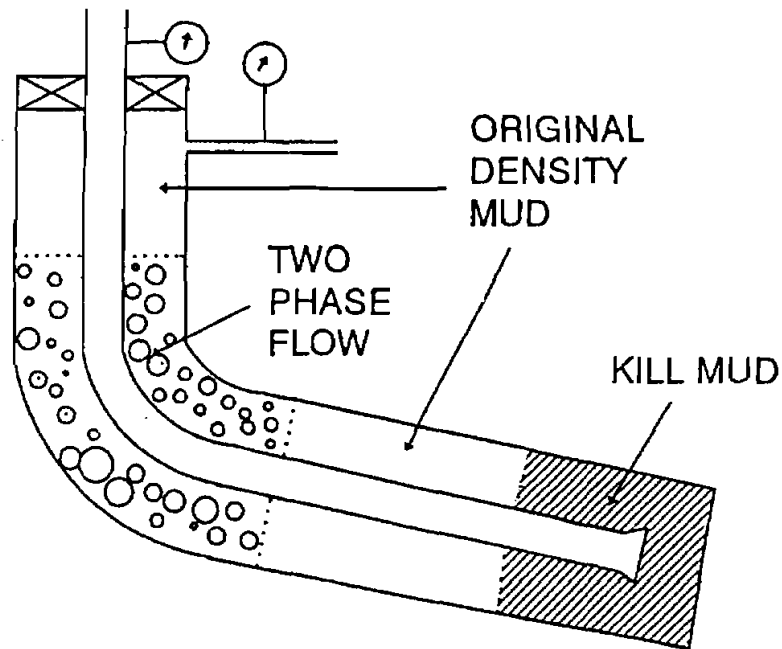


Figure 2-3. Annulus Model

The original drilling mud section preceding the kill mud does not mix with the gas in the two-phase region. The interface between them is distinct and never changes except by moving ahead with the ODM section. The two-phase mixture section includes the section with both dissolved gas and free gas (true two-phase region) and section with dissolved gas only (single-phase actually). The interface between ODM and the two-phase mixture section below is constantly changing since the gas may slip relative to the average mixture velocity and dissolved gas may move ahead due to dispersion.

The pressure drop in the liquid regions is determined the same way as for drill pipe. Either the Bingham Plastic or Power Law model is used for the frictional pressure loss calculation.

The pressure drop in the two-phase section needs special treatment. For water-based mud, two models are used for this section: 1) one treats the section as a single-bubble and 2) the other treats it as a two-phase bubble-flow region. For oil-based mud, only the two-phase flow model can be used.

Once the pressure drop in the two-phase flow-section ( $\Delta P_{fp}$ ) is determined, the pressure at the choke inlet can be calculated as:

$$P_{choke} = P_{bh} - \Delta (P_{f,k} + P_{h,k}) - \Delta (P_{f,ODM} + P_{h,ODM}) - \Delta P_{fp} \quad (2-7)$$

The pressure drop in the ODM section may include both of the sections below and above the two-phase region depending on the circulation time.

The pressure at other points of interest can be evaluated in a similar way.

## 2.5 SINGLE-BUBBLE MODEL (LeBlanc and Lewis, 1967)

As the name implies, the gas enters the wellbore at the bottom as an immiscible slug, retains constant composition, remains immiscible and undergoes no phase change. This single-bubble of gas stays at the bottom of the well when circulation begins. The length of gas column is determined by the pressure and temperature at the bottom of the column. The single-bubble model applies only to water-based mud.

Assume the pressure and temperature at the interface between the gas column and the mud below is  $P_i$  and  $T_i$ , respectively, then the gas volume is

$$V_i = \left( \frac{PV}{ZT} \right)_{bh} \cdot \left( \frac{ZT}{P} \right)_i \quad (2-8)$$

from which the gas column length can be determined. Hydrostatic head or frictional pressure loss becomes readily available.  $V$  is measured by the pit gain.

## 2.6 TWO-PHASE FLOW MODEL

During both kick-in and kill period, gas and liquid flow simultaneously in the annulus. Gas may dissolve into or evolve from the liquid phase, depending on the local pressure, temperature, and bubble-point pressure conditions. Furthermore, free gas may move faster relative to the mixture velocity due to gas slippage. To describe this complex, two-phase flow problem, a two-phase flow model is required. Eight variables will give a complete description of the system. These include gas and mud densities, liquid holdup, gas and mud velocities, pressure, temperature, and gas solubility. The temperature distribution in the annulus is assumed to be known and constant throughout the process. Then, seven equations relating the remaining variables are required to obtain a solution.



The seven equations used to describe the one-dimensional mixture system in the annulus are based on the work of Santos, 1991:

$$\frac{\partial}{\partial t} (\lambda \rho_l) + \frac{\partial}{\partial x} (\lambda \rho_l v_l) = \dot{\lambda} \quad (2-9)$$

$$\frac{\partial}{\partial t} [(1 - \lambda) \rho_g] + \frac{\partial}{\partial x} [(1 - \lambda) \rho_g v_g] = -\dot{\lambda} \quad (2-10)$$

$$0.0016 \frac{\partial}{\partial t} [\lambda \rho_l v_l + (1 - \lambda) \rho_g v_g] + 0.0016 \frac{\partial}{\partial x} [\lambda \rho_l v_l^2 + (1 - \lambda) \rho_g v_g^2] + \frac{\partial P}{\partial x} + \left(\frac{\partial P}{\partial x}\right)_f + \left(\frac{\partial P}{\partial x}\right)_h = 0 \quad (2-11)$$

$$\lambda = f(v_g, v_l, \mu_g, \mu_l, \sigma_l, \rho_l, \rho_g, d_c) \quad (2-12)$$

$$\rho_g = 0.361 \gamma_g P / (TZ) \quad (2-13)$$

$$\rho_l = \frac{\rho_l^o}{B(P, T, R_s)} \quad (2-14)$$

$$R_s = f(P, T, P_b) \quad (2-15)$$

- $\lambda$  = Liquid holdup, fraction
- $t$  = Time, seconds
- $\rho_l$  = Liquid density, ppg
- $\rho_l^o$  = Liquid density at surface conditions, ppg
- $\rho_g$  = Gas density, ppg
- $v_l$  = Liquid velocity, ft/sec
- $v_g$  = Gas velocity, ft/sec
- $x$  = Spatial dimension, ft
- $p$  = Pressure, psi
- $P_b$  = Bubble-point pressure, psi
- $\gamma_g$  = Specific gravity of gas
- $T$  = Temperature, °R
- $B$  = Formation volume factor, Rcf/Scf

Eqs. 2-9 and 2-10 are the mass-balance equations for the mud and gas, respectively. Eq. 2-11 is the momentum-balance equation for the gas/mud mixture, and Eq. 2-12 is an empirical correlation for predicting liquid holdup from velocities and liquid and gas properties. Eq. 2-13 is the EOS (equation of state for gas phase).

Eq. 2-11 is used instead of separate momentum-balance equations for each phase because of the unknown nature of the interactive forces between the gas and mud phases. This formulation of separated gas/liquid flow is one form of the "drift flux" model.

Eq. 2-14 calculates the liquid density utilizing the formation volume factor. For water-based mud, it is assumed that there is no gas dissolved in the liquid, the formation volume factor equals 1, the liquid density equals the density at the surface conditions, which is constant. As for oil-based mud, gas will either dissolve into or evolve from the liquid, thus decreasing or increasing the liquid density. The formation volume factor is calculated from the following equations (Van Slyke and Huang, 1990).

$$B = 1 + \frac{R_s}{2600 - 4.5 T} - \left( 5.1 \times 10^{-6} - (400 - T) (7 \times 10^{-9}) \right) P \quad (2-16)$$

$$+ \left( 3.8 \times 10^{-8} - (400 - T) (1 \times 10^{-10}) R_s P \right)$$

When liquid is saturated

$$B = \left( 1.028 + \frac{T - 150}{2000} \right) + 10^{-6} \left( \left( 2.15 + \frac{T - 150}{1000} \right) \frac{P}{1000} + 82 \right) P \quad (2-17)$$

Eq. 2-15 calculates the solubility under the prevailing pressure and temperature conditions. The solubility depends on the amount of gas available for dissolve. If the available gas is more than the amount required to saturate the mud, then solubility equals the value under saturated conditions, which is calculated from correlations of O'Brian et al. If the available gas is not enough to saturate the mud, all the gas will be dissolved. The solubility is determined by the material balance. Since the amount of gas dissolved depends on the liquid density, and liquid density depends on the amount of gas dissolved, two variables have to be solved simultaneously. The detailed procedure is quite involved and is not included in this manual. However, the correlation of O'Brian et al. is documented below.

## 2.7 GAS SOLUBILITY CORRELATION (O'Brian et al., 1988)

O'Brian et al. performed an experiment to determine gas solubility in the drilling fluid under different pressure and temperatures. The drilling fluid is composed of three components: oil, brine, and emulsifiers. Gas is composed of two components: hydrocarbon and CO<sub>2</sub>.

First, the solubility of individual component gas in individual component drilling fluid is estimated. The gas mixture solubility in drilling fluid mixture is calculated as being the volume weighted sum of individual solubilities.

1. The general equation for the solubility of gas in oil and emulsifiers:

$$R_{g,o,e} = \left( \frac{P}{a T^b} \right)^n \quad (2-18)$$

Where a, b and n are shown in the following table.

TABLE 2-1. Correlation of Constants

Oil	a	b	n
Hydrocarbon gas in base oil	1.922	0.2552	$0.3576 + 1.168\gamma_g + (0.0027 - 0.00492\gamma_g)T - (4.51 \times 10^{-6} - 8.198 \times 10^{-6}\gamma_g)T^2$
CO <sub>2</sub> in base oil	0.059	0.7134	1
Hydrocarbon gas in emulsifier	4.162	0.1770	$0.40 + 1.65\gamma_g - 1.01\gamma_g^2$
CO <sub>2</sub> in emulsifier	0.135	0.8217	1

2. Solubility of hydrocarbon gas in brine.

$$\begin{aligned}
 R_{g,b} &= (A + BT + CT^2) B_s \\
 A &= 5.5601 + 8.49 \times 10^{-3} p - 3.06 \times 10^{-7} p^2 \\
 B &= -0.03484 - 4.0 \times 10^{-5} P \\
 C &= 6.0 \times 10^{-5} + 1.5102 \times 10^{-7} P \\
 B_s &= \text{Exp}[(-0.06 + 6.69 \times 10^{-5}T)S]
 \end{aligned} \quad (2-19)$$

3. Solubility of CO<sub>2</sub> in brine.

$$\begin{aligned}
 R_{g,CO_2} &= (A + BP + CP^2 + DP^3) B_s \\
 A &= 95.08 - 0.93T + 2.28 \times 10^{-3} T^2 \\
 B &= 0.1626 - 4.025 \times 10^{-4}T + 2.5 \times 10^{-7} T^2 \\
 C &= -2.62 \times 10^{-5} - 5.39 \times 10^{-8}T + 5.13 \times 10^{-10} T^2 \\
 D &= 1.39 \times 10^{-9} + 5.94 \times 10^{-12}T - 3.61 \times 10^{-14} T^2 \\
 B_s &= 0.92 - 0.0229(s)
 \end{aligned} \quad (2-20)$$

4. Solubility of mixture gas in individual component drilling fluid.

$$R_{so,e,br} = (R_{sb} f_h + R_{sco_2} f_{co_2})_{o,e,br} \quad (2-21)$$

5. Solubility of mixture gas in mixture drilling fluid:

$$R_{sm} = R_{so} f_o + R_{se} f_e + R_{sbr} f_{br} \quad (2-22)$$

R — Solubility, Scf/bbl

f — Volume fraction

Subscript:

o — Oil

e — Emulsifier

br — Brine

h — Hydrocarbon

co<sub>2</sub> — Carbon dioxide

In the current version of the well-control program, it is assumed that there is no CO<sub>2</sub> in the gas, and 85% of the drilling fluid is oil and 15% is brine. There is no emulsifier in the drilling fluid.

## 2.8 SOLUTION ALGORITHM (Santos, 1991)

The two-phase flow model constitutes a nonlinear system with seven unknowns: pressure, gas and liquid velocities, gas and liquid density, liquid holdup, and gas solubility. These seven unknowns are functions of time and position along the wellbore. Numerical solutions have to be employed.

First, the one-dimensional wellbore is divided into a series of small blocks. The partial differential equation set (Eq. 2-9 to Eq. 2-15) is then discretized based on this division using finite-difference method. To accommodate the cross-sectional area variation in the annulus, it is required that a block cannot span two sections with different cross-sectional areas. This guarantees that the boundaries between different sections are boundaries of blocks. Furthermore, each section of constant cross-sectional area can be divided into smaller blocks according to the calculation interval specified by the user. An example is shown in Figure 2-4.

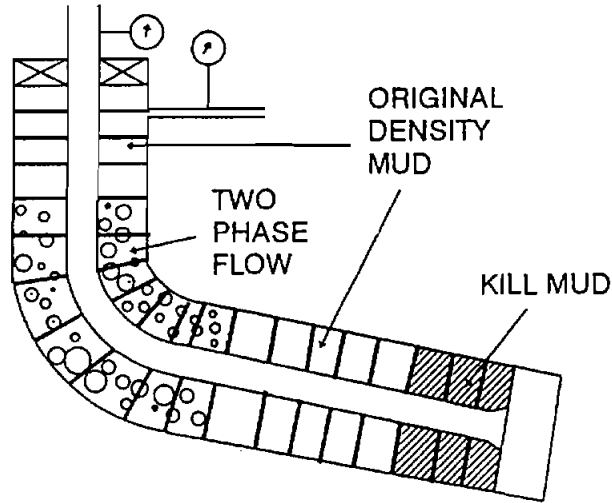


Figure 2-4. Example Annulus Division

### 2.8.1 Finite Difference Equations

The finite difference approximation of Eq. 2-9 to 2-15 can then be written as:

$$\frac{\Delta x_i}{\Delta t_k} \left[ (\lambda \rho_1)^{k+1} - (\lambda \rho_1)^k \right]_i = (\lambda v_1 \rho_1)_{i-1}^{k+1} - (\lambda v_1)_i^{k+1} + \dot{\chi}_i^{k+1} \quad (2-23)$$

$$\frac{\Delta x_i}{\Delta t_k} \left( [(1-\lambda)\rho_g]^{k+1} - [(1-\lambda)\rho_g]^k \right)_i = [(1-\lambda)\rho_g v_g]_{i-1}^{k+1} - [(1-\lambda)\rho_g v_g]_i^{k+1} - \dot{\chi}_i^{k+1} \quad (2-24)$$

$$0.0016 \frac{\Delta x_i}{\Delta t_k} \left( \left[ \lambda \rho_1 v_1 + (1-\lambda)\rho_g v_g \right]_i^{k+1} - \left[ \lambda \rho_1 v_1 + (1-\lambda)\rho_g v_g \right]_i^k \right) = 0.0016 \left[ \lambda \rho_1 v_1^2 + (1-\lambda)\rho_g v_g^2 \right]_{i-1}^{k+1} - 0.0016 \left[ \lambda \rho_1 v_1^2 + (1-\lambda)\rho_g v_g^2 \right]_i^{k+1} \quad (2-25)$$

$$- (P_i - P_{i-1}) - \left( \frac{dp}{dx} \right)_f \Delta x_i - 0.052 \left( 0.5 \left[ \lambda \rho_1 + (1-\lambda)\rho_g \right]_i^{k+1} + 0.5 \left[ \lambda \rho_1 + (1-\lambda)\rho_g \right]_{i-1}^{k+1} \right) \Delta h$$

$$\lambda_i^{k+1} = f \left[ (v_g)_i^{k+1}, (v_1)_i^{k+1}, \mu_g, \mu_l, (\rho_g)_i^{k+1}, \rho_l, d_c \right] \quad (2-26)$$

$$(\rho_g)_i^{k+1} = 0.361 \gamma_g P_i^{k+1} / (TZ)_i^{k+1} \quad (2-27)$$

$$(\rho_l)_i^{k+1} = \rho_l^o / B(p_i^{k+1}, T_i, (R_s)_i^{k+1}) \quad (2-28)$$

$$(R_s)_i^{k+1} = f(p_i^{k+1}, T_i, (P_b)^{k+1}) \quad (2-29)$$

A fully implicit formulation is used in the above equations.

### 2.8.2 Boundary Conditions

Different boundary conditions are used for different periods. During the gas kick-in period, it is assumed the choke is fully open. The bottom-hole pressure and influx rate are determined from this condition using iterative method.

During the circulation period, the interface between the two-phase region and original mud below moves forward constantly. The conditions at the bottom boundary of the two-phase region change as well. However, the liquid holdup at the boundary always equals 1, indicating no more gas is added into the two-phase region. The pressure at the boundary is calculated from the bottom-hole pressure. Assuming the bottom/m boundary is at block j, the boundary conditions can be expressed as:

$$\begin{aligned} \lambda_j^{k+1} &= 1 \\ P_j^{k+1} &= P_{bh} - \Delta(P_{fk} + P_{h,k}) - \Delta(P_{f,ODM} + P_{h,ODM}) \\ (v_l)_j^{k+1} &= (v_g)_j^{k+1} \end{aligned} \quad (2-30)$$

The liquid velocity at the boundary is determined by pump rate and cross-sectional area at the boundary.

### 2.8.3 Initial Conditions

Initial conditions at which gas influx begins are determined based on the single-phase calculation. Before gas influx begins, the well is flowing at the normal pump rate and the choke is fully open. There is no gas in the annulus. The pressure calculation starts from choke and proceeds downward until the bottom-hole pressure is determined. This process can be expressed by the following equation:

$$P_i^o = P_{i+1}^o + \left( \frac{dp}{dx} \right)_f \Delta x_i + \left( \frac{dp}{dx} \right)_h \Delta x_i \quad (2-31)$$

#### 2.8.4 Solution Procedure

Because of the nonlinear nature of the flow equations, the solution of the system requires use of an iterative process. The following step-wise procedure is used to solve the system:

1. Estimate the pressure  $P_i^{k+1}$ .
2. Calculate gas density  $(\rho_g)_i^{k+1}$  using Eq. 2-27.
3. Calculate the gas mass transfer between liquid and gas phase, gas solubility and liquid density.
4. Estimate liquid holdup  $\lambda_i^{k+1}$ .
5. Calculate the liquid and gas velocities with Eqs. 2-23 and 2-24.
6. With the gas and liquid properties, gas and liquid velocities, liquid holdup from Step 4, and inclination angle, use two-phase flow correlations to calculate  $\lambda_i^{k+1}$ , compare this value and the estimated value in Step 4. If they are sufficiently close, go to Step 7. If not, re-estimate  $\lambda_i^{k+1}$  and repeat the process from Step 4 until convergence on liquid holdup is reached.
7. Calculate  $P_i^{k+1}$

Step 1. If they are sufficiently close, stop the process. If not, re-estimate pressure and repeat the process from Step 1 until convergence on pressure is reached.

The procedure starts from the bottom of the hole where liquid holdup is 1 and pressure equals the formation pressure. The procedure is repeated for the adjacent downstream blocks. The calculations proceed until the fluid properties at all block boundaries are determined.

Three two-phase flow correlations are used in the program. Section 2.11 documents these correlations.

## 2.9 RHEOLOGY MODEL

The models most commonly used in the drilling industry to describe fluid behavior are the Bingham plastic and power-law rheological models. They can be used to calculate frictional pressure drop, swab and surge pressures, etc. **WELCON2** is based on equations derived in *Applied Drilling Engineering* (Bourgoyne et al., 1986) and API SPEC 10.

### 2.9.1 Bingham Plastic Model

The Bingham plastic model is defined by Eq. 2-32 and is illustrated in Figure 2-5.

$$\begin{aligned}
 \tau &= \mu_p \dot{\gamma} + \tau_y & ; & \quad \tau > \tau_y \\
 \dot{\gamma} &= 0 & ; & \quad \tau_y \geq \tau \geq -\tau_y \\
 \tau &= \mu_p \dot{\gamma} - \tau_y & ; & \quad \tau < -\tau_y
 \end{aligned}
 \tag{2-32}$$

where:

- $\tau_y$  = Yield stress
- $\mu_p$  = Plastic viscosity
- $\tau$  = Shear stress
- $\dot{\gamma}$  = Shear rate

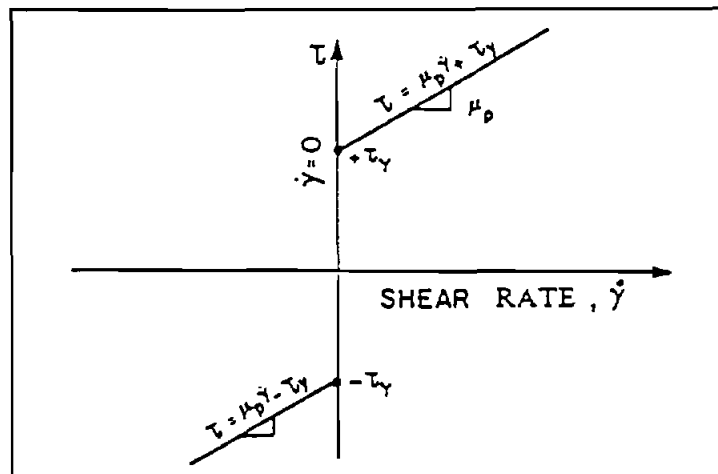


Figure 2-5. Shear Stress Vs. Shear Rate for a Bingham Plastic Fluid (Bourgoyne et al., 1986)

As shown in Figure 2-5, a threshold shear stress known as the yield point ( $\tau_y$ ) must be exceeded before mud movement is initiated.



The mud properties  $\mu_p$  and  $\tau_y$  are calculated from 300- and 600-rpm readings of the viscometer as follows:

$$\begin{aligned}\mu_p &= \theta_{600} - \theta_{300} \\ \tau_y &= \theta_{300} - \mu_p\end{aligned}\tag{2-33}$$

where:

$\theta_{600}$ ,  $\theta_{300}$  = shear readings at 600 and 300 rpm, respectively.

Calculation of frictional pressure drop for a pipe or annulus requires knowledge of the mud flow regime (laminar or turbulent).

### 1. Mean Velocity

The mean velocities of fluid are calculated by Eq. 2-34 and 2-35.

For pipe flow:

$$\bar{v} = \frac{Q}{2.448d^2}\tag{2-34}$$

For annular flow:

$$\bar{v} = \frac{Q}{2.448(d_2^2 - d_1^2)}\tag{2-35}$$

Where:

- $\bar{v}$  = Mean velocity, ft/sec
- Q = Flow rate, gal/min
- d = Pipe diameter, in.
- $d_2$  = Casing or hole ID, in.
- $d_1$  = Casing or liner OD, in.

### 2. Hedstrom Number

The Hedstrom number,  $N_{HE}$ , is a dimensionless parameter used for fluid flow regime prediction.

For pipe flow:

$$N_{HE} = \frac{37,100 \rho \tau_y d^2}{\mu_p^2}\tag{2-36}$$

For annular flow:

$$N_{HE} = \frac{24,700 \rho \tau_y (d_2 - d_1)^2}{\mu_p^2}\tag{2-47}$$

Where:

- $\rho$  = Mud weight, lb/gal

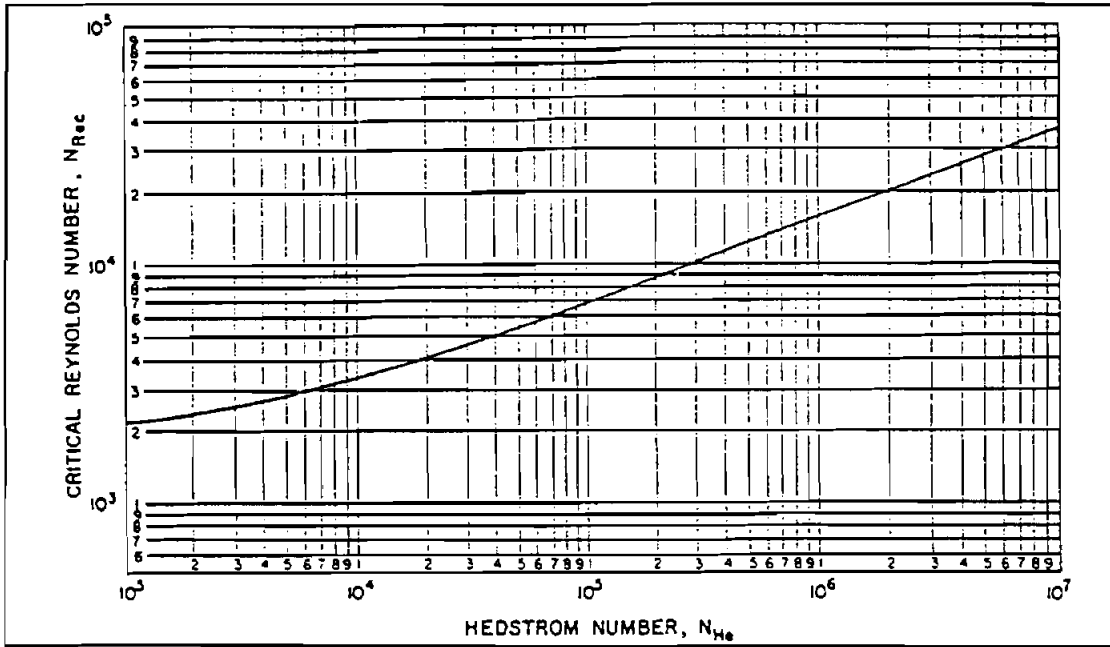


Figure 2-6. Critical Reynolds Numbers for Bingham Plastic Fluids  
(Bourgoyne et al., 1986)

### 3. Reynolds Number

Reynolds number,  $N_{Re}$ , is another common dimensionless fluid flow parameter.

For pipe flow:

$$N_{Re} = \frac{928 \rho \bar{v} d}{\mu_p} \quad (2-38)$$

For annular flow:

$$N_{Re} = \frac{757 \rho \bar{v} (d_2 - d_1)}{\mu_p} \quad (2-39)$$

### 4. Critical Reynolds Number

The critical Reynolds number marks the transition from laminar flow to turbulent flow. The correlation between Hedstrom number and critical Reynolds number is presented in Figure 2-6. The data in Figure 2-6 have been digitized in the program for easy access.

### 5. Frictional Pressure Drop Calculation

For pipe flow, the frictional pressure drop is given by:

(1) Laminar flow ( $N_{Re} < \text{Critical } N_{Re}$ )

$$\frac{dP_f}{dL} = \frac{\mu_p \bar{v}}{1500 d^2} + \frac{\tau_y}{225 d} \quad (2-40)$$

(2) Turbulent flow ( $N_{Re} \geq \text{Critical } N_{Re}$ )

$$\frac{dP_f}{dL} = \frac{f \rho \bar{v}^2}{25.8 d} \quad (2-41)$$

where  $f$  is the friction factor given by

$$\sqrt{\frac{1}{f}} = 4 \log (N_{Re} \sqrt{f}) - 0.395 \quad (2-42)$$

For annular flow, the frictional pressure drop is:

(1) Laminar flow ( $N_{Re} < \text{Critical } N_{Re}$ )

$$\frac{dP_f}{dL} = \frac{\mu_p \bar{v}}{1000 (d_2 - d_1)^2} + \frac{\tau_y}{200 (d_2 - d_1)} \quad (2-43)$$

(2) Turbulent flow ( $N_{Re} \geq \text{Critical } N_{Re}$ )

$$\frac{dP_f}{dL} = \frac{f \rho \bar{v}^2}{21.1 (d_2 - d_1)} \quad (2-44)$$

where  $f$  is determined using Eq. 2-42.

### 2.9.2 Power-Law Model

The power-law model is defined by Eq. 2-45 and illustrated in Figure 2-7.

$$\tau = K \dot{\gamma}^n \quad (2-45)$$

where:

$K$  = Consistency index, equivalent centipoise (Bourgoyne et al., 1986)

$n$  = Flow behavior index, dimensionless

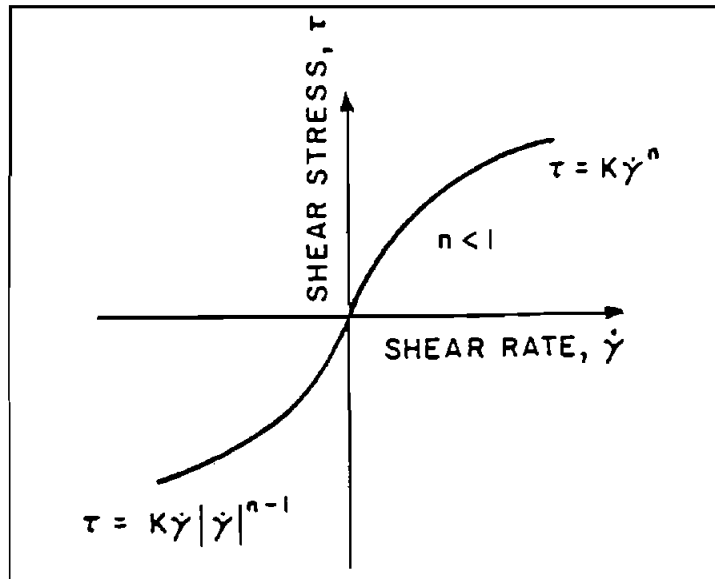


Figure 2-7. Shear Stress Vs. Shear Rate for a Power-Law Fluid (Bourgoyne et al., 1986)

The fluid properties  $n$  and  $K$  are calculated as follows:

$$n = 3.32 \log \frac{\theta_{600}}{\theta_{300}} \quad (2-46)$$

$$K = \frac{510 \theta_{300}}{511^n}$$

The critical Reynolds number must be determined before the frictional pressure drop can be calculated.

#### 1. Mean Velocity

For pipe flow:

$$\bar{v} = \frac{Q}{2.448d^2} \quad (2-47)$$

For annular flow:

$$\bar{v} = \frac{Q}{2.448(d_2^2 - d_1^2)} \quad (2-48)$$

For pipe flow:

4. Frictional Pressure Drop Calculation

behavior index  $n$ .

The critical Reynolds number can be read from Figure 2-8 for a given flow

3. Critical Reynolds Number

$$N_{Re} = \frac{109,000 p \sqrt{(2-n)} K}{0.0208 (d_2 - d_1)^n} \left[ \frac{2 + 1/n}{2 + 1/n} \right] \quad (2-51)$$

For annular flow:

$$N_{Re} = \frac{89,100 p \sqrt{(2-n)} K}{0.0416 d^n} \left( \frac{3 + 1/n}{3 + 1/n} \right) \quad (2-50)$$

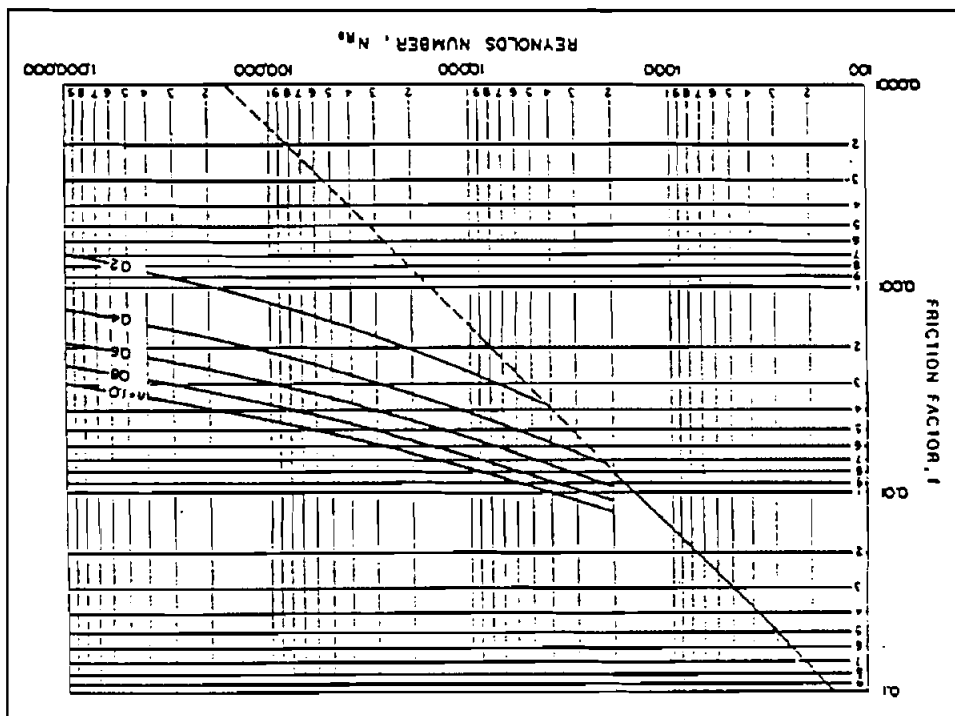
For pipe flow:

2. Reynolds Number

Critical  $N_{Re} = 2000$  for  $n > 0.45$   
 Critical  $N_{Re} = 5960 - 8800 n$  for  $0.2 \leq n \leq 0.45$   
 Critical  $N_{Re} = 4200$  for  $n < 0.2$

The data in Figure 2-8 can be approximated by the following (Leitão et al., 1990):

Figure 2-8. Friction Factors for Power-Law Fluid Model (Bourgoyne et al., 1986)



(1) Laminar flow: ( $N_{Re} < \text{Critical } N_{Re}$ )

$$\frac{dP_f}{dL} = \frac{K \bar{v}^n}{144,000 d^{(1+n)}} \left[ \frac{3 + 1/n}{0.0416} \right]^n \quad (2-52)$$

(2) Turbulent flow ( $N_{Re} \geq \text{Critical } N_{Re}$ )

$$\frac{dP_f}{dL} = \frac{f \rho \bar{v}^2}{25.8 d} \quad (2-53)$$

where the frictional factor  $f$  is given by:

$$\sqrt{\frac{1}{f}} = \frac{4.0}{n^{0.75}} \log \left( N_{Re} f^{(1-n/2)} \right) - \frac{0.395}{n^{1.2}} \quad (2-54)$$

For annular flow:

(1) Laminar flow: ( $N_{Re} < \text{Critical } N_{Re}$ )

$$\frac{dP_f}{dL} = \frac{K \bar{v}^n}{144,000 (d_2 - d_1)^{(1+n)}} \left[ \frac{2 + 1/n}{0.0208} \right]^n \quad (2-55)$$

(2) Turbulent flow ( $N_{Re} \geq \text{Critical } N_{Re}$ )

$$\frac{dP_f}{dL} = \frac{f \rho \bar{v}^2}{21.1(d_2 - d_1)} \quad (2-56)$$

where  $f$  is calculated using Eq. 2-54.

## 2.10 EQUIVALENT CIRCULATING DENSITY

Of particular importance is the equivalent circulating density (ECD) at the bottom of the hole and casing shoe. The ECD is the density of fluid that will have the same static hydrostatic pressure as the circulating pressure at a certain point (bottom of the hole), i.e.,

$$ECD = \frac{P_o}{0.052 \times TVD} \quad , \text{ (lb/gal)} \quad (2-57)$$

where

$P_o$  = pressure at the point, psi

TV D = true vertical depth at the point ft.

## 2.11 TWO-PHASE FLOW CORRELATIONS

Two-phase flow correlations are used in the model to predict the gas slippage in the annulus during the course of gas circulations. There are a number of correlations available in the industry. We selected

three of them for this well-control program. The following correlations use SI units. The pressure drop calculated from these correlations has to be converted to English units before being used in Eq. 2-11.

### 2.11.1 Beggs-Brill Correlation (Beggs and Brill, 1973)

This empirical correlation was developed from air-water two-phase flow experiments. It applies to pipes of all inclination angles. The following is the procedure to calculate the liquid holdup:

- (1) Calculate total flux rate

$$v_m = v_{sl} + v_{sg} \quad (2-58)$$

- (2) Calculate no-slip holdup

$$\lambda_{ns} = \frac{v_{sl}}{v_{sl} + v_{sg}} \quad (2-59)$$

- (3) Calculate the Froude number,  $N_{FR}$

$$N_{FR} = \frac{v_m^2}{g d} \quad (2-69)$$

- (4) Calculate liquid velocity number

$$N_{Lv} = v_{sl} \left( \frac{\rho_L}{g \sigma_L} \right)^{0.25} \quad (2-61)$$

- (5) To determine the flow pattern which would exist if flow were horizontal, calculate the correlating parameters,  $L_1$ ,  $L_2$ ,  $L_3$ , and  $L_4$ :

$$\begin{aligned} L_1 &= 316 \lambda_{ns}^{0.302} & L_2 &= 0.0009252 \lambda_{ns}^{-2.4684} \\ L_3 &= 0.10 \lambda_{ns}^{-1.4516} & L_4 &= 0.5 \lambda_{ns}^{-6.738} \end{aligned} \quad (2-62)$$

- (6) Determine flow pattern using the following limits:

Segregated:

$$\begin{aligned} &\lambda_{ns} < 0.01 \text{ and } N_{FR} < L_1 \\ \text{or} &\lambda_{ns} \geq 0.01 \text{ and } N_{FR} < L_2 \end{aligned} \quad (2-63)$$

Transition:

$$\lambda_{ns} \geq 0.01 \text{ and } L_2 < N_{FR} \leq L_3$$

Intermittent:

$$0.01 \leq \lambda_{ns} < 0.4 \text{ and } L_3 < N_{FR} \leq L_1$$

$$\text{or } \lambda_{ns} \geq 0.4 \text{ and } L_3 < N_{FR} \leq L_4$$

Distributed:

$$\lambda_{ns} < 0.4 \text{ and } N_{FR} \geq L_1$$

$$\text{or } \lambda_{ns} \geq 0.4 \text{ and } N_{FR} > L_4$$

(7) Calculate the horizontal holdup  $\lambda_o$

$$\lambda_o = \frac{a \lambda_{ns}^b}{N_{FR}^c} \quad (2-64)$$

where a, b, and c are determined for each flow pattern from the table:

Flow Pattern	a	b	c
Segregated	0.98	0.4846	0.0868
Intermittent	0.845	0.5351	0.0173
Distributed	1.065	0.5824	0.0609

(8) Calculate the inclination correction factor coefficient.

$$C = (1 - \lambda_{ns}) \ln (d \lambda_{ns}^e N_{Lv}^f N_{FR}^g) \quad (2-65)$$

where d, e, f, and g are determined for each flow condition from the table:

Flow Pattern	d	e	f	g
Segregated uphill	0.011	-3.768	3.539	-1.614
Intermittent uphill	2.96	0.305	-0.4473	0.0978
Distributed uphill	No Correction		C = 0	
All flow patterns downhill	4.70	-0.3692	0.1244	-0.5056

(9) Calculate the liquid holdup inclination correction factor

$$\psi = 1 + c [\sin(1.8\theta) - 0.333 \sin^3(1.8\theta)] \quad (2-66)$$

where  $\theta$  is the deviation from horizontal axis.

(10) Calculate the liquid holdup

$$\lambda = \lambda_o \psi \quad (2-67)$$



(11) Apply Palmer correction factor:

$$\begin{aligned} \lambda &= 0.918 \cdot \lambda && \text{for uphill flow} \\ \lambda &= 0.541 \cdot \lambda && \text{for downhill flow} \end{aligned} \quad (2-68)$$

(12) When flow is in transition pattern, take the average as follows:

$$\lambda = a \cdot \lambda_1 + (1 - a) \lambda_2; \quad a = \frac{L_3 - N_{FR}}{L_3 - L_2} \quad (2-69)$$

where  $\lambda_1$  is the liquid holdup calculated assuming flow is segregated,  $\lambda_2$  is the one assuming the flow is intermittent.

(13) Calculate frictional factor ratio

$$\frac{f_{tp}}{f_{ns}} = e^s \quad (2-70)$$

where

$$S = \frac{\ln(y)}{-0.0523 + 3.182 \ln(y) - 0.8725[\ln(y)]^2 + 0.01853[\ln(y)]^4}$$

$$\text{and } y = \frac{\lambda_{ns}}{\lambda^2}$$

S becomes unbounded at a point in the interval  $1 < y < 1.2$ ; and for y in this interval, the function S is calculated from

$$S = \ln(2.2y - 1.2)$$

(14) Calculate frictional pressure gradient

$$(N_{Re}_{ns}) = \rho_{ns} \cdot v_m \cdot d_e / \mu_{ns} \quad (2-71)$$

Use this no-slip Reynolds number to calculate no-slip friction factor using Moody's diagram,  $f_{ns}$ ; then convert it into Fanning friction factor,  $f_{ns} = f_{ns}'/4$ .

The two-phase friction factor will be

$$f_{tp} = f_{ns} \cdot \frac{f_{tp}}{f_{ns}} \quad (2-72)$$

The frictional pressure gradient is

$$\left( \frac{dp}{dx} \right)_f = \frac{2 f_{tp} \rho_{ns} \cdot v_m^2}{d_e} \quad (2-73)$$

NOTE: In the well-control model, it is assumed that when inclination angle is greater than  $45^\circ$ , there is no slippage between gas and liquid.

### 2.11.2 Hagedorn-Brown Correlation (Brown and Beggs, 1977)

The correlation used here is actually a combination of two correlations: Hagedorn-Brown correlation for slug flow and Griffith correlation for bubble flow. They apply only to vertical wells.

Check the flow regime to determine whether to continue with the Hagedorn-Brown correlation or proceed to the Griffith correlation for bubble flow.

$$A = 1.071 - \frac{0.2218 (v_{sl} + v_{sg})^2}{d_e \cdot 0.3048^2} \quad (2-74)$$

If  $A < 0.13$ , then  $A = 0.13$ .

$$B = \frac{v_{sg}}{v_{sl} + v_{sg}} \quad (2-75)$$

If  $B-A$  is positive or has a value of zero, continue with the Hagedorn-Brown correlation.

If  $B-A$  is negative, proceed with the Griffith correlation.

Griffith correlation:

$$\lambda = 1 - 0.5 \left( 1 + \frac{v_m}{v_s} - \sqrt{\left(1 + \frac{v_m}{v_s}\right)^2 - 4 \cdot \frac{v_{sg}}{v_s}} \right) \quad (2-76)$$

$$v_s = 0.8 \cdot 0.3048$$

Hagedorn-Brown correlation:

(1) Calculate liquid viscosity number and coefficient.

$$N_L = \mu_L \left( \frac{g}{\rho_L \sigma_L^3} \right)^{\frac{1}{4}} \quad (2-77)$$

$$CN_L = \frac{0.0019 + 0.0322 \cdot N_L - 0.6642 N_L^2 + 4.9951 N_L^3}{1 - 10.0147 N_L + 33.8696 N_L^2 + 277.2817 N_L^3}$$

If  $N_L < = 0.002$ , then  $CN_L = 0.0019$

If  $N_L > = 0.4$ , then,  $CN_L = 0.0115$

(2) Calculate liquid, gas velocity number, and pipe diameter number.

$$N_{LV} = v_{sl} \left( \frac{\rho_L}{g \sigma_L} \right)^{1/4}$$

$$N_{GV} = v_{sg} \left( \frac{\rho_L}{g \sigma_L} \right)^{1/4}$$

$$\phi = \frac{N_{LV}}{N_{GV}^{0.575}} \left( \frac{\bar{P}}{14.7} \right)^{0.10} \left( \frac{CN_L}{N_d} \right) \quad (2-78)$$

$$\frac{\lambda}{\psi} = \left( \frac{0.0047 + 1123.32 \cdot \phi + 729489.64 \cdot \phi^2}{1 + 1097.1566 \cdot \phi + 722153.97 \cdot \phi^2} \right)^{1/2}$$

(3) Determine the secondary correction factor correlating parameter

$$\phi = \frac{N_{GV} N_L^{0.380}}{N_d^{2.14}} \quad (2-79)$$

$$\psi = \frac{1.0886 - 69.9473 \phi + 2334.3497 \phi^2 - 12896.683 \phi^3}{1 - 53.4401 \phi + 1517.9369 \phi^2 - 8419.8115 \phi^3}$$

(4) Calculate liquid holdup

$$\lambda = \frac{\lambda}{\psi} \cdot \psi \quad (2-80)$$

(5) Calculate frictional pressure gradient.

$$\left( \frac{dp}{dx} \right)_f = \frac{2f \cdot \rho_{ns} \cdot v_m^2}{d_e} \cdot \frac{\rho_{ns}}{\rho_s} \quad (2-81)$$

$f$  = Fanning friction factor

$\rho_{ns}$  = No-slip average of densities

$\rho_s$  = Slip average of densities

NOTE: The Hagedorn-Brown correlation applies only to vertical wells. However, in the well control program, it is assumed that gas flows at the same velocity as the liquid when inclination angle is greater than 45°. As far as the sections where inclination angle is between 0 and 45°, the Hagedorn-Brown correlation is still used as if the well were vertical.

### 2.11.3 Hasan-Kabir Correlation (Hasan and Kabir, 1992)

This correlation is a recent development in multiphase flow technology. It was established based on the hydrodynamic conditions and experiment observations. It applies to flow in annulus of inclination up to 80°.

#### 1. Flow pattern identification.

The flow occurs in four different patterns depending on the superficial velocities and properties. Figure 2-9 shows a typical flow regime map for wellbores.

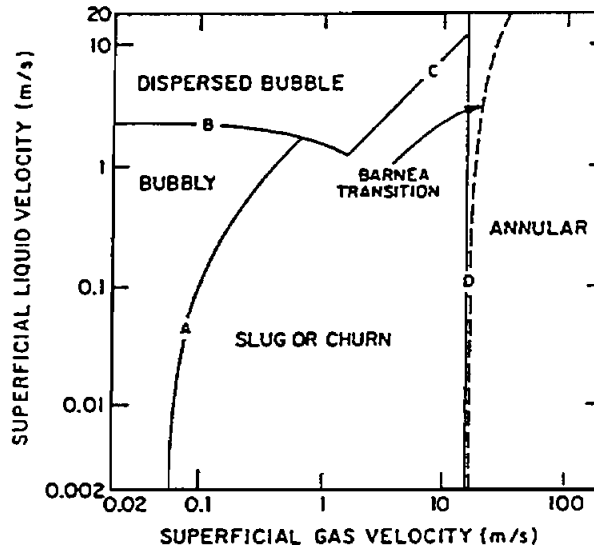


Figure 2-9. Typical Flow Regime Map for Wellbores

- a) Boundary A: transition from bubbly flow to slug or churn flow

$$v_{sg} = (0.429 v_{sl} + 0.357 \cdot v_s) \sin \theta$$

$$v_s = 1.53 \left( \frac{g \sigma_L (\rho_L - \rho_g)}{\rho_L^2} \right)^{\frac{1}{4}} \quad (2-82)$$

$\theta$ : deviation from horizontal axis.

- b) Boundary B: transition from bubbly or slug flow to dispersed bubble

$$d = \left[ 0.725 + 4.15 \sqrt{\frac{v_{sg}}{v_m}} \right] \left( \frac{\sigma_L}{\rho_L} \right)^{0.6} \left( \frac{2f v_m^3}{d_c} \right)^{-0.4} \quad (2-83)$$

$$d_c = 2 \sqrt{\frac{0.4 \sigma_L}{(\rho_L - \rho_g) g}}$$

When  $d \leq d_c$  and when superficial gas velocity stays on the left of Boundary C, the flow is in dispersed bubble.

c) Boundary C: transition from slug to dispersed bubble.

$$v_{sg} = 1.083 v_{sl} + 0.52 v_s \quad (2-84)$$

d) Boundary D: transition from slug to annular flow.

$$v_{sg} = 3.1 \left( \frac{g \sigma_L (\rho_L - \rho_g)}{\rho_g^2} \right)^{0.25} \quad (2-85)$$

2. Liquid holdup calculation.

For bubbly or dispersed bubble flow

$$\lambda = 1 - \frac{v_{sg}}{1.2 v_m + v_s} \quad (2-86)$$

For slug or churn flow

$$v_t = \left( 0.345 + 0.1 \frac{d_T}{d_c} \right) \sqrt{\sin \theta} (1 + H \cos \theta)^{1.2} \sqrt{\frac{g d_c (\rho_L - \rho_g)}{\rho_L}} \quad (2-87)$$

$$\lambda_{TB} = 1 - \frac{v_{sg}}{1.2 v_m + v_t} \quad (2-88)$$

$$a = 1 - 0.1(1.2 v_m + v_s)/v_{sg}$$

$$\lambda = 1 - (a \cdot \lambda_{TB} + 0.1) \quad \text{if } v_{sg} \geq 0.4 \quad (2-89)$$

$$a = 1 - 0.25(1.2 v_m + v_s)$$

$$\lambda = 1 - (a \cdot \lambda_{TB} + 0.25 v_{sg}) \quad \text{if } v_{sg} < 0.4 \quad (2-90)$$

For annular flow

$$f_m = \frac{v_{sg} \cdot \rho_g}{v_{sl} \cdot \rho_L + v_{sg} \rho_g}$$

$$x = \left( \frac{1 - f_m}{f_m} \right)^{0.9} \sqrt{\frac{\rho_g}{\rho_L}} \left( \frac{\mu_L}{\mu_g} \right)^{0.1} \quad (2-91)$$

$$\lambda = 1 - \frac{1}{(1 + x^{0.8})^{0.378}}$$

3. Frictional pressure gradient calculation.

For bubble, slug, or dispersed bubble flow

$$N_{Re} = \frac{\rho_L v_m d_c}{\mu_L}$$

$$f_m = \frac{0.046}{N_{Re}^{0.2}}$$

$$\rho_m = \lambda \rho_L + (1 - \lambda) \rho_g \quad (2-92)$$

$$\left( \frac{dp}{dx} \right)_f = \frac{2 f_m \cdot \rho_m \cdot v_m^2}{d_c}$$

For annular flow

$$v_{sgc} = v_{sg} \mu_g \sqrt{\frac{\rho_g}{\rho_l} / \sigma_L} \quad (2-93)$$

If  $v_{sgc} < 4 \times 10^{-4}$ , then

$$E = 0.0055 (10^4 v_{sgc})^{2.86}$$

If  $v_{sgc} \geq 4 \times 10^{-4}$ , then

$$E = 0.857 \cdot \log (10^4 \cdot v_{sgc}) - 0.2$$

$$E_{gc} = \frac{v_{sg}}{v_{sg} + E \cdot v_{sl}}$$

$$\rho_c = E_{gc} \cdot \rho_g + (1 - E_{gc}) \rho_l$$

$$fg = 0.046 \left( \frac{\rho_g v_{sg} d_c}{\mu_g} \right)^{-0.2}$$

$$ff = fg(1 + 75 \cdot \lambda)$$

$$\left( \frac{dp}{dx} \right)_f = \frac{2 \cdot ff \cdot \rho_c v_g^2}{d_c}$$

NOTE: It is assumed in the program that there is no gas slippage when inclination angle is greater than 45°. Therefore, the correlation is actually not used in this range.

## 3. Program Installation

### 3.1 BEFORE INSTALLING

#### 3.1.1 Hardware and System Requirements

**WELCON2** is written in Visual Basic®. It runs in either standard or enhanced mode of Microsoft Windows 3.0 or higher. The basic requirements are:

- Any IBM-compatible machine built on the 80286 processor or higher (with math co-processor).
- 2 megabytes of RAM; 4 megabytes is recommended.
- Hard disk.
- Mouse.
- CGA, EGA, VGA, 8514, Hercules, or compatible display. (EGA or higher resolution is recommended).
- MS-DOS version 3.1 or higher.
- Windows version 3.0 or higher in standard or enhanced mode.

These are the minimum system requirements. Due to the tremendous amount of calculations involved in **WELCON2**, we strongly recommend that **WELCON2** be run on a 80386 processor or higher with math co-processor. At least four megabytes of RAM is highly recommended. To save memory space, a scheme of overlay is used in the program; that is, part of the program is loaded into the memory when needed and unloaded from the memory when finished. To speed up this load or unload process, we strongly suggest the program be installed on a hard drive and be operated from the hard drive.

The amount of calculation (or calculation time) depends to a great extent on speed of the machine and number of intervals used, which depends on the total length of the well and the length of the calculation interval specified in **PDI File**. We have run the **TEST** files on the different machines we have with different number of intervals. The results are tabulated in the following table. As can be seen from the table, the calculation time increases by 3 to 4 times every time the length of the calculation interval is halved. **WELCON2** runs very slowly on a 80286 processor, especially the ones without math co-processor.

**TABLE 3-1. Calculation Time Comparison**

		TIME: MINUTES:SECONDS		
Calculation Interval (ft)	Number of Intervals	80486 50 MHZ (8 Meg)	80486 33 MHZ (8 Meg)	80386 25 MHZ (4 Meg)
200	28	00:10	00:14	00:40
100	57	00:27	00:44	02:01
50	115	01:26	02:17	06:29
25	230	04:41	07:16	21:09

NOTE: Math co-processor is present on all the machines. TEST files are used for these runs. Options selected: Engineer's Method, Bingham-Plastic Model, water-based mud, Hasan-Kabir correlation.

For assistance with the installation or use of **WELCON2** contact:

Weiping Yang or Russell Hall  
Maurer Engineering Inc.  
2916 West T.C. Jester Boulevard  
Houston, Texas 77018-7098 U.S.A.  
Telephone: (713) 683-8227 Fax: (713) 683-6418

### **3.1.2 Check the Program Disk**

The program disk you received is a 3½-inch, 1.44 MB disk containing twenty files. These twenty files are as follows:



```
SETUPKIT.DL_
VBRUN100.DL_
VER.DL_
COMMDLG.DLL
GSWDLL.DLL
GSW.EXE
SETUP.EXE
SETUP1.EXE
WELCON2.EXE
SETUP.LST
TEST.SDI
TEST.WT1
TEST.WP1
TEST.PJT
CMDIALOG.VBX
GAUGE.VBX
GRAPH.VBX
GRID.VBX
MDICHILD.VBX
```

We recommend that all **.VBX** and **.DLL** files that have the potential to be used by other DEA-44/67 Windows application be installed in your Microsoft **WINDOWS\SYSTEM** subdirectory. This applies to all the **.VBXs** and **.DLLs** included here. The **WELCON2** executable (**WELCON2.EXE**) file should be placed in its own directory (default "C:\WELCON2") along with the example data files **TEST.W\*IS**. All these procedures will be done by a simple setup command explained in Section 3.2.

In order to run **WELCON2**, the user must install all the files into the appropriate directory on the hard disk. Please see Section 3.2 to setup **WELCON2**.

It is recommended that the original diskette be kept as a backup, and that working diskettes be made from it.

### **3.1.3 Backup Disk**

It is advisable to make several backup copies of the program disk and place each in a different storage location. This will minimize the probability of all disks developing operational problems at the same time.

The user can use the **COPY** or **DISKCOPY** command in DOS, or the **COPY DISKETTE** on the disk menu in the **File Manager** in Windows.

## **3.2 INSTALLING WELCON2**

The following procedure will install **WELCON2** from the floppy drive onto working subdirectories of the hard disk (i.e., copy from A: drive onto C: drive subdirectory **WELCON2** and **WINDOWS \SYSTEM**).

1. Start Windows by typing "WIN" <ENTER> at the DOS prompt.
2. Insert the program disk in drive B:\.
3. In the File Manager of Windows, choose **Run** from the **File** menu. Type **B:\setup** and press Enter.
4. Follow the on-screen instructions.

This is all the user needs to setup **WELCON2**. After setup, there will be a new Program Manager Group which contains the icon for **WELCON2** as shown in Figure 3-1.

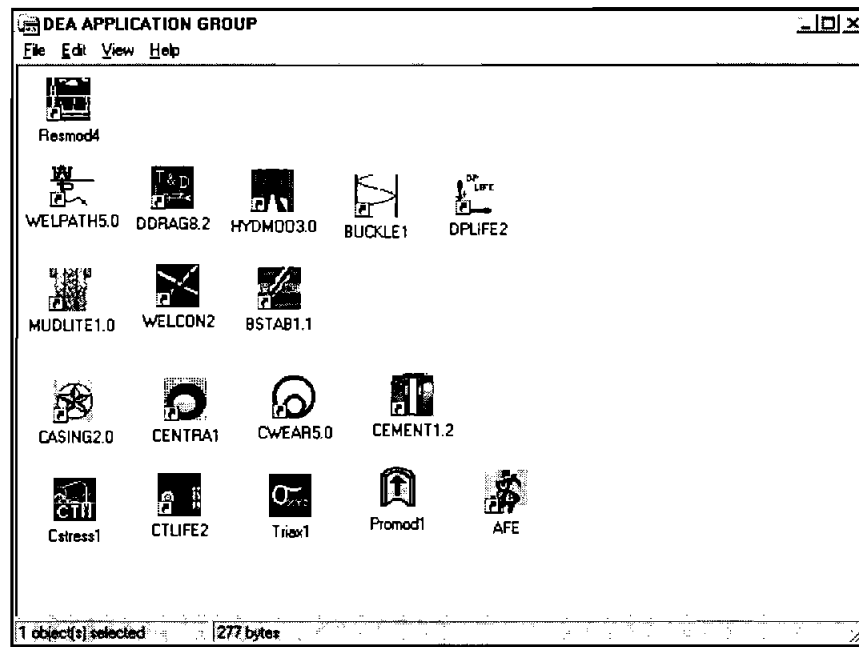


Figure 3-1. DEA APPLICATION GROUP Window Created by Set Up

### 3.3 STARTING WELCON2

#### 3.3.1 Start WELCON2 from Group Window

To run **WELCON2** from Group Window, the user simply double-clicks the "WELCON2" icon, or when the icon is focused, press <ENTER>.

#### 3.3.2 Use Command-Line Option from Windows

In the **Program Manager**, choose **Run** from the **File** menu. Then type **C:\WELCON2\WELCON2.EXE <ENTER>**.

### 3.4 ALTERNATIVE SETUP

When SETUP procedure described previously fails, follow these steps to install the program:

1. Create a subdirectory on drive C: **C:\WELCON2**.
2. Insert source disk in drive B: (or A:).
3. Type: **C:\WELCON2 <ENTER>**.
4. At prompt **C:\WELCON2**, type:  
**Copy B:\WELCON2.EXE <ENTER>**  
**Copy B:\TEST.\* <ENTER>**.
5. Type: **CD C:\WINDOWS <ENTER>**.
6. At prompt **C:\WINDOWS**, type:  
**Copy B:\VBRUN100.DL\_ VBRUN100.DLL <ENTER>**.
7. Type: **CD SYSTEM**.
8. At prompt **C:\WINDOWS\SYSTEM**, type:  
**Copy B:\\*.DLL <ENTER>**  
**Copy B:\GSW.EXE <ENTER>**  
**Copy B:\\*.VBX <ENTER>**.
9. Type: **CD.. <ENTER>** then key in "WIN" **<ENTER>** to start Windows 3.0 or later version.
10. Click menu "File" under "PROGRAM MANAGER," select item "New...," click on "PROGRAM GROUP" option, then [OK] button.
11. Key in "DEA APPLICATION GROUP" after label "Description:," then click on [OK] button. A group window with the caption of "DEA APPLICATION GROUP" appears.
12. Click on menu "File" again, Select "NEW...," click on "PROGRAM ITEM" option, then, [OK] button.
13. Key in "WELCON2" after label "Description," key in "C:\WELCON2\WELCON2.EXE" after label "COMMAND LINE," then click on [OK] button. The WELCON2 icon appears.
14. Double click the icon to start the program.



## 4. Quick Start With Example

### 4.1 INTRODUCTORY REMARKS

**WELCON2** runs in a Windows environment. It is assumed that the user is familiar with Windows, and that his or her computer is equipped with Windows 3.0 or later.

For information about Windows in a concise and convenient form, **10 Minute Guide to Microsoft Windows 3** by Katherine Murray and Doug Sabotin, published by Sams, is recommended.

In this quick start, step-by-step instructions take the user rapidly through the program. To save time and space, data will be input from prefabricated files, **TEST.SDI**, **TEST.WT1**, and **TEST.WP1**, which are included on the program disk and which were stored in directory **C:\WELCON2** during the **SETUP** process in Section 3. Later in the section, we combine these three files into a single-project file, **TEST.PJT**, which allows all three data files to be called up in a single operation.

### 4.2 GETTING STARTED

1. Call up Windows and make **DEA APPLICATION GROUP** the active window, as shown in Figure 4-1.

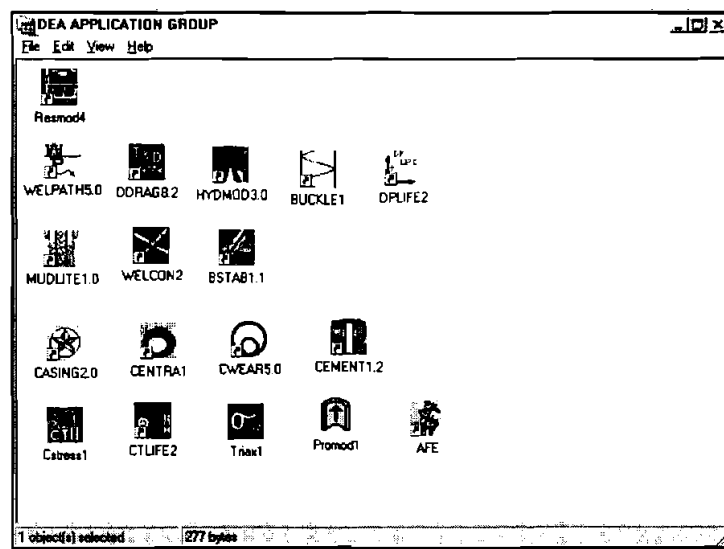


Figure 4-1. DEA APPLICATIONS GROUP Window

2. Double click on the well control icon.
3. When the information screen (Figure 4-2) appears, click on the [OK] button. This will open the Data Input Window, shown in Figure 4-3.

WELL CONTROL PROGRAM (version 2.1)

DEA-44/DEA-67  
 Project to Develop And Evaluate Horizontal  
 Drilling Technology  
 And  
 Project to Develop And Evaluate Slim-Hole And  
 Coiled-Tubing Technology  
 By  
 Maurer Engineering Inc.

This copyrighted 1993 confidential report and computer program are for the sole use of Participants on the Drilling Engineering Association DEA-44 and/or DEA-67 Projects and their affiliates, and are not to be disclosed to other parties. Data output from the program can be disclosed to the third parties. Participants and their affiliates are free to make copies of this report and program for their in-house use only.

Maurer Engineering Inc. makes no warranty or representation, either expressed or implied, with respect to the program or documentation, including their quality, performance, merchantability, or fitness for a particular purpose.

OK

Quit

Figure 4-2. Disclaimer

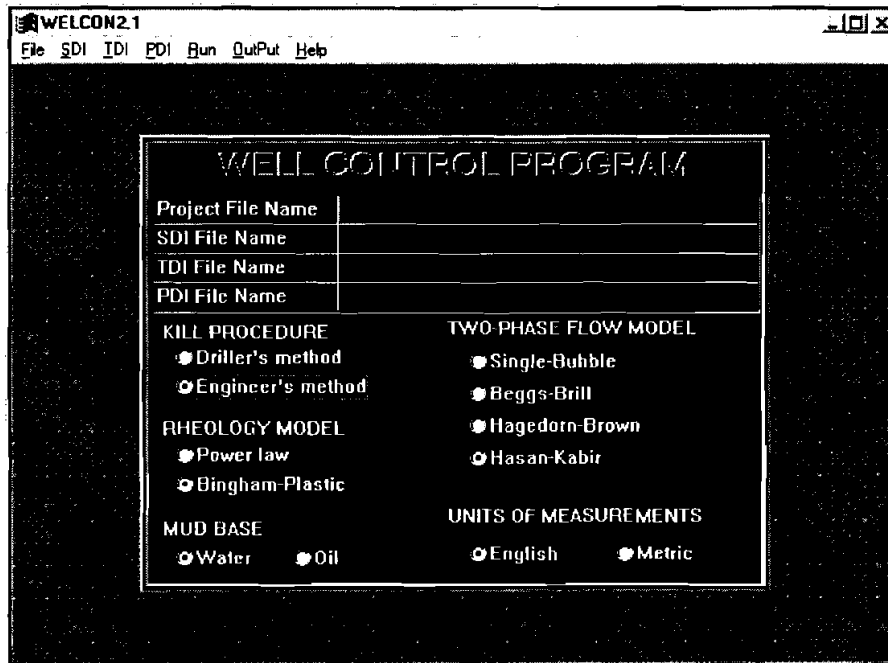


Figure 4-3. Main Menu: Data Input Window

4. When the **Data Input Window**, Figure 4-3, appears, notice that there are five sets of choices to be made in this **Data Input** window. These are:
  1. Kill Procedure – Driller's or Engineer's Method;
  2. Rheology Model – Power-Law or Bingham Plastic Model;
  3. Mud Base – Water-Based or Oil-Based Mud;
  4. Two-Phase Flow Correlation – Single Bubble, Beggs and Brill, Hagedorn-Brown, or Hasan-Kabir; and
  5. Units of Measure – English or Metric.

The user's decision is made by clicking on the button in front of each listed option. Decisions can be made any time before running the program.

If not using the mouse, move the cursor from one decision field to another by using the tab key. Move within a decision field by using the arrow keys.

5. After setting these five options, click on **SDI** in the menu bar at the top of the screen. This will open the **Survey Data Input** window, shown in Figure 4-4.

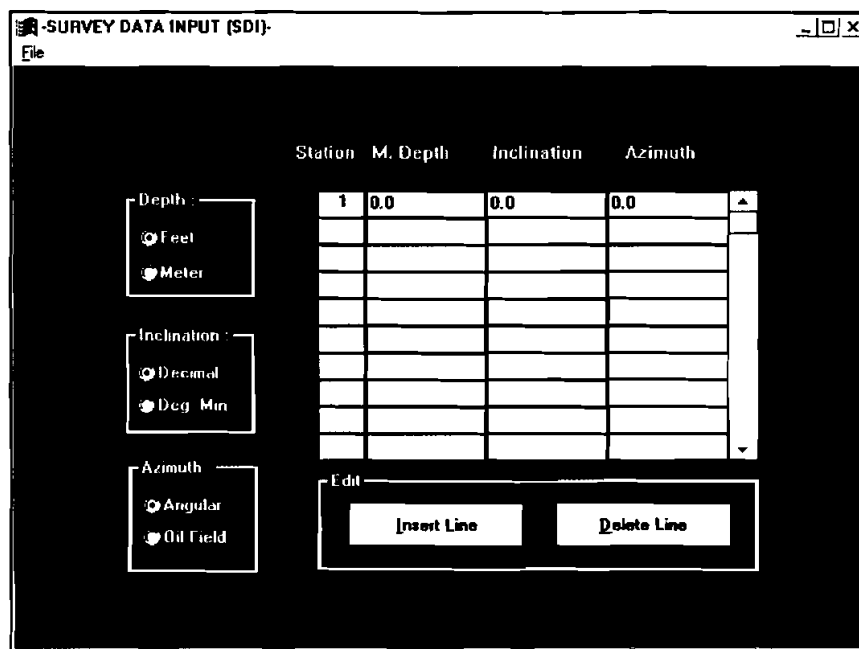


Figure 4-4. Survey Data Input Window

If not using a mouse, activate the menu bar with the <ALT> key. Use arrow keys to move along the menu bar. Use <ENTER> key to make selection.

6. When the **Survey Data Input** window opens, click on **File** as shown in Figure 4-4. This will open the **File** window, shown in Figure 4-5.

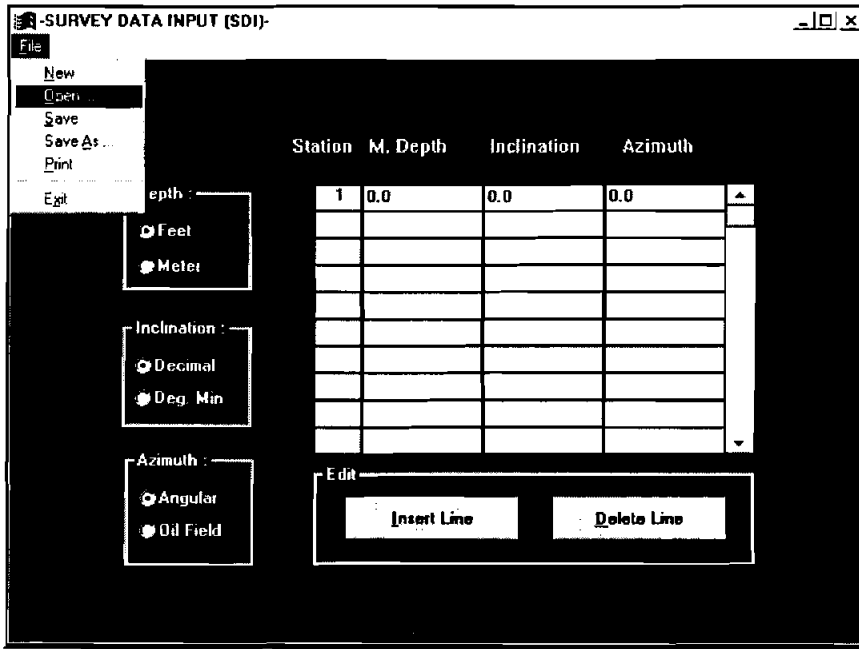


Figure 4-5. File Selection Window

- When the **File** window opens, click on **Open**. This will open the **SDI File Open** window, shown in Figure 4-6.

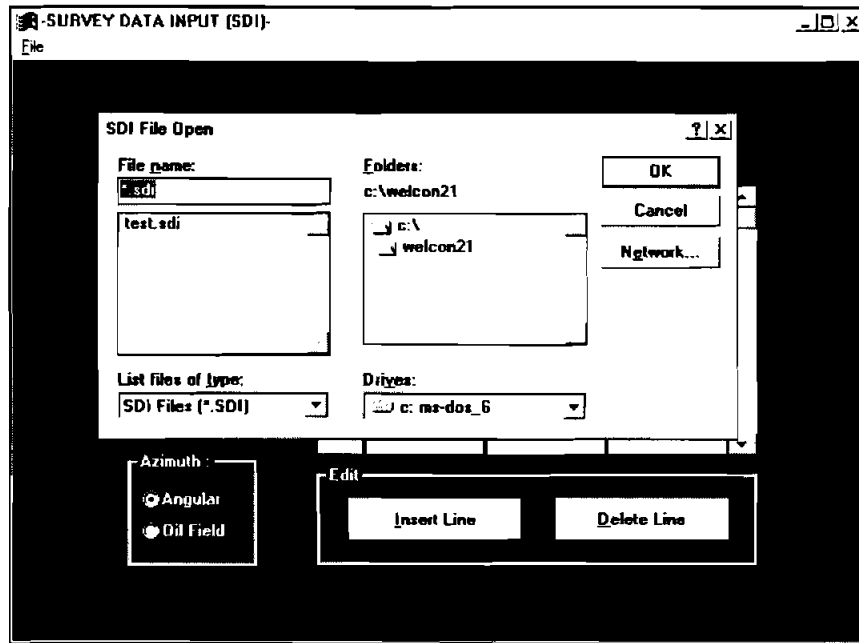


Figure 4-6. File Window



When the **SDI File Open** window opens, click on **C:\** in the **Drive** box. This will cause the list of **\*.SDI** files stored in drive **C:\WELCON2\** to appear in the **File Name** box at the upper left of the window, as shown in Figure 4-6. Now, click on **Test.SDI**, then click on **[OK]**. This will open the **Survey Data Input Window**, and fill it with data, as shown in Figure 4-7.

The screenshot shows a window titled "SURVEY DATA INPUT-C:\WELCON2\TEST.SDI". On the left, there are three groups of radio button options: "Depth" with "Feet" and "Meter" (Meter is selected), "Inclination" with "Decimal" and "Deg. Min." (Decimal is selected), and "Azimuth" with "Angular" and "Oil Field" (Angular is selected). In the center is a table with columns "Station", "M. Depth", "Inclination", and "Azimuth". The table contains 10 rows of data. Below the table are two buttons: "Insert Line" and "Delete Line".

Station	M. Depth	Inclination	Azimuth
1	0.0	0.0	0.0
2	100.0	0.0	0.0
3	200.0	0.0	0.0
4	300.0	0.0	0.0
5	400.0	0.0	0.0
6	500.0	0.0	0.0
7	600.0	0.0	0.0
8	700.0	0.0	0.0
9	800.0	0.0	0.0
10	900.0	0.0	0.0

Figure 4-7. Survey Data Input Window—Filled

Before leaving the **Survey Data Input** window, notice the three sets of options which are available. These are:

1. Depth – Feet or Meters;
2. Inclination – Decimal degrees or Degrees and Minutes; and
3. Azimuth – Angular or Oil Field Measure.

To change any of these, click on the desired option. If not using a mouse, use the tab key to move from one field to another, and use the arrow keys to move within a field. As the user moves from one value to another, the highlight will move accordingly. Default choices are Feet, Decimal, and Angular, respectively.

Before leaving this **Survey Data Input** window, set these three options to suit your needs.

8. Now, click on **File** on the menu bar above the **Survey Data Input** window. When the **File** window opens, as shown in Figure 4-8, click on **Exit**.

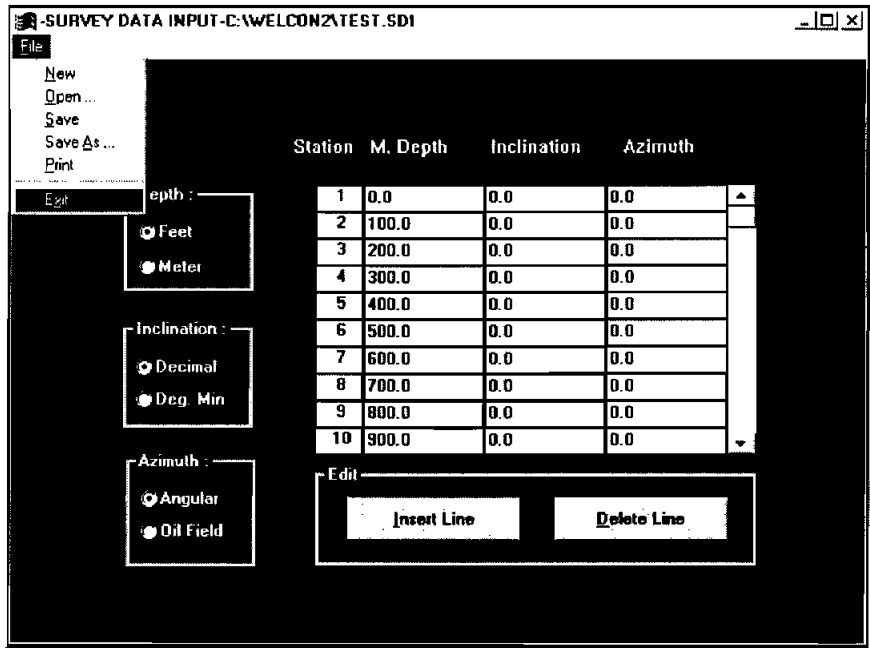


Figure 4-8. Back to File Selection Window

- This will bring back the Input Data Window with the SDI Filename box now listing C:\WELCON2\TEST.SDI, as shown in Figure 4-9.

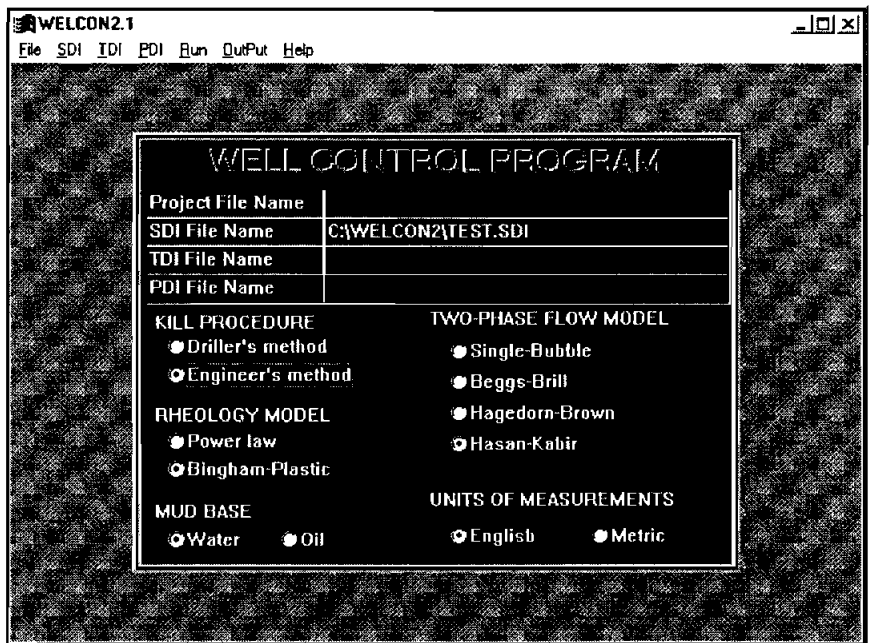


Figure 4-9. Input Data Window

- Click on **TDI** on the menu bar at the top of the window. This will open the **Tubular Data Input** window, shown in Figure 4-10. All data spaces in this window are blank.

**PUMP DATA**

Pump output (bbbls/stroke)

**NOZZLE DATA**

No of Jets      ID (32nd in)

1     

2     

3     

4     

5     

Total Area (sq. in)

**DRILL STRING DATA**

#	Description	ID (in)	OD (in)	Length (ft)	Volume (bbbls)	TOTAL
1						
2						
3						
4						
5						

\* Input from bottom up

**WELL DATA**

Big type

Land      Oil Shore

#	Description	ID (in)	Length (ft)	Volume (bbbls)	TOTAL
1					
2					
3					
4					
5					

\* Input from top down

Figure 4-10. Tubular Data Input Window

- Click on **File** at the upper left of this window. This will open the **File** windows.
- Click on **Open** in this window. This will open the **TDI File Open** window.
- Click on **Test.WT1** and then on **[OK]** in this window.
- This will reopen the **Tubular Data Input Data Input** window and fill it with numerical data, as shown in Figure 4-11.

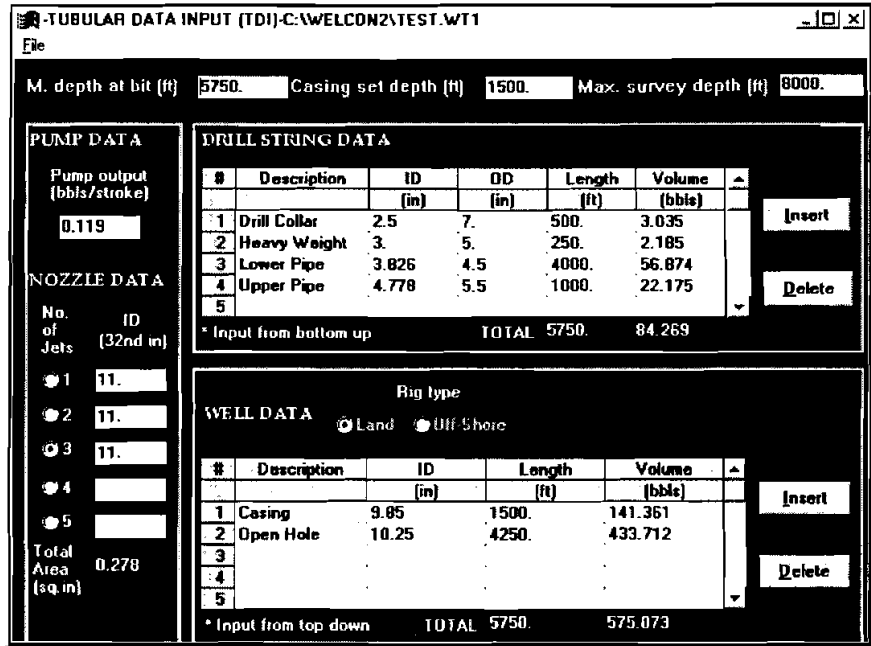


Figure 4-11. Tubular Data Input Window—Filled

15. Then click on **File** at the left end of the menu bar.
16. When the **File** window opens, click on **Exit**.
17. This will reopen the **Data Input Window**, and add the title **C:\WELCON2\TEST.WT1** to the **TDI File name** box, as shown in Figure 4-12.

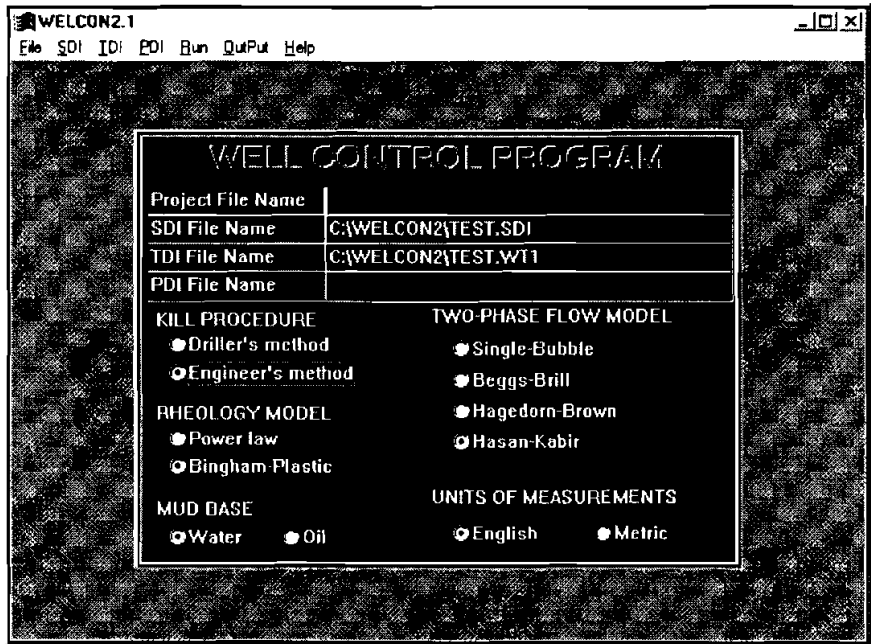


Figure 4-12. Data Input Window

- Click on **PDI** on the menu bar at the top of the window. This will open the **Parameter Data Input** window, shown in Figure 4-13. All Data spaces in this window are blank, except for those at the lower left of the window where measured depth at the ends of each calculation interval are listed. The annulus volume in bbls of each calculation interval is also listed.

**SHUT-IN DATA**

Drill pipe pressure (psi)

Casing pressure (psi)

Pit gain (bbls)

**GAS INFLUX DATA**

Specific gravity

Viscosity (cp)  E

Surface tension (dynes/cm)  E

Permeability (md)

Porosity

Rate of penetration (ft/hr)

Click on **E** to estimate the parameters

**ORIGINAL DRILLING MUD DATA**

Mud weight (ppg)

Plastic viscosity (cp)

Yield point (lb/100 sq ft)

Normal pump rate (gal/min)

Slow pump rate (gal/min)

Pres. drop reading (psi)  E  
(at slow pump rate)

**KILL MUD DATA**

Mud weight (ppg)  E

Plastic viscosity (cp)

Yield point (lb/100 sq ft)

Calculation interval (ft)	100.	Estimator	Estimator	Estimator
#	M. depth (ft)	Volume (bbls)	Temperature (F)	Pore P. Grad. (ppg)
0	5750.	-		
1	5650.	5.445		
2	5550.	5.445		
3	5450.	5.445		
4	5350.	5.445		

Floating point depth (ft)

Figure 4-13. Parameter Data Input Window

- Click on **File** at the upper left of this window. This will open the **TDI File Open** window.
- Click on **Test.WP1** and then on **[OK]** in this window.

21. This will reopen the **Parameter Data Input** window and fill it with numerical data, as shown in Figure 4-14.

The screenshot shows the 'PARAMETER DATA INPUT (PDI)' window for file 'C:\WELCON2\TEST.WP1'. It contains several sections of input fields and a table.

**SHUT-IN DATA**

- Drill pipe pressure (psi): 200.
- Casing pressure (psi): 200.
- Pit gain (bbbls): 20.0

**GAS INFLUX DATA**

- Specific gravity: 0.7
- Viscosity (cp): 0.018 [E]
- Surface tension (dynes/cm): 80. [E]
- Permeability (md): 500.0
- Porosity: 2
- Rate of penetration (ft/hr): 10.0

**ORIGINAL DRILLING MUD DATA**

- Mud weight (ppg): 9
- Plastic viscosity (cp): 6.689
- Yield point (lbf/100 sq ft): 1.02
- Normal pump rate (gal/min): 400.
- Slow pump rate (gal/min): 150.
- Pres. drop reading (psi) (at slow pump rate): 300. [E]

**KILL MUD DATA**

- Mud weight (ppg): 10.18 [E]
- Plastic viscosity (cp): 6.689
- Yield point (lbf/100 sq ft): 1.02

Click on [E] to estimate the parameters

**Table:**

#	M. depth (ft)	Volume (bbbls)	Estimator Temperature (F)	Estimator Pore P. Grad. (ppg)	Estimator Frac. P. Grad. (ppg)
0	5750.	-	112.5	8.5	15.5
1	5700.	2.723	112.5	8.5	15.5
2	5650.	2.723	112.5	8.5	15.5
3	5600.	2.723	112.5	8.5	15.5
4	5550.	2.723	112.5	8.5	15.5

Calculation interval (ft): 50.

Floating point depth (ft): 2000.

Figure 4-14. Parameter Data Input Window—Filled

There are a number of user inputs and options in the **Parameter Data Input** window. These choices have all been made and incorporated into the **Test.WP1** file to expedite the execution of this example run. The **Parameter Data Input** will be discussed in the next section of this manual.

22. Click on **File** at the left end of the menu bar. When the **File** window opens, click on **Exit**. This will return to the **Input Data** window, as shown in Figure 4-15.

The screenshot shows the 'WELCON2.1' window with a menu bar (File, SDI, IDI, PDI, Run, OutPut, Help). The main area displays the 'WELL CONTROL PROGRAM' settings.

**Project File Name**

- SDI File Name: C:\WELCON2\TEST.SDI
- TDI File Name: C:\WELCON2\TEST.WT1
- PDI File Name: C:\WELCON2\TEST.WP1

**KILL PROCEDURE**

- Driller's method
- Engineer's method

**RHEOLOGY MODEL**

- Power law
- Bingham-Plastic

**MUD BASE**

- Water
- Oil

**TWO-PHASE FLOW MODEL**

- Single-Bubble
- Beggs-Brill
- Hagedorn-Brown
- Hasan-Kabir

**UNITS OF MEASUREMENTS**

- English
- Metric

Figure 4-15. Data Input Window

Now, all three data file boxes in the **Data Inlet** window have been filled with the chosen names of the three files.

At this time, the user can create a **Project** file which will contain all three of the input data files. Calling up this **Project** file will simultaneously input all three data files for future computation. The project file is established as follows.

23. Click on **File** at the left end of the menu bar. When the **Project File** window opens, click on **Save Project**. See Figure 4-16.

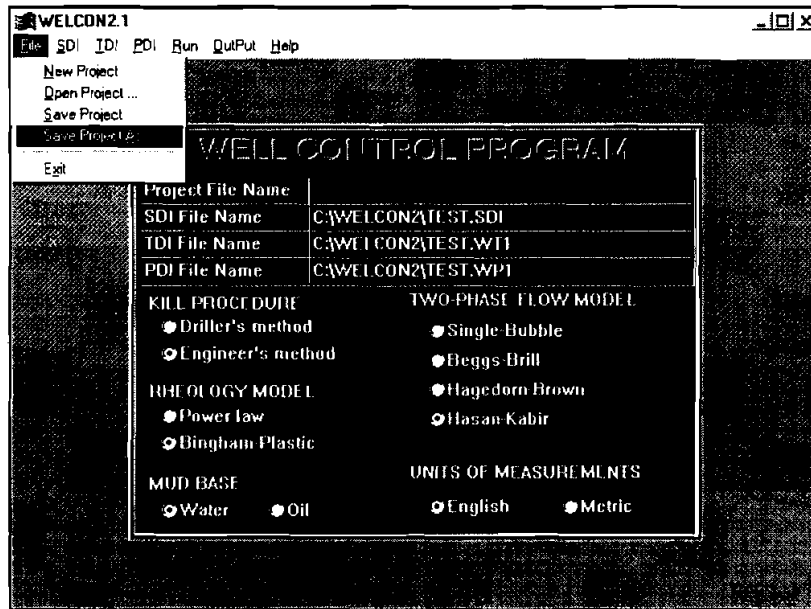


Figure 4-16. File Selection Window: New Project

24. This will open the **Save Project as** window, as shown in Figure 4-17.

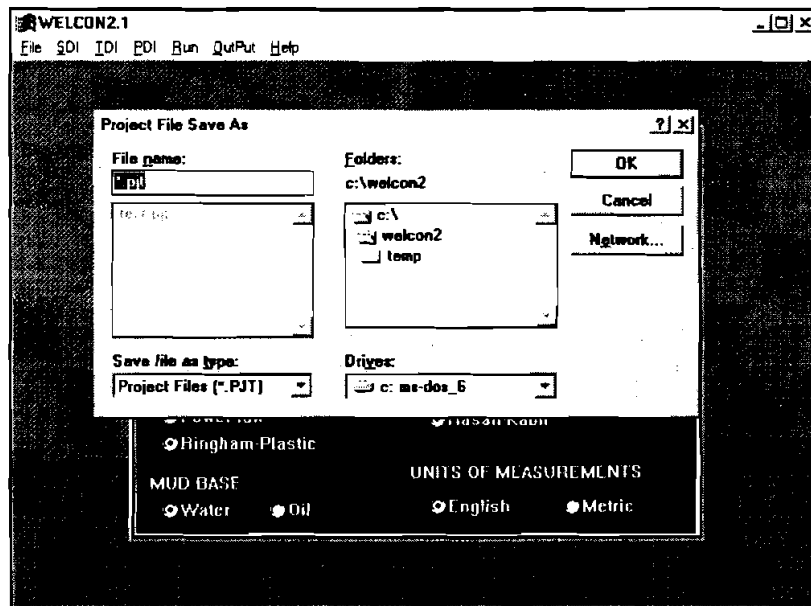


Figure 4-17. Project File Save Window

In the box directly below **File Name** write the name of the project file with the extension **.PJT**. For this example, this name is **TEST.PJT**. Then click on the **[OK]** box.

25. This will bring back the **Input Data** window. Now, the project file designation **C:\WELCON2\TEST.PJT** has been added to the list of titles in the boxes at the top of the window. This is shown in Figure 4-18.

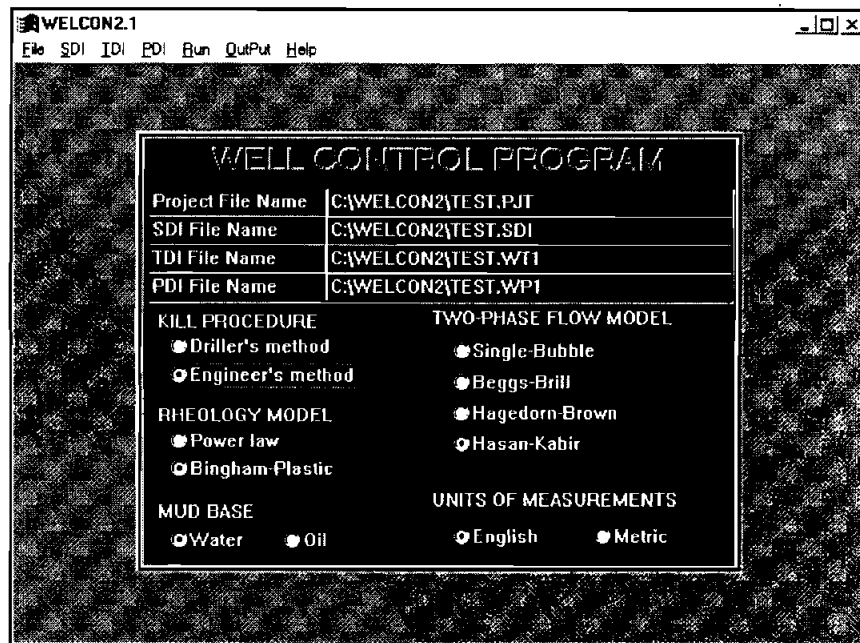


Figure 4-18. Data Input Window: Filled

26. Now, click on **Run** on the menu bar. A monitoring panel appears. On the panel, an indicator displays the percent of computation completed as a function of time. When the indicator reaches 100%, the panel disappears. Also on the panel are some labels indicating the pressure and rate information as a function of time. When calculation finishes, the **Input Data** window will return to the screen.
27. Click on **Output** on the menu bar. This will cause an option window to appear. The option window displays all the options available for three different plots, namely, pressure or ECD plot, pit gain and/or gas flow plot, pressure gradient plot. For pressure or ECD plot, the horizontal axis can be time or strokes pumped, the Y-axis can be either pressure or ECD. The plot can have various combinations of different curves. If the check box preceding the curve name is checked, the curve will be included in the plot. Other plots work in a similar way.

The counting of time or strokes pumped may start when gas begins to kick-in (start of kick) or when circulation is initiated (start of circulation). This option is selected in the box "Time Origin." The curve combination and time origin have to be determined before clicking on **Window**.



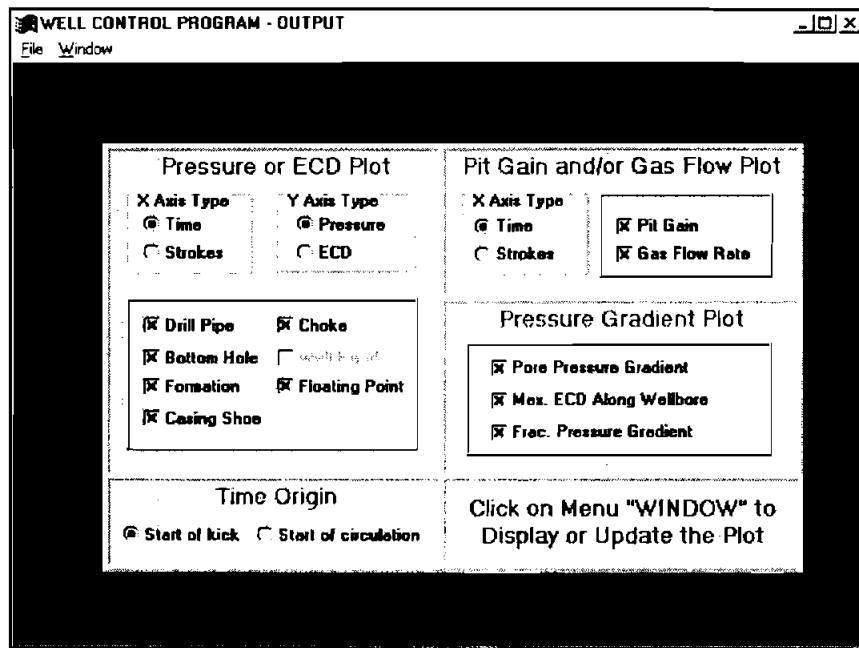


Figure 4-19. Output Option Window

28. Click on **Window** on the menu bar. This opens the **Graphic Output** window, shown in Figure 4-20. The first three items are for the arrangement of a group of child windows. They can be used only when there is at least one child window on the screen. The other five items are different child windows. Clicking on any one of them will bring out the corresponding child window. The child window "Tabulated Results" always displays the tabulated results for **Active Graph Child Window**.

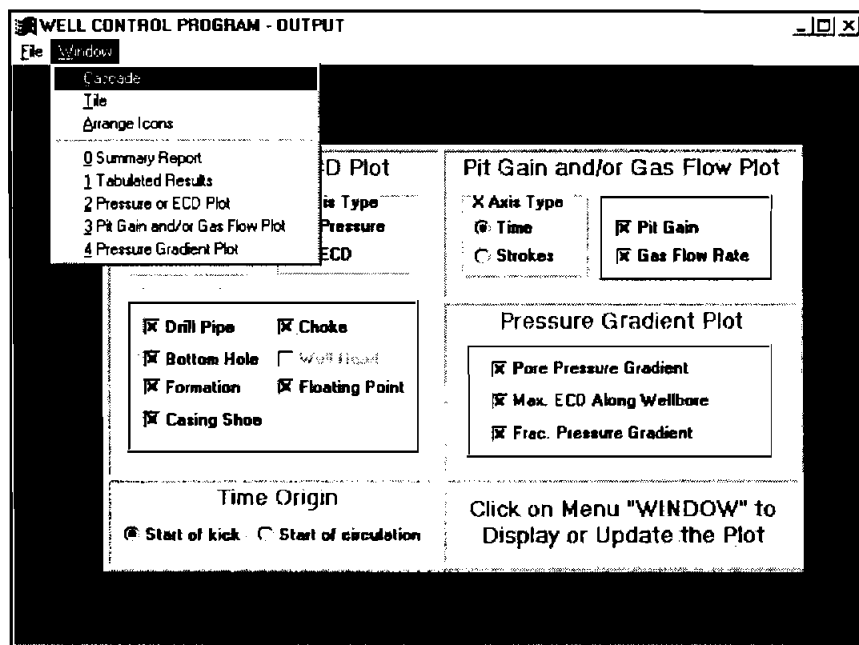


Figure 4-20. Output Format Window

29. Click on **Pressure** or **ECD** to display the graph shown in Figure 4-21. The number of curves displayed on this plot depends on the options selected.

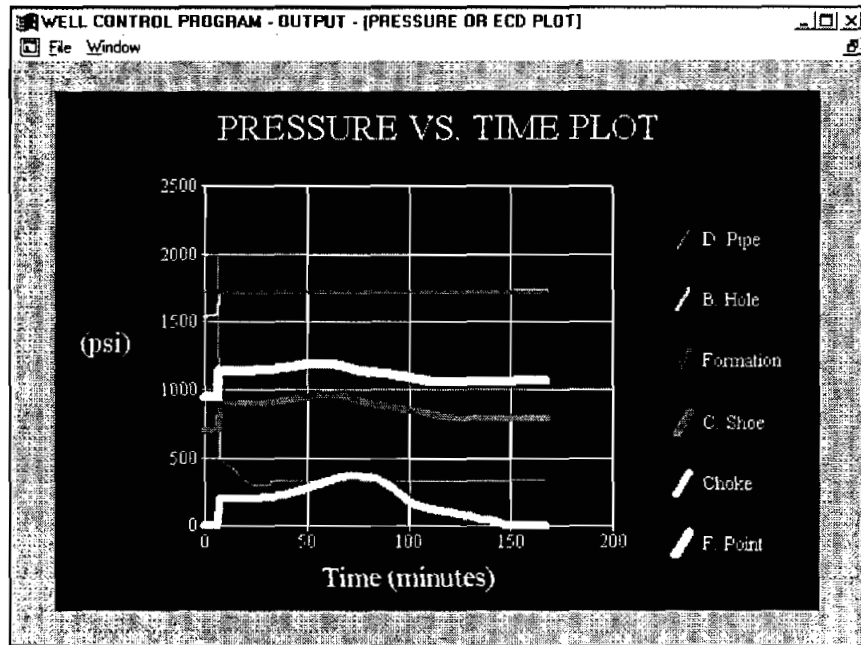


Figure 4-21. Output Graph

30. To display another plot, click on **Window** on the menu bar. When the **Graphic Output** window opens, select another plot in the list by clicking on it.

31. After viewing several of the graphs, they may be presented in a multiple display, as shown in Figures 4-22 and 4-23. Figure 4-22 is generated by clicking on Cascade in the Graphic Output window.

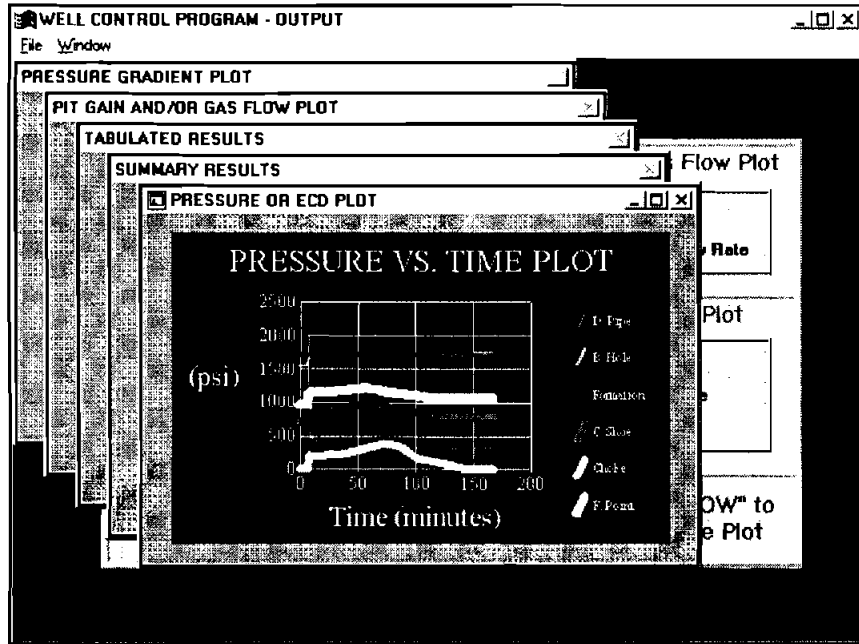


Figure 4-22. Cascade Window

Figure 4-23 is generated by clicking on Tile. These are standard WINDOWS 3 operations, and will not be detailed further.

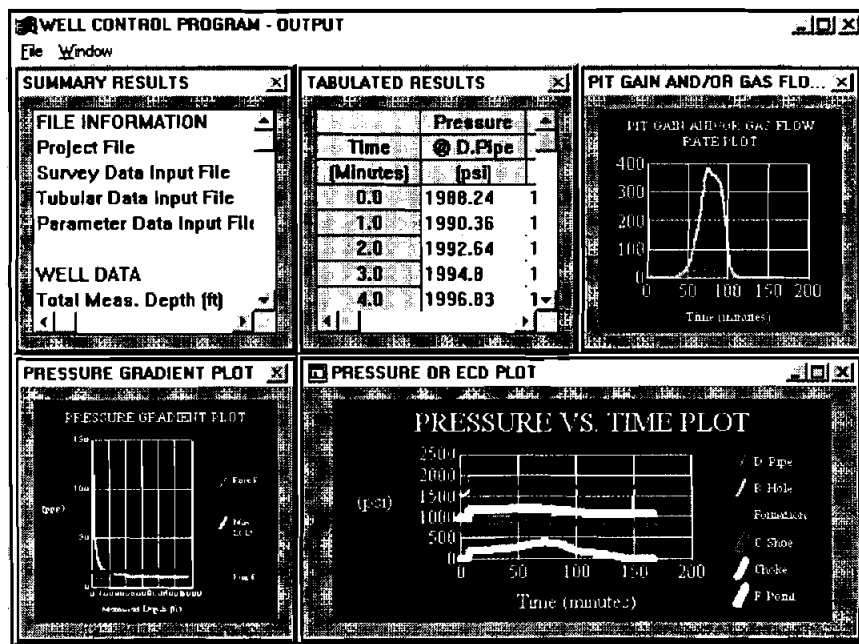


Figure 4-23. Tile Window

32. To print any of the screen displays, click on **File** at the left end of the menu bar. When the **File** window opens, click on **Print**. Figure 4-24 is the printed output of the **Choke Pressure** graph.

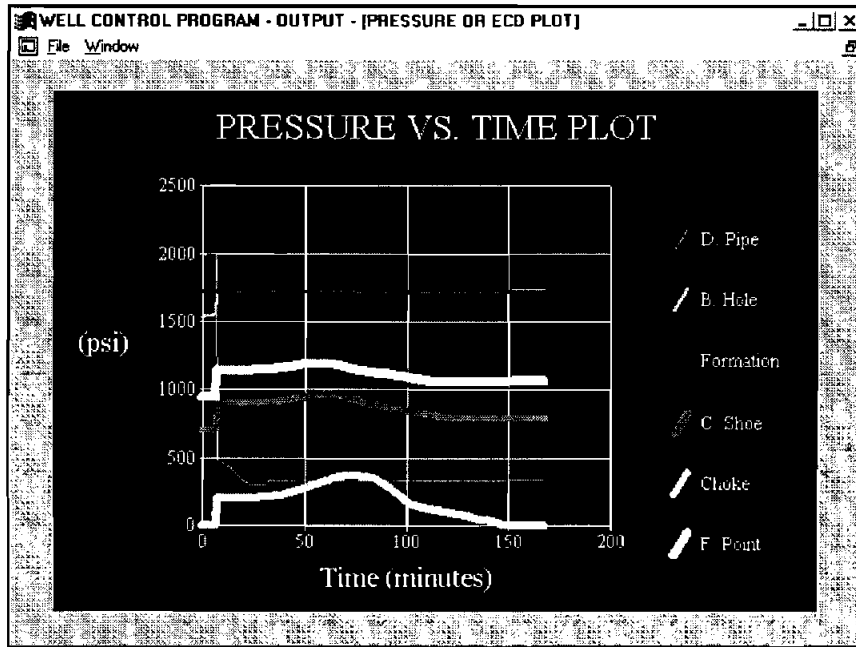


Figure 4-24. Full Size Plot

33. To leave the graphic displays, click on **File** at the left end of the menu bar. When the **File** window opens, click on **Exit**. This will return the user to the **Input Data** window.
34. The **Help** option at the right end of the menu bar will open the **Help** window. The two options available in this window are **Assistance** and **About..**. Clicking on **Assistance** will open the window shown in Figure 4-25, which gives phone and FAX numbers and individuals to contact for assistance with the program.

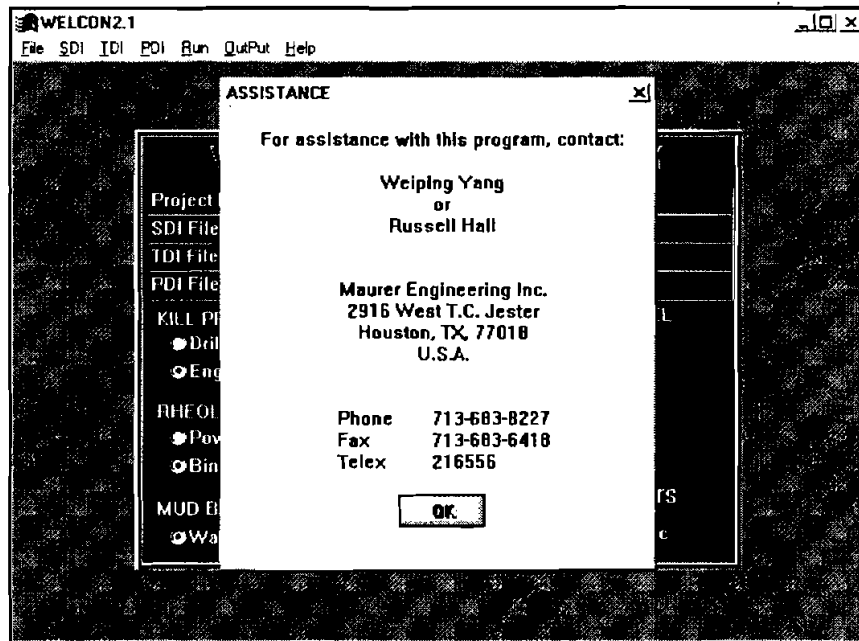


Figure 4-25. Help Window

Clicking on **About..** in the **Help** window opens a window with information about the program, and a listing of the equipment you are using to run the program.

35. To leave the program, click on **File** on the menu bar. When the **File** window opens, click on **Exit**.



## 5. Options and Choices of the Model

### 5.1 INPUT DATA

There are five choices to be made in the **Input Data** window, shown in Figure 5-1.

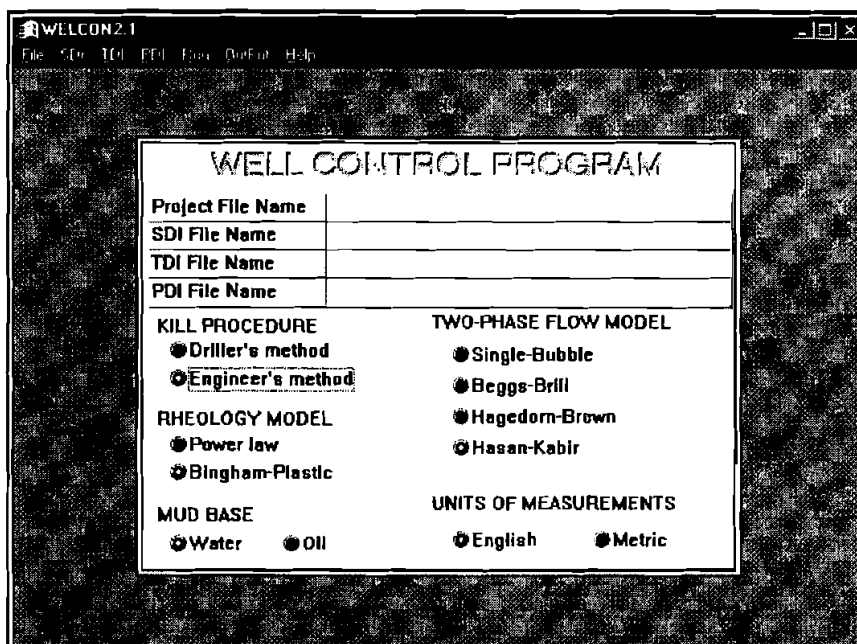


Figure 5-1. Input Data Window

1. **Kill procedure.** Either Driller's or Engineer's method.
  - A. In the Driller's method, mud weight is not increased as the kick is circulated out. At the end of this procedure, there is still pressure at both the drill pipe and choke.
  - B. In the Engineer's method, the well is shut in and the mud weight necessary to kill the well is determined. The mud weight is raised to this value, and the kick is circulated out. At the conclusion of this process, both drill pipe and choke pressure are atmospheric when circulation stops.
2. **Rheology Model.** Either Power-Law or Bingham Plastic.

Either of these models will give essentially the same results over the dynamic range used in the kill procedure. Most field measurements assume the Bingham plastic model, although there are conversions available to express Fann V.G. readings in terms of the power-law constants. If the pressure drop measured at slow pump rate is input (**Parameter Data Input**), a correction factor will be applied to the friction drop calculated for mud flow. This should greatly reduce any error resulting from the choice of flow model.

### 3. Two-Phase Flow Model.

Here the user is on his or her own. The choice of multiphase correlation model is a matter of experience or intuition. A number of the inputs required for the Beggs and Brill, Hasan-Kabir, and Hagedorn and Brown models are not measurable, and must be estimated by the user. The single-bubble model yields the highest choke pressure, and may be considered to represent the worst possible scenario.

4. **Metric or English.** Either set of units can be accommodated by the program.

## 5.2 SDI AND TDI DATA INPUTS

Input to these two data files is straightforward, and will not be elaborated here.

## 5.3 PARAMETER DATA INPUT

The **Parameter Data Input** window is shown in Figure 5-2.

PARAMETER DATA INPUT (PDI)

File

**SHUT-IN DATA**

Drill pipe pressure (psi)

Casing pressure (psi)

Pit gain (bbls)

**GAS INFLUX DATA**

Specific gravity

Viscosity (cp)  E

Surface tension (dynes/cm)  E

Permeability (md)

Porosity

Rate of penetration (ft/hr)

Click on  to estimate the parameters

**ORIGINAL DRILLING MUD DATA**

Mud weight (ppg)

Plastic viscosity (cp)

Yield point (lb/100 sq ft)

Normal pump rate (gal/min)

Slow pump rate (gal/min)

Pres. drop reading (psi)  E

(at slow pump rate)

**KILL MUD DATA**

Mud weight (ppg)  E

Plastic viscosity (cp)

Yield point (lb/100 sq ft)

Calculation interval (ft)	100.	Estimator	Estimator	Estimator
#	M. depth (ft)	Volume (bbls)	Temperature (F)	Pore P. Grad. (ppg)
0	5750.	-		
1	5650.	5.445		
2	5550.	5.445		
3	5450.	5.445		
4	5350.	5.445		

Floating point depth (ft)

Figure 5-2. Parameter Data Input Window

Starting down the left-side column, the first four items must be supplied by the user, i.e.,

1. Drill-pipe pressure,
2. Casing pressure,
3. Pit gain, and
4. Specific gravity of gas. (air = 1.00)



5. Viscosity, can either be supplied by the user, or, if the user chooses to click on [E], the program will use the formation pressure and temperature, and the gas specific gravity to calculate the gas viscosity.
6. Surface tension of the mud, may either be entered by the user, or, if the user clicks on [E], a default value of 80 dynes/cm will be supplied. This is the surface tension of clean water. It is required in some of the multiphase correlations.
7. User must enter permeability, porosity and rate of penetration. These parameters will be used in the calculation of gas influx rate.
8. Starting down the right column, items #10, #11, and #12 are, respectively, mud weight, plastic viscosity, and yield point of the original density mud. The user must supply these.
9. Normal pump rate is the pump rate before shut-in. It must be supplied by the user.
10. Pump pressure may be supplied by the user. Pressure is determined by the slow pump rate and slow pumping test. This value will be compared with the frictional pressure drop calculated using the mud properties in items #10, #11, and #12, and the flow path geometry listed in the Tubular Data Input. A correction factor will be determined from this comparison. This factor will be used to correct the friction pressure drop computed for the single-phase mud flow to agree with that observed in the slow pump rate test.

If the user elects to click on the [E], the program will calculate a frictional pressure drop for the mud flow, and place it in this box.

The program will calculate the mud weight of the kill mud when the user clicks on [E] for item #16. Items #17 and #18, kill mud plastic viscosity and yield point, must be supplied by the user.

After entering the data for example, the top of the **Parameter Data Input** is shown in Figure 5-3.

**PARAMETER DATA INPUT (PDI)-C:\WELCON2\TEST.WP1**

**SHUT-IN DATA**

Drill pipe pressure (psi) 200.  
 Casing pressure (psi) 200.  
 Pit gain (bbbls) 20.0

**GAS INFLUX DATA**

Specific gravity 0.7  
 Viscosity (cp) 0.018 E  
 Surface tension (dynes/cm) 80. E  
 Permeability (md) 500.0  
 Porosity .2  
 Rate of penetration (ft/hr) 10.0

Click on  to estimate the parameters

**ORIGINAL DRILLING MUD DATA**

Mud weight (ppg) 9  
 Plastic viscosity (cp) 6.689  
 Yield point (lb/100 sq ft) 1.02  
 Normal pump rate (gal/min) 400.  
 Slow pump rate (gal/min) 150.  
 Pres. drop reading (psi) 300. E  
 (at slow pump rate)

**KILL MUD DATA**

Mud weight (ppg) 10.18 E  
 Plastic viscosity (cp) 6.689  
 Yield point (lb/100 sq ft) 1.02

Calculation interval (ft) 50.

#	M. depth (ft)	Volume (bbbls)	Estimator Temperature (F)	Estimator Pore P. Grad. (ppg)	Estimator Frac. P. Grad. (ppg)
0	5750.	-			
1	5700.	2.723			
2	5650.	2.723			
3	5600.	2.723			
4	5550.	2.723			

Floating point depth (ft) 2000.

Figure 5-3. Parameter Data Input Window: Partially Filled

The three empty columns at the bottom of the window must now be filled.

Click on the [Estimator] button of the **Temperature** column to open the **Temperature Estimation** window, as shown in Figure 5-4.

**PARAMETER DATA INPUT (PDI)-C:\WELCON2\TEST.WP1**

**SHUT-IN DATA**

Drill pipe pressure (psi) 200.  
 Casing pressure (psi) 200.  
 Pit gain (bbbls) 20.0

**GAS INFLUX DATA**

Specific gravity 0.7  
 Viscosity (cp) 0.018 E  
 Surface tension (dynes/cm) 80. E  
 Permeability (md) 500.0  
 Porosity .2  
 Rate of penetration (ft/hr) 10.0

Click on  to estimate the parameters

**ORIGINAL DRILLING MUD DATA**

Mud weight (ppg) 9  
 Plastic viscosity (cp) 6.689  
 Yield point (lb/100 sq ft) 1.02  
 Normal pump rate (gal/min) 400.  
 Slow pump rate (gal/min) 150.  
 Pres. drop reading (psi) 300. E  
 (at slow pump rate)

**KILL MUD DATA**

Mud weight (ppg) 10.18 E  
 Plastic viscosity (cp) 6.689  
 Yield point (lb/100 sq ft) 1.02

Calculation interval (ft) 50.

#	M. depth (ft)	Volume (bbbls)	Estimator Temperature (F)	Estimator Pore P. Grad. (ppg)	Estimator Frac. P. Grad. (ppg)
0	5750.	-			
1	5700.	2.723			
2	5650.	2.723			
3	5600.	2.723			
4	5550.	2.723			

Floating point depth (ft) 2000.

**TEMPERATURE ESTIMATION**

Surface temperature (F) 80  
 Temp. gradient (Deg/100 ft) 1

Accept Discard

Figure 5-4. Temperature Data Window

Enter surface temperature and temperature gradient in degrees F/100 ft or in degrees C/30 meters) and click on the [Accept] button to enter the temperature readings into the temperature column in the **Parameter Data Input** window, as shown in Figure 5-5.

**-PARAMETER DATA INPUT (PD)-C:\WELCONZ\TEST.WP1**

File

<b>SHUT-IN DATA</b>		<b>ORIGINAL DRILLING MUD DATA</b>	
Drill pipe pressure (psi)	200.	Mud weight (ppg)	9
Casing pressure (psi)	200.	Plastic viscosity (cp)	6.689
Pit gain (bbbls)	20.0	Yield point (lb/100 sq ft)	1.02
<b>GAS INFLUX DATA</b>		Normal pump rate (gal/min)	400.
Specific gravity	0.7	Slow pump rate (gal/min)	150.
Viscosity (cp)	0.018 E	Pres. drop reading (psi)	300. E
Surface tension (dynes/cm)	80. E	(at slow pump rate)	
Permeability (md)	500.0	<b>KILL MUD DATA</b>	
Porosity	-.2	Mud weight (ppg)	10.18 E
Rate of penetration (ft/hr)	10.0	Plastic viscosity (cp)	6.689
		Yield point (lb/100 sq ft)	1.02

Click on  to estimate the parameters

Calculation interval (ft)	50.	Estimator	Estimator	Estimator
#	M. depth	Volume	Temperature	Pore P. Grad.
	(ft)	(bbbls)	(F)	(ppg)
0	5750.	-	112.5	
1	5700.	2.723	112.5	
2	5650.	2.723	112.5	
3	5600.	2.723	112.5	
4	5550.	2.723	112.5	

Floating point depth (ft) 2000.

Figure 5-5 Temperature Data Entered

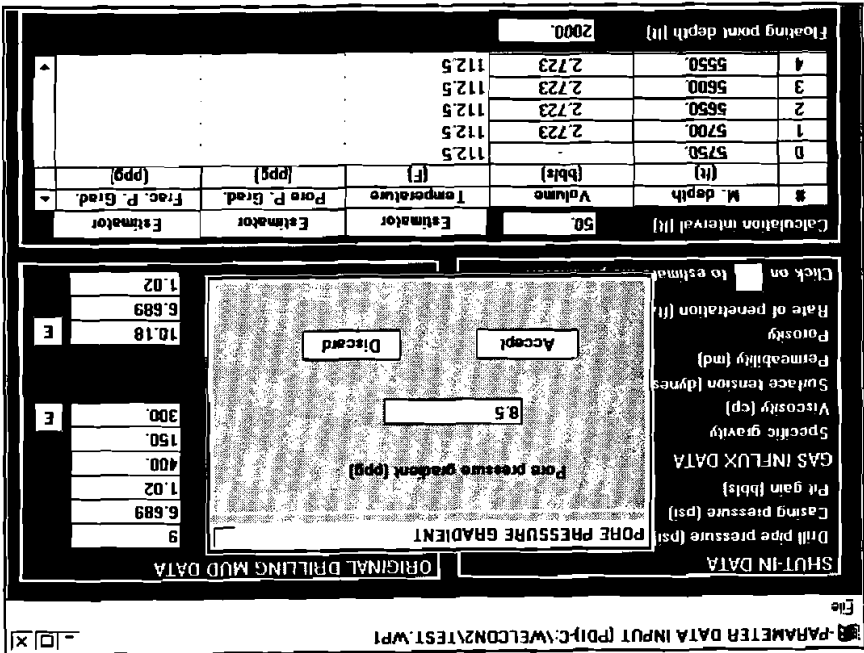


Figure 5-6. Pore Pressure Gradient Window

Enter surface temperature and temperature gradient in degrees F/100 ft or in degrees C/30 meters) and click on the **[Accept]** button to enter the temperature readings into the temperature column in the **Parameter Data Input** window, as shown in Figure 5-5.

**-PARAMETER DATA INPUT (PDI)-C:\WELCON2\TEST.WP1** [ ] [X]

File

<b>SHUT-IN DATA</b>		<b>ORIGINAL DRILLING MUD DATA</b>	
Dull pipe pressure (psi)	200.	Mud weight (ppg)	9
Casing pressure (psi)	200.	Plastic viscosity (cp)	6.689
Pit gain (bbls)	20.0	Yield point (lb/100 sq ft)	1.02
<b>GAS INFLUX DATA</b>		Normal pump rate (gal/min)	400.
Specific gravity	0.7	Slow pump rate (gal/min)	150.
Viscosity (cp)	0.018 E	Pres. drop reading (psi)	300. E
Surface tension (dynes/cm)	80. E	(at slow pump rate)	
Permeability (md)	500.0	<b>KILL MUD DATA</b>	
Porosity	.2	Mud weight (ppg)	10.18 E
Rate of penetration (ft/hr)	10.0	Plastic viscosity (cp)	6.689
Click on <input type="checkbox"/> to estimate the parameters		Yield point (lb/100 sq ft)	1.02

Calculation interval (ft)	50.	Estimator	Estimator	Estimator
#	M. depth	Volume	Temperature	Pore P. Grad.
	(ft)	(bbls)	(F)	(ppg)
0	5750.	-	112.5	
1	5700.	2.723	112.5	
2	5650.	2.723	112.5	
3	5600.	2.723	112.5	
4	5550.	2.723	112.5	
Floating point depth (ft)		2000.		

Figure 5-5. Temperature Data Entered

Individual entries in these three columns (**Temperature**, **Pore P. Grad.**, and **Frac. P. Grad.**) may be edited or added by clicking onto them and typing in the desired change.

The **Calculation Interval** is also a user input, and is edited by clicking onto the box and entering the desired change.

In a similar manner, the **PORE PRESSURE GRADIENT** window and the **FRACTURE PRESSURE GRADIENT** are opened, filled, and the results entered into the **Parameter Data Input** window. These two windows are shown in Figures 5-6 and 5-7.

Figure 5-7. Fracture Pressure Gradient Window

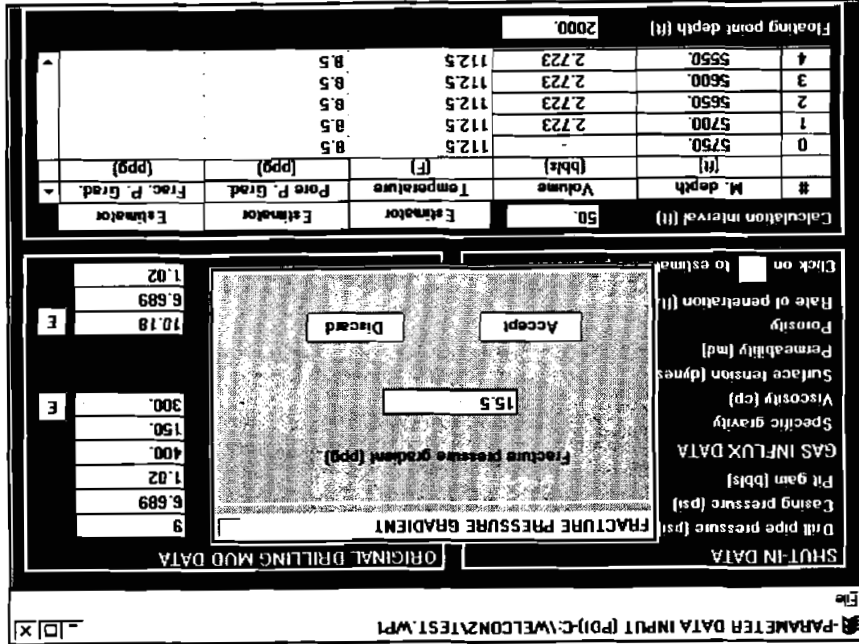
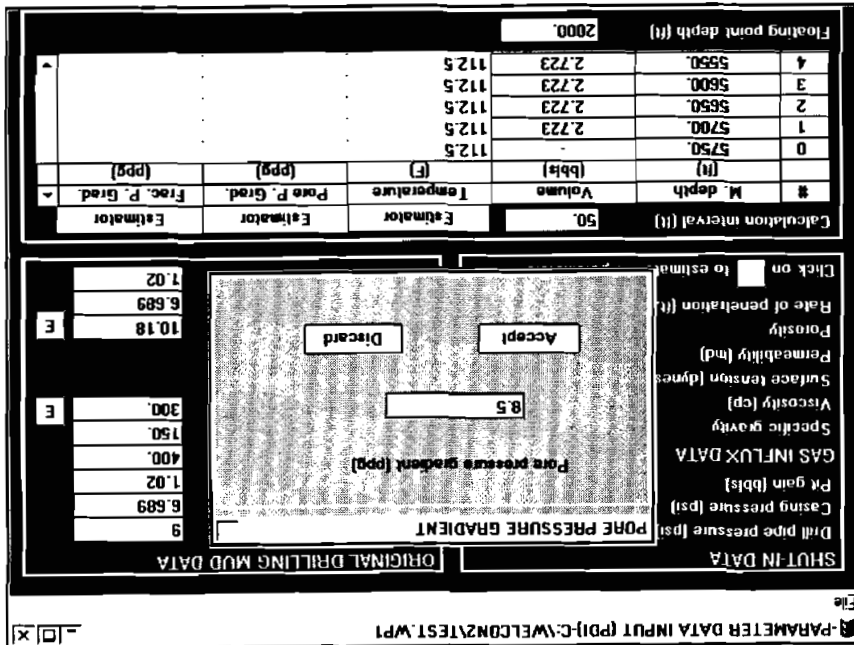


Figure 5-6. Pore Pressure Gradient Window



The completely filled Parameter Data Input window is shown in Figure 5-8.

**PARAMETER DATA INPUT (PDI)-C:\WELCON2\TEST.WP1**

File

<b>SHUT-IN DATA</b>		<b>ORIGINAL DRILLING MUD DATA</b>	
Drill pipe pressure (psi)	200.	Mud weight (ppg)	9
Casing pressure (psi)	200.	Plastic viscosity (cp)	6.689
Pit gain (bbbls)	20.0	Yield point (lb/100 sq ft)	1.02
<b>GAS INF LUX DATA</b>		Normal pump rate (gal/min)	400.
Specific gravity	0.7	Slow pump rate (gal/min)	150.
Viscosity (cp)	0.018 E	Pres. drop reading (psi)	300. E
Surface tension (dynes/cm)	80. E	(at slow pump rate)	
Permeability (md)	500.0	<b>KILL MUD DATA</b>	
Porosity	.2	Mud weight (ppg)	10.18 E
Rate of penetration (ft/hr)	10.0	Plastic viscosity (cp)	6.689
Click on <input type="checkbox"/> to estimate the parameters		Yield point (lb/100 sq ft)	1.02

Calculation interval (ft)	50.	Estimator	Estimator	Estimator
#	M. depth	Volume	Temperature	Pore P. Grad.
	(ft)	(bbbls)	(F)	(ppg)
0	5750.	-	112.5	8.5
1	5700.	2.723	112.5	8.5
2	5650.	2.723	112.5	8.5
3	5600.	2.723	112.5	8.5
4	5550.	2.723	112.5	8.5
Floating point depth (ft)		2000.		

Figure 5-8. Filled Parameter Data Input Window

In this window, the pump pressure (300 psia) was user input. Clicking the [E] button on the Pump Pressure line will replace the user input value with a calculated value, 340.05, as shown in Figure 5-9.

**PARAMETER DATA INPUT (PDI)-C:\WELCON2\TEST.WP1**

File

<b>SHUT-IN DATA</b>		<b>ORIGINAL DRILLING MUD DATA</b>	
Drill pipe pressure (psi)	200.	Mud weight (ppg)	9
Casing pressure (psi)	200.	Plastic viscosity (cp)	6.689
Pit gain (bbbls)	20.0	Yield point (lb/100 sq ft)	1.02
<b>GAS INF LUX DATA</b>		Normal pump rate (gal/min)	400.
Specific gravity	0.7	Slow pump rate (gal/min)	150.
Viscosity (cp)	0.018 E	Pres. drop reading (psi)	340.05 E
Surface tension (dynes/cm)	80. E	(at slow pump rate)	
Permeability (md)	500.0	<b>KILL MUD DATA</b>	
Porosity	.2	Mud weight (ppg)	10.18 E
Rate of penetration (ft/hr)	10.0	Plastic viscosity (cp)	6.689
Click on <input type="checkbox"/> to estimate the parameters		Yield point (lb/100 sq ft)	1.02

Calculation interval (ft)	50.	Estimator	Estimator	Estimator
#	M. depth	Volume	Temperature	Pore P. Grad.
	(ft)	(bbbls)	(F)	(ppg)
0	5750.	-	112.5	8.5
1	5700.	2.723	112.5	8.5
2	5650.	2.723	112.5	8.5
3	5600.	2.723	112.5	8.5
4	5550.	2.723	112.5	8.5
Floating point depth (ft)		2000.		

Figure 5-9. Calculated Pump Pressure

As a final comment, Figure 5-10 presents a composite output graph of choke pressure versus time for all four flow models.

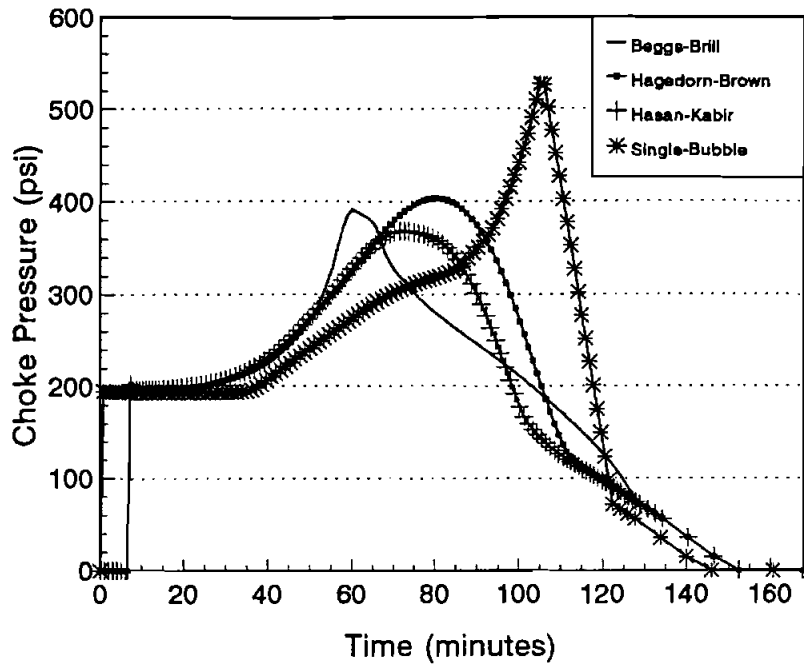


Figure 5-10. Choke Pressure for Four Models.

This result seems to be typical in that the single-bubble model yields the highest choke pressure, while the outputs of the other models are lower and closely grouped.



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