DEVELOPMENT OF A MATERIAL-BALANCE AND INFLOW-PERFORMANCE MODEL FOR OIL AND GAS-CONDENSATE RESERVOIRS

Diploma Thesis

by

Gunnar Borthne

Division of Petroleum Engineering and Applied Geophysics

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SUMMARY

A simulation model for oil and gas-condensate production based on material-balance and inflow-performance calculations has been developed. The material-balance procedure can utilize PVT data from the general PVT formulation. This formulation is based on flash separation of the oil and gas, separately, to stock-tank conditions from each pressure step in a differential-liberation or constant-volume depletion process. This requires slightly altered definitions of the traditional black-oil parameters.

The main underlying assumptions about the reservoir are that it is a homogeneous, isotropic, horizontal, cylindrical, uniform thickness reservoir bounded by no-flow boundaries and modelled as a single cell, which is initially saturated with one hydrocarbon phase and connate water. The drive mechanisms are solution-gas drive (without gas cap) for oil, and depletion drive for gas-condensate reservoirs. The producing gas/oil ratio is constant throughout the reservoir. Capillary pressure, gravity and coning are not considered.

The inflow-performance routine of the model is based on pseudo-pressure calculations which are performed by the numerical integration of a pressure function.

The model can simulate production from an entire oil and gas field with multiple wells. All the wells are assumed to be "equivalent" and produce at the same average reservoir conditions, and have the same inflow-performance relationship. Thus, calculations are performed on a well-basis and multiplied by the number of wells to obtain field production quantities. The field target and minimum rates of the preferred phase, the minimum bottomhole or wellhead pressure, and the number of wells control the execution. These are specified on the input as functions of time. The well and time control facilities of the simulator are exemplified.

Subject to extension, the model is suitable for field studies at an early stage of field development when data are scarce. It could also be used for optimization as a part of an economic field development model since it can be quickly processed on the computer (e.g., several times faster than the commercial, general, fully implicit three-dimensional reservoir simulator ECLIPSE).

At present, the model provides a good basis for further develop-

ments. Some possible extensions which would increase its versatility, are: incorporation of or interaction with a tubing model, interface to an economic field development model (as mentioned above), implementation of other drive-mechanism procedures (e.g., gas cap, aquifer, injection), and consideration of water or gas coning problems.

Test runs are presented in the report. Comparisons with other models indicate that the material-balance procedure of the program presented here works correctly in the cases tested. The inflow-performance calculations give a good approximation of a one-dimensional, one-well simulation. Another test indicated that the choice of PVT formulation can have a significant influence on the simulation results.

Chapter 1

INTRODUCTION

In recent years, the economics of the development and production of oil and gas fields has grown more and more important. (Lately, this has been emphasized by the sudden fall in oil prices.) Economists are engaged in developing models for the simulation and planning of the development of entire oil and gas fields to improve knowledge and overall profitability, and one requirement is an easy-to-use, fast-processing reservoir model which can be incorporated in such an economic "total" model. The reservoir model developed here might, after some extensions, be suitable for this purpose. It is also intended to be employed by reservoir engineers for reservoir predictions at an early stage when few field data are known and a preliminary prediction is sought.

The model, called GMS (a material-balance and inflow-performance model for oil and gas-condensate reservoirs), is based on (1) a single-cell, material-balance description of the reservoir and (2) the calculation of inflow performance by means of a pseudopressure function. Some decades ago, before computers were generally used for numerical reservoir simulations, the material-balance approach to analyzing reservoirs was widespread. Farouq Ali and Nielsen[1] found that field observations have been in remarkably good agreement with material-balance calculations, and believe that such calculations are not "passé". Thus, the material-balance approach is still considered valuable as a quick analytic tool.

Pressure loss in the production string is not considered in this study. This would have to be included to make the model suitable for interaction with an economic model. The development of an interface with the economic model would then also be necessary.

Both the gas and oil phases present in the reservoir are considered to contribute oil and gas at the surface. For fluid systems near the critical point, a considerable amount of oil is condensed from the free reservoir gas when the pressure is lowered.[2] This oil is then added to the oil which originates from the free oil in the reservoir. Analogously, the gas from free reservoir gas and the gas liberated from oil, together, represent the total gas volume recovered. Because of this, the material-balance and pseudopressure

procedures of the model have been formulated to utilize pressure-volume-temperature (PVT) fluid data calculated by the general PVT formulation.[3,4] This formulation implies that:

(1) the solution gas/oil ratio in oil,
(2) the solution oil/gas ratio in gas, and
(3) the densities at standard conditions ("surface densities") of
  (a) the oil from solution in free reservoir gas,
  (b) the oil from free reservoir oil,
  (c) the gas from solution in free reservoir oil, and
  (d) the gas from free reservoir gas,

are functions of the reservoir pressure. The definitions of the black-oil parameters from this formulation are slightly different from the conventional ones.[5]

Pseudopressure and inflow-performance calculations rely on the assumption of a constant producing GOR throughout the reservoir. This assumption has already been applied by other researchers.[6] However, with the general formulation used here, the equations and solution procedures become somewhat different.

Suul and Whitson have developed a model similar to GMS, which they have called CONREM.* This is a compositional model dealing with dry-gas and gas-condensate fluid systems. GMS, which is a black-oil model, is mainly concerned with the oil fluid systems. Due to its general formulations, GMS may, however, be able to handle the whole range of fluid systems (oil, volatile oils, condensates and gas) with acceptable accuracy.

* CONREM was developed by Trond J. Suul and Curtis H. Whitson, at The Norwegian Institute of Technology, U. of Trondheim (1981).

Chapter 2

PVT FORMULATIONS

2.0 Introduction

PVT data, which describe the pressure-volume-temperature relations of reservoir fluids, are essential as input to calculations and predictions of oil and gas production. Knowledge of such data can be obtained in various ways. Laboratory tests or computer simulations of the tests are two of the most common approaches. The basic data are obtained from laboratory tests which are performed on a fluid sample that is representative for the reservoir fluid.

Dependent on the sampling technique, preparatory work is required on the fluid sample prior to laboratory measurements. This work includes the recombination of fluids, pressurizing and heating to reservoir conditions.[7] The following discussion briefly states what is done in the laboratory or simulated on the computer to generate the wanted data. The following sections illustrate how PVT data from different PVT formulations can be utilized.

2.1 A Brief Survey of Laboratory Procedures

The starting point of the laboratory tests is a cell charged with a reservoir-fluid sample. The pressure in the cell can be adjusted by withdrawal and injection of mercury or a piston. A portion of the fluid can be ejected through valves into other test equipment. The temperature in the cell is usually maintained at reservoir temperature until the cell pressure has reached one atmosphere.

2.1.1 Constant-Composition (Mass) Expansion

When conducting a constant-composition expansion test, also called a flash test or a pressure-volume (PV) test, the pressure is lowered in increments to predetermined pressures. At each pressure step equilibrium between gas and oil is reached by thorough agitation of the cell. The volumes of oil and liberated gas are recorded. Since no hydrocarbon material is removed from the cell during the test, the total mixture composition in the cell remains fixed at the

original composition.

2.1.2 Differential Liberation

The differential-liberation test is performed on oils and begins in the same manner as the PV test. Mercury is withdrawn from the cell, gas is released from solution and the cell is agitated until the gas is in equilibrium with the oil. This is repeated for a series of predetermined pressure steps. But in this test *all* the liberated gas at each pressure step is removed from the cell after equilibrium is reached. The gas is removed by injecting mercury while the pressure in the cell is kept constant. The injected and withdrawn mercury volumes indicate the liberated gas volume at reservoir conditions and oil shrinkage at each stage of liberation. The ejected gas is collected in a sample container and may be analyzed at each stage of liberation. The differential liberation process is a stepwise equilibrium process. Total composition remaining in the cell changes at each step.

2.1.3 Constant-Volume Depletion

The constant-volume depletion (CVD) test is performed on rich gases (i.e., gases with a high content of dissolved oil) and volatile oils. The procedure is similar to the differential-liberation procedure. When mercury is withdrawn from the cell, oil may evolve due to retrograde condensation (i.e., condensation that occurs in reverse of conventional behaviour). Since the initial fluid is completely gaseous, all the gas is not ejected as in the differential test. Instead, mercury is injected and gas removed at constant pressure until the initial volume is reached. The CVD process is described in more detail by Whitson and Torp.[4]

2.1.4 Flash Separation Test

Another commonly performed test is the flash separation test. Bubblepoint oil is flashed through a separator system of one, two, or three (or more) stages which resembles a true field surface installation. The volume of bubblepoint oil feed, gas volumes liberated at each stage and the residual stock-tank oil volume are measured. This process may be repeated for several combinations of separator conditions.

2.2 Liberation Mechanisms in the Reservoir and in the Production Equipment

The liberation mechanisms applied in laboratory experiments are only approximations of the real processes taking place in the reservoir, in the production tubing, and in the surface equipment. Most engineers consider the liberation of oil and gas in the reservoir to be a differential process and the liberation in the production equipment to approach a flash process.[7] Generally, the flash and differential-liberation PVT data are not equal.

2.2.1 Oil and Gas Liberation in the Reservoir

A differential liberation process implies that the oil and its liberated gas are removed from each other just after liberation. This causes the total composition to change with time. If this process is to take place in the reservoir, the oil and gas velocities must be different. In a solution-gas-drive reservoir, differential liberation is considered to occur near the wellbore at an early stage of depletion. The relative gas permeability is low due to small gas saturation, so the oil flows more rapidly and bypasses the gas. The velocities of the oil and gas are also considered to be different later in the production history when the gas saturation and gas relative permeability are larger, and the gas mobility exceeds that of the oil. Consequently, though flash liberation best represents the average reservoir liberation mechanism for a short period when gas mobility is low, later, a differential process is a better approximation.

If the hydrocarbon mixture is a rich gas and the reservoir fluid is at the dewpoint pressure, retrograde condensation will occur as the pressure is lowered. This liberation process is most likely best approximated by a CVD experiment where only gas is produced, as long as thermodynamic equilibrium exists between the two phases in the reservoir.[3]

2.2.2 Oil and Gas Liberation in the Flow String and Separator

The common assumption is that the liberation taking place in the flow string (from the bottom of the well to the separator) is an adiabatic flash liberation. The reasons for this is that all the fluid entering the bottom must be removed at the top, and that the two-phase flow conditions promote sufficient agitation to obtain equilibrium between the oil and gas in the string. As the gas in the string may originate from elsewhere than the oil, the process is not necessarily equal to an isothermal laboratory test.

The flash liberation probably represents the liberation process in the surface separator quite well. The incoming oil and gas are in equilibrium, and with steady well flow, each subsequent volume has the same composition. Constant volumes of oil and gas are continuously in contact in the separator. The production separation is done through a number of separation stages (2-4), which is reproduced in the surface test.

2.3 Calculating PVT Data: Methods and Assumptions

Petroleum engineers need PVT data that represent the composite liberation system. Approximations of such data can be made in different ways by using different assumptions. The conventional, the general and the "constant-surface-density" formulations are described below. The general formulation should yield more accurate results because fewer assumptions are made.

The resulting data are: formation volume factors, solution gas/oil ratios, the densities and viscosities of the oil and gas.

2.3.1 The Conventional Formulation

This method represents the conventional way of measuring and computing PVT data for oil systems. The following assumptions are applied to approximate the combined liberation system:

1. The amount of gas in solution in a bubblepoint liquid is defined by the flash liberation test to stock-tank conditions.

2. The amount of gas liberated in the reservoir from bubblepoint pressure to a given pressure is defined by the differential-liberation process.

3. The amount of gas in solution at any reservoir pressure, with respect to a bubblepoint liquid, is the difference in the gas originally in solution (flash) and the gas which is differentially liberated.

4. The relationship between the formation volume factors of flash and differentially separated samples remains constant over the entire pressure range of interest.

5. The formation volume factor of the bubblepoint liquid is determined by the flash-liberation process to separator conditions and then to the stock tank.

These points can be restated in terms of equations:

$$B_o = B_{od} \frac{B_{ofb}}{B_{odb}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.1)$$

$$R_s = R_{sp} - \left[(R_L)_{st}\right] \frac{B_{ofb}}{B_{odb}} \qquad \ldots\ldots\ldots\ldots\ldots (2.2)$$

$$B_g = \frac{z_{res}\, T_{res}\, p_{stc}}{z_{stc}\, T_{stc}\, p_{res}} \qquad \ldots\ldots\ldots\ldots\ldots (2.3)$$

where B_o = oil formation volume factor, Rm^3/Sm^3

B_{od} = oil volume (Rm^3) at reservoir pressure required to

yield one Sm^3 of stock-tank oil when differentially liberated to stock-tank conditions, Rm^3/Sm^3

B_{ofb} = volume of bubblepoint oil (Rm^3) required to yield one Sm^3 of stock-tank oil when flashed through the separator system to stock-tank conditions, Rm^3/Sm^3

B_{odb} = volume of bubblepoint oil (Rm^3) required to yield one Sm^3 of stock-tank oil when differentially liberated to stock-tank conditions, Rm^3/Sm^3

R_s = solution gas/oil ratio in oil, Sm^3/Sm^3

R_{sp} = gas volume (Sm^3) liberated at the separator per stock-tank Sm^3 of oil by flashing bubblepoint oil, Sm^3/Sm^3

$(R_L)_{st}$ = standard volume (Sm^3) of gas liberated by differential liberation from the initial bubblepoint pressure to another reservoir pressure, referred to a Sm^3 of liquid at standard conditions, Sm^3/Sm^3

B_g = gas formation volume factor, Rm^3/Sm^3

z = compressibility factor (real gas deviation factor), dimensionless

T = temperature, K

p = pressure, Pa

and subscripts res = reservoir, stc = standard conditions.

2.3.2 The General Formulation

A test which represents a composite liberation is suggested by Dodson *et al.*[3] : The sample is differentially liberated to predetermined pressures. At each pressure an oil volume is removed from the cell and flashed to stock-tank conditions. The gas liberated by the flash is the gas in solution, and the oil shrinkage resulting from the flash yields the oil formation volume factor. An extension of this procedure is described by Whitson and Torp.[4] As with the Dodson procedure, the sample is differentially liberated to preset pressures. At each pressure *both* an oil volume and a gas volume are removed and flashed separately to stock-tank conditions. When the oil is flashed, solution gas is liberated, and when the gas is flashed, oil may evolve due to retrograde condensation. The resulting calculated parameters are those used in the general material-balance procedure and the pseudopressure calculations described in the following chapters (see Fig 2.1).

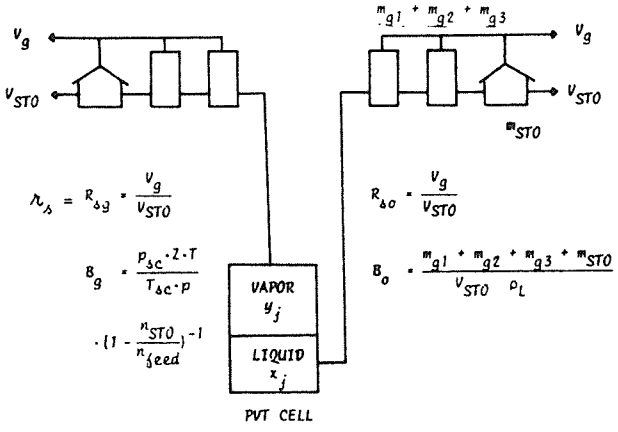


Fig 2.1 - Schematic of the procedure for calculating black-oil PVT properties. After Whitson and Torp.[4]

In the general formulation, the following assumptions are applied:

1. The amount of solution gas in oil at any pressure is defined by flashing the oil from the current pressure to stock-tank conditions.

2. The amount of solution oil in gas at any pressure is defined by flashing the gas from the current pressure to standard conditions.

3. Oil and gas liberation is defined by the differential-liberation process in the reservoir.

4. The oil formation volume factor is the volume of oil at reservoir conditions divided by the volume of oil at stock-tank conditions from the flash of the reservoir oil.

5. Gas formation volume factor is the volume of gas at reservoir conditions divided by the volume of gas at standard conditions from the flash of the reservoir gas.

6. Densities of oil and gas at standard conditions are functions of the reservoir pressure. These density functions are determined by flashing oil and gas separately to standard conditions (see Fig. 2.1) several times, starting from different reservoir pressures. Since oil and gas at reservoir pressure are flashed separately, two oil qualities and two gas qualities result, each having its own surface density.

The densities mentioned under item 6 above are in many applications only used as density ratios (specific-gravity ratios) (ρ^*) : (oil from gas) / (oil from oil) and (gas from oil) / (gas from gas).

2.3.3 The Constant-Surface-Density Formulation

This formulation is identical to the general formulation except that the density ratios are all assumed to be equal to one.

2.4 Applicability of the PVT Formulations

PVT data calculated by the conventional method can in general be used by all material-balance procedures, pseudopressure calculations and other applications. The conventional formulation described above does not incorporate the solution oil/gas ratio in oil (r_s) nor does it consider more than one surface density of oil and gas. This means that when using conventional PVT data for an application that is formulated for general PVT data, one has to assume r_s equal to zero and the density ratios equal to one.

PVT data from the general PVT formulation include the solution oil/gas ratio in oil and the variable surface densities of the two qualities of the oil and gas. The formulation of the material-balance and pseudopressure function must be different from the formulations developed for conventional PVT data to make use of PVT data from the general formulation. Because of that, a somewhat different solution procedure is needed. This subject will be discussed in more detail below.

Chapter 3

MATERIAL-BALANCE FORMULATIONS AND SOLUTION PROCEDURES

3.0 Introduction

This chapter describes three different material-balance (MB) formulations, (1) MB for dry gas, (2) the Tarner MB[10] for solution-gas-drive reservoirs, and (3) a MB called the general material balance. The latter has been implemented in the GMS program. This MB is on a differential form like the Muskat MB,[10] referring to conditions at the last step, while the Tarner MB is on an integral form, referring to initial conditions. The general formulation is general in the sense that all the quantities calculated from the general PVT formulation, described above, are incorporated. However, some other restrictions prevail: for all MB's the reservoir is represented by a homogeneous, isotropic single cell bounded by no-flow boundaries. Thus, the "general" MB is not in fact general in the widest sense. As MB's are zero-dimensional, the pressure distribution in the reservoir is not considered. The volumes of reservoir fluids withdrawn determine the reduction in average reservoir pressure. See also Section 4.1.

3.1 Dry-Gas Material Balance

The MB for dry gas is quite simple,

$$\frac{G_p}{G} = 1 - \frac{B_{gi}}{B_g} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

where G_p = cumulative gas production, Sm^3

G = initial gas volume in place, Sm^3

B_g = gas formation volume factor, Rm^3/Sm^3

and subscript i means "initial".

3.2 The Tarner Material Balance

The Tarner material balance is presented in a form proposed by Tracy.[8-10] It is based on PVT data calculated by the conventional PVT formulation. Eq. 3.2 is the main equation which is solved for successive pressure steps. The solution procedure implemented in the TARNER program is presented here.

$$N(B_o - B_{oi}) + N(R_{si} - R_s)B_g = N_p(B_o - R_sB_g) + G_pB_g \qquad (3.2)$$

This can be rearranged to give

$$1 = N'_p\phi_n + G'_p\phi_g \qquad (3.3)$$

where

$$\phi_n = \frac{B_o - R_sB_g}{B_o - B_{oi} + (R_{si} - R_s)B_g} \qquad (3.4)$$

$$\phi_g = \frac{B_g}{B_o - B_{oi} + (R_{si} - R_s)B_g} \qquad (3.5)$$

$$N'_p = N_p / N \qquad (3.6a)$$

$$G'_p = G_p / N \qquad (3.6b)$$

and

N = initial oil volume in place, Sm^3

N_p = cumulative oil production, Sm^3

N'_p = recovery of oil, fraction

G'_p = variable defined by Eq. 3.6b

B_o = oil formation volume factor, Rm^3/Sm^3

R_s = solution gas/oil ratio in oil, Sm^3/Sm^3

ϕ_n and ϕ_g = variables defined by Eqs. 3.4 and 3.5, dimensionless

i = subscript meaning "initial".

Procedure:

Estimate the producing gas/oil ratio R'_k at the lower pressure (step k) and calculate the corresponding average gas/oil ratio between the two pressure steps j and k.

$$R_{avg} = (R_j + R_k) / 2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.7)$$

The incremental oil production, ΔN_p, can now be estimated from an expanded version of Eq. 3.3 (see Eq. 3.8).

$$1 = (N_{pj} + \Delta N_p)\phi_{nk} + (G_{pj} + R_{avg}\,\Delta N_p)\phi_{gk} \quad \ldots\ldots (3.8)$$

where ΔN_p = incremental oil production, Sm^3

R = producing gas/oil ratio, Sm^3/Sm^3

and subscripts: avg = average, j = current timestep, k = next timestep.

ΔN_p is isolated and added to the previously produced oil volume to give total produced oil volume at the end of step k.

$$N_{pk} = N_{pj} + \Delta N_p \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.9)$$

With the material balance expressed as

$$\frac{(N - N_p)B_o}{S_o} = \frac{N\,B_{oi}}{(1 - S_w)} \quad \ldots\ldots\ldots\ldots\ldots (3.10)$$

the oil saturation S_o can be estimated. The relative permeability

ratio k_{rg}/k_{ro} at step k is calculated from a plot or a table of k_{rg}/k_{ro} versus saturation. Then a new value for the producing gas/oil ratio is calculated using

$$R_k = \frac{k_{rg}\mu_o B_o}{k_{ro}\mu_g B_g} + R_s \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.11)$$

where S_o = oil saturation, fraction

S_w = water saturation, fraction

k_{rg} = relative permeability to gas, fraction

k_{ro} = relative permeability to oil, fraction

μ_g = gas viscosity, Pa s

μ_o = oil viscosity, Pa s

The new R_k value obtained here serves as input to the trial-and-error procedure in Eq. 3.7. Trial and error should be continued until sufficient accuracy is achieved. The accuracy is controlled by evaluating the right-hand side of Eq. 3.8 which should give $1 \pm \varepsilon$, $|\varepsilon| \leq 10^{-5}$, as an example.

3.3 A General Reservoir Material Balance

The law of conservation of mass for flow in porous media,[11] in a suitable form, is:

$$\frac{\partial(m_p)}{\partial t} + \tilde{q}_p = -\nabla.\left(\frac{k\varrho\nabla p}{\mu}\right) V_b \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.12)$$

where p = pressure, Pa

k = permeability, m^2

ϱ = density, kg/m^3

μ = viscosity, Pa s

V_b = reservoir bulk volume, m^3

$\tilde{q}_p$ = mass production rate from the reservoir, kg/s

m_p = mass of oil and gas in the reservoir, kg

t = time, s

and the mathematical operators: ∂ = partial derivative, ∇ = gradient, m^{-1}, and $\nabla.$ = divergence, m^{-1}.

The reservoir is considered to be a single cell. Since there is no mass flux across the boundaries of the cell, the right hand side of Eq. 3.12 equals zero, giving

$$\frac{\partial(m_p)}{\partial t} + \tilde{q}_p = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.13)$$

Discretizing Eq. 3.13 and multiplying by Δt yields

$$\Delta(m_p) + \tilde{q}_p \, \Delta t = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.14)$$

where Δt = timestep length, s

The general MB[5] developed here is based on data from the general PVT formulation. The following definitions apply:

ϱ_{oo}^{STC} = density of oil from free reservoir oil, kg/m^3

ϱ_{og}^{STC} = density of oil from free reservoir gas, kg/m^3

ϱ_{gg}^{STC} = density of gas from free reservoir gas, kg/m^3

ϱ_{go}^{STC} = density of gas from free reservoir oil, kg/m^3

$$B_o = V_o^R \; / \; V_{oo}^{STC} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.15)$$

$$B_g = V_g^R \; / \; V_{gg}^{STC} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.16)$$

$$R_s = V_{go}^{STC} / \; V_{oo}^{STC} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.17)$$

$$r_s = V_{og}^{STC} / \; V_{gg}^{STC} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.18)$$

where r_s = solution oil/gas ratio in gas (oil solubility in free reservoir gas), Sm^3/Sm^3

V_o^R = volume of free reservoir oil, Rm^3

V_g^R = volume of free reservoir gas, Rm^3

V_{oo}^{STC} = stock-tank oil volume from flash separation of the free reservoir oil (V_o^R), Sm^3

V_{og}^{STC} = stock-tank oil volume from flash separation of the free reservoir gas (V_g^R), Sm^3

V_{gg}^{STC} = stock-tank gas volume from flash separation of the free reservoir gas (V_g^R), Sm^3

V_{go}^{STC} = stock-tank gas volume from flash separation of the free reservoir oil (V_g^R), Sm^3

These variables are functions of the reservoir pressure. Note that reservoir volumes are indicated with the unit Rm^3 (Reservoir m^3), and surface (or standard-condition volumes) are indicated with Sm^3.

If *all* the reservoir fluid is separated as shown in Fig. 2.1, this results in an oil mass, m_o, and a gas mass, m_g, at standard conditions (STC). These oil and gas masses originate from free reservoir oil and free reservoir gas as follows: Oil mass,

$$m_o = m_{oo} + m_{og} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.19)$$

where m_o = total mass of oil at STC from both free oil and free gas, kg

m_{oo} = mass of oil at STC existing in the reservoir as free oil, kg

m_{og} = mass of oil at STC existing in the reservoir as free gas, kg

Analogous for the mass of gas:

$$m_g = m_{gg} + m_{go} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.20)$$

where m_g = total mass of gas at STC from both free oil and free gas, kg

m_{gg} = mass of gas at STC existing in the reservoir as free gas, kg

m_{go} = mass of gas at STC existing in the reservoir as free oil, kg

Reservoir terms.

These masses can be expressed in terms of reservoir and fluid variables:

$$m_{oo} = \frac{\phi\, S_o\, \varrho_{oo}^{STC}}{B_o} V_b \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.21)$$

$$m_{og} = \frac{\phi\, S_g\, r_s\, \varrho_{og}^{STC}}{B_g} V_b \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.22)$$

$$m_{gg} = \frac{\phi\, S_g\, \varrho_{gg}^{STC}}{B_g} V_b \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.23a)$$

$$m_{go} = \frac{\phi\, S_o\, R_s\, \varrho_{go}^{STC}}{B_o} V_b \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.23b)$$

where S_o = oil saturation, fraction

S_g = gas saturation, fraction

ϕ = formation porosity, fraction

while the other variables are defined above.

The formation porosity is considered to be a function of pressure because of the formation compressibility. The equation below is an approximation to this,

$$\phi = \phi_i\, e^{[c_f(p-p_i)]} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.24)$$

where c_f = formation compressibility, Pa^{-1}

p = pressure, Pa

subscript i = initial

Production terms.

The oil production mass flux, $\check{q}_o$, comes from free oil and free gas, and is defined as:

$$\check{q}_o = \check{q}_{of} + \check{q}_{os} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.25)$$

where $\check{q}_o$ = total surface oil mass flux, kg/s

$\check{q}_{of}$ = oil mass flux from free reservoir oil, kg/s

$\check{q}_{os}$ = oil mass flux from solution in free reservoir gas, kg/s

or stated in terms of volumetric rates and solubilities:

$$\check{q}_{of} = q_{of}\, \varrho_{oo}^{STC} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.26)$$

$$\check{q}_{os} = q_{gf}\, r_s\, \varrho_{og}^{STC} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.27)$$

where q_{of} = oil production rate from free reservoir oil, at standard conditions, Sm^3/s

q_{gf} = gas production rate from free reservoir gas, at standard conditions, Sm^3/s

The gas production rates are:

$$\check{q}_g = \check{q}_{gf} + \check{q}_{gs} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.28)$$

$$\check{q}_{gf} = q_{gf}\, \varrho_{gg}^{STC} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.29)$$

$$\check{q}_{gs} = q_{of}\, R_s\, \varrho_{go}^{STC} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.30)$$

where $\check{q}_g$ = total surface gas mass flux, kg/s

$\check{q}_{gf}$ = gas mass flux from free reservoir gas, kg/s

$\check{q}_{gs}$ = gas mass flux from solution in free reservoir oil, kg/s

Note: A new notation is introduced here. A quote mark (") attached to a variable means that the variable has been divided by the reservoir bulk volume (e.g., $q'' = q/V_b$).

Substituting the corresponding changes in the reservoir masses and production terms into Eq. 3.14, four mass-balance equations result:

$$\Delta\left(\frac{\phi\, S_o\, \varrho_{oo}^{STC}}{B_o}\right) + q''_{of}\, \varrho_{oo}^{STC}\, \Delta t = 0 \qquad \ldots\ldots\ldots \quad (3.31)$$

$$\Delta\left(\frac{\phi\, S_g\, r_s\, \varrho_{og}^{STC}}{B_g}\right) + q''_{gf}\, r_s\, \varrho_{og}^{STC}\, \Delta t = 0 \qquad \ldots\ldots \quad (3.32)$$

$$\Delta\left(\frac{\phi\, S_g\, \varrho_{gg}^{STC}}{B_g}\right) + q''_{gf}\, \varrho_{gg}^{STC}\, \Delta t = 0 \qquad \ldots\ldots\ldots \quad (3.33)$$

$$\Delta\left(\frac{\phi\, S_o\, R_s\, \varrho_{go}^{STC}}{B_o}\right) + q''_{of}\, R_s\, \varrho_{go}^{STC}\, \Delta t = 0 \qquad \ldots\ldots \quad (3.34)$$

Adding Eqs. 3.31 and 3.32, Eqs. 3.33 and 3.34, and dividing by ϱ_{oo}^{STC} and ϱ_{gg}^{STC}, respectively, gives one equation for surface oil production and another for surface gas production:

$$\Delta\left[\phi\left(\frac{S_o}{B_o} + \frac{S_g\, r_s}{B_g}\cdot\frac{\varrho_{og}^{STC}}{\varrho_{oo}^{STC}}\right)\right] + q''_{of}\, \Delta t + q''_{gf}\, \Delta t\, r_s\, \frac{\varrho_{og}^{STC}}{\varrho_{oo}^{STC}} = 0$$

$$\ldots\ldots \quad (3.35)$$

and

$$\Delta[\phi(\frac{S_g}{B_g} + \frac{S_o\ R_s}{B_o}.\frac{\varrho_{go}^{STC}}{\varrho_{gg}^{STC}})] + q''_{gf}\ \Delta t + q''_{of}\ \Delta t\ R_s\ \frac{\varrho_{go}^{STC}}{\varrho_{gg}^{STC}} = 0 \qquad \ldots\ldots (3.36)$$

Rates of both free oil and free gas are present in Eqs. 3.35 and 3.36. In order to eliminate one of them from the equations, Darcy's law is used to distribute the production between the two phases. The reservoir oil and gas rates are given by :

$$q''_{gf}\ B_g = C_1\ \frac{k_{rg}}{\mu_g} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (3.37)$$

$$q''_{of}\ B_o = C_2\ \frac{k_{ro}}{\mu_o} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (3.38)$$

where C_1 and C_2 are constants. Capillary pressure is assumed to be zero, so C_1 equals C_2. The gas/oil ratio in the reservoir is obtained by dividing Eq. 3.37 by Eq. 3.38:

$$\frac{q''_{gf}\ B_g}{q''_{of}\ B_o} = \frac{k_{rg}/\mu_g}{k_{ro}/\mu_o} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (3.39)$$

rearranging Eq. 3.39 and multiplying by Δt gives:

$$\frac{\Delta G''_{pf}}{\Delta N''_{pf}} = \frac{k_{rg}\ \mu_o\ B_o}{k_{ro}\ \mu_g\ B_g} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (3.40)$$

$$\Delta G''_{pf} = q''_{gf}\ \Delta t \qquad \ldots\ldots\ldots\ldots\ldots\ldots (3.41)$$

$$\Delta N''_{pf} = q''_{of}\ \Delta t \qquad \ldots\ldots\ldots\ldots\ldots\ldots (3.42)$$

where $\Delta G''_{pf}$ = incremental gas production during the last timestep from free reservoir gas, Sm^3

$\Delta N''_{pf}$ = incremental oil production during the last timestep from free reservoir oil, Sm^3

and the mark " indicates that the variable has been divided by V_b.

Eqs. 3.40, 3.41 and 3.42 are substituted into Eqs. 3.35 and 3.36 and the resulting equations are:

$$\Delta\{\phi[\frac{S_o}{B_o} + \frac{S_g\, r_s}{B_g}(\frac{\varrho_{og}^{STC}}{\varrho_{oo}^{STC}})]\} + \Delta N''_{pf}\,[1 + r_s(\frac{\varrho_{og}^{STC}}{\varrho_{oo}^{STC}})\frac{k_{rg}\mu_o B_o}{k_{ro}\mu_g B_g}] = 0 \quad \ldots\ldots (3.43)$$

and

$$\Delta\{\phi[\frac{S_g}{B_g} + \frac{S_o\, R_s}{B_o}(\frac{\varrho_{go}^{STC}}{\varrho_{gg}^{STC}})]\} + \Delta N''_{pf}\,[\frac{k_{rg}\mu_o B_o}{k_{ro}\mu_g B_g} + R_s(\frac{\varrho_{go}^{STC}}{\varrho_{gg}^{STC}})] = 0 \quad \ldots\ldots (3.44)$$

Solution of Eqs. 3.43 and 3.44 for a timestep Δt is made by trial and error. Note the following definitions:

$$\varrho_o^* \equiv \frac{\varrho_{og}^{STC}}{\varrho_{oo}^{STC}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.45)$$

$$\varrho_g^* \equiv \frac{\varrho_{go}^{STC}}{\varrho_{gg}^{STC}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.46)$$

$$AO_k \equiv \phi(\frac{S_o}{B_o} + \frac{S_g\, r_s\, \varrho_o^*}{B_g}) \text{ at } k \quad \ldots\ldots\ldots\ldots (3.47)$$

$$AG_k \equiv \phi(\frac{S_g}{B_g} + \frac{S_o\, R_s\, \varrho_g^*}{B_o}) \text{ at } k \quad \ldots\ldots\ldots\ldots (3.48)$$

$$RO_k \equiv \left(1 + \frac{r_s \varrho_o^* k_{rg}\mu_o B_o}{k_{ro}\mu_g B_g}\right) \text{ at } k \qquad \ldots\ldots\ldots\ldots (3.49)$$

$$RG_k \equiv \left(R_s \varrho_g^* + \frac{k_{rg}\mu_o B_o}{k_{ro}\mu_g B_g}\right) \text{ at } k \qquad \ldots\ldots\ldots\ldots (3.50)$$

Eqs. 3.43 and 3.44 in terms of these definitions will be:

$$AO_k - AO_{k-1} + \Delta N''_{pf}\, RO_{avg} = 0 \qquad \ldots\ldots\ldots\ldots (3.51)$$

$$AG_k - AG_{k-1} + \Delta N''_{pf}\, RG_{avg} = 0 \qquad \ldots\ldots\ldots\ldots (3.52)$$

where k is the timestep counter. The AO and AG terms state the conditions in the reservoir at two different times, while the terms $\Delta N''_{pf}$, RO and RG must reflect average properties during the timestep. RO and RG should be averaged in some way:

$$RO_{avg} = \frac{1}{\Delta t} \int_t^{t+\Delta t} RO(p)\, \frac{\partial p}{\partial t}\, dt \qquad \ldots\ldots\ldots\ldots (3.53)$$

Though this would be satisfactory, it would be impractical to estimate. Hence, an arithmetic average is used instead.

$$RO_{avg} = (RO_k + RO_{k-1}) / 2 \qquad \ldots\ldots\ldots\ldots (3.54)$$

$$RG_{avg} = (RG_k + RG_{k-1}) / 2 \qquad \ldots\ldots\ldots\ldots (3.55)$$

Note that

$$\Delta N''_p = \Delta N''_{pf}\, RO_{avg} \qquad \ldots\ldots\ldots\ldots (3.56)$$

$$\Delta G''_p = \Delta N''_{pf}\, RG_{avg} \qquad \ldots\ldots\ldots\ldots (3.57)$$

Solution procedure when preferred phase is oil.

1. Specify oil rate, q''_o , and timestep length, Δt.
2. Calculate incremental total oil production, $\Delta N''_p$.
3. Assume average reservoir pressure, p_R, and calculate the pressure-dependent properties: B_o , B_g , R_s , r_s , μ_o , μ_g , ϱ^*_o , ϱ^*_g and ϕ.
4. Calculate oil saturation, S_o , from Eq. 3.43, which is rewritten as Eq. 3.58 below. AO_{k-1} was calculated at the last timestep, so S_o is the only unknown.

$$\{\phi[\frac{S_o}{B_o} + \frac{(1-S_w-S_o)\, r_s\, \varrho^*_o}{B_g}]\}_k - AO_{k-1} + \Delta N''_p = 0 \quad . . (3.58)$$

5. Calculate the gas saturation: $S_g = 1 - S_w - S_o$.
6. Calculate relative permeability ratio as a function of gas saturation. This is done by linear interpolation on $\log(k_{rg}/k_{ro})$ versus S_g. If k_{rg} or k_{ro} is zero, the logarithm is approximated by a large negative or positive number, respectively.
7. Now, AO_k , AG_k , RO_k and RG_k can be calculated, (See Eqs. 3.47 - 3.50)
8. Calculate incremental oil production from free reservoir oil, $\Delta N''_{pf}$, (see Eqs. 3.54, 3.56 and 3.59). This variable connects the oil and gas equations.

$$\Delta N''_{pf} = \Delta N''_p \,/\, RO_{avg} \quad . . . . . (3.59)$$

9. Calculate the incremental gas volume produced, $\Delta G''_p$, from Eqs. 3.57.

$$\Delta G''_p = \Delta N''_{pf}\, RG_{avg} \quad . . . . . (3.57)$$

10. Calculate the material-balance error, ΔE, from the gas material-balance equation. Since the oil material-balance equation is satisfied, it gives no contribution to the error.

$$\Delta E = AG_k - AG_{k-1} + \Delta G''_p \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.60)$$

Solution procedure when preferred phase is gas.

1. Specify gas rate, q''_g , and timestep length, Δt.
2. Calculate incremental total gas production, $\Delta G''_p$.
3. Assume average reservoir pressure, p_R, and calculate the pressure-dependent properties: B_o , B_g , R_s , r_s , μ_o , μ_g , ϱ^*_o , ϱ^*_g and ϕ.
4. Calculate oil saturation, S_o , from Eq. 3.44 which is rewritten as Eq. 3.61 below. AG_{k-1} was calculated at the last timestep, so S_o is the only unknown.

$$\left\{\phi\left[\frac{(1-S_w-S_o)}{B_g} + \frac{S_o R_s \varrho^*_g}{B_o}\right]\right\}_k - AG_{k-1} + \Delta G''_p = 0 \quad \ldots (3.61)$$

5. Calculate the gas saturation: $S_g = 1 - S_w - S_o$.
6. Calculate relative permeability ratio as a function of gas saturation. This is done by linear interpolation on $\log(k_{rg}/k_{ro})$ versus S_g. If k_{rg} or k_{ro} is zero, the logarithm is approximated by a large negative or positive number, respectively.
7. Now, AO_k , AG_k , RO_k , and RG_k can be calculated, (See Eqs. 3.47 - 3.50)
8. Calculate incremental oil production from free reservoir oil, $\Delta N''_{pf}$, (see Eqs. 3.55, 3.57 and 3.62). This variable connects the oil and gas equations.

$$\Delta N''_{pf} = \Delta G''_p \; / \; RG_{avg} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.62)$$

9. Calculate the incremental oil volume produced, $\Delta N''_p$, from Eqs. 3.56.

$$\Delta N''_p = \Delta N''_{pf} \; RO_{avg} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.56)$$

10. Calculate the material-balance error, ΔE, from the oil material-balance equation since the gas material balance is satisfied.

$$\Delta E = AO_k - AO_{k-1} + \Delta N''_p \quad \ldots\ldots\ldots\ldots\ldots \quad (3.63)$$

3.3.1 A Comment to the Implementation in GMS.

The relative permeability ratio (RPR), k_{rg}/k_{ro}, is calculated as a function of gas saturation by interpolation in tables. If the rate and pressure, during material-balance iterations, are too far from the values giving a material-balance error equal to zero, the gas saturation as calculated by the MB routine (see the procedures outlined above) might be outside the interval of the gas-saturation table. This gas saturation can *not* be used for interpolation. In such cases, the interpolation variable is set equal to the endpoint of the gas-saturation table being closest to the calculated saturation, and RPR is found from this endpoint saturation. This approach does not create any problems for the subsequent calculations because as the RPR → 0, the gas saturation → 0 and as RPR → ∞, the gas saturation → maximum possible gas saturation, asymptotically (see Appendix B.1 for plot of RPR).

Though saturation values might be *"unphysical"* (i.e., negative or greater than unity) during the iteration process, the material-balance error is a monotonous, smooth function of pressure for the whole pressure range. Because of this, the unphysical gas saturations can be used *unaltered* in all the equations following the RPR interpolation (see Appendix A.6).

3.4 Material Balance with Constant Surface Densities

This material-balance formulation is identical to the general MB except for the surface-density ratios (ρ^*) which are not included in the equations here. The same effect is obtained by employing the general MB and specifying ρ^* equal to unity on input.

Chapter 4

INFLOW-PERFORMANCE RELATIONSHIPS (IPR)

4.0 Introduction

The purpose of the inflow-performance calculations of GMS is to estimate the *bottomhole flowing pressure* (BHFP) of the well. The calculations are based on equations which relate reservoir and fluid properties, average reservoir pressure and BHFP. These equations are essentially the same as some equations applied for well test analysis,[12] although they are solved differently. In well test analysis, the rate and pressure history is known and reservoir and fluid parameters have to be estimated, whereas in reservoir simulation, rate and pressure are calculated as functions of time.

In reservoir simulation the reservoir is usually divided into several cells (gridblocks), and a set of differential equations describing the interactions between these cells is solved numerically.[13] GMS has a *zero-dimensional* description of the reservoir (one cell) where the MB procedure calculates the average reservoir pressure, while the IPR procedure calculates the BHFP.

4.1 Assumptions and Basic Ideas

The MB and IPR approach require several assumptions about the reservoir, the production system and the fluid system. These assumptions are listed below and discussed in the subsequent sections.

The idealized reservoir which is being simulated is assumed to be homogeneous, isotropic, bounded by no-flow boundaries (closed), horizontal and of uniform thickness. Each well has a cylindrical drainage radius (see Section 4.1.2). Initially, the entire pore volume is filled with oil at or above the bubblepoint pressure, or gas at or above the dewpoint pressure in addition to connate water. It is assumed that the production mechanism is solution-gas drive without a gas cap for oil reservoirs, and depletion drive for gas reservoirs. The effects of capillary pressure, gravity, and gas or water coning are neglected. Production is assumed to take place under pseudosteady-state conditions and at a constant production rate (see

Section 4.1.1).

The inflow-performance routine of the model is based on pseudo-pressure calculations which are performed by the numerical integration of a pressure function. This pressure function accounts for both the free and solution flow of the preferred phase in the reservoir. Pseudopressure and inflow-performance calculations rely on an assumption of a constant producing GOR throughout the reservoir.

More about the assumptions

As a consequence of having a closed hydrocarbon reservoir with no gravity effects and initially only one mobile phase, gas or water coning problems do not exist and are not dealt with in this study. Since the reservoir is closed, there is no aquifer influence. Secondary recovery methods (e.g., water or nitrogen injection) are not considered.

All real reservoirs are inhomogeneous and anisotropic, and there are different ways of accounting for this. In models which simulate directional flow, the reservoir is divided into several cells, which makes a reservoir description more detailed. Nevertheless, one still has to find representative data for each cell, which might be difficult at an early stage of the development of a field. Input description of heterogeneities might be generated by stochastic methods,[14] but again this requires a certain minimum of reservoir information in order to be useful.

Initially, the reservoir contains only one hydrocarbon phase (gas or oil), but as the pressure is lowered, a second phase evolves. If the initial fluid is oil, gas will evolve, and if the initial fluid is gas, oil will evolve due to retrograde condensation. These liberation mechanisms are highly dependent on the PVT properties of the fluids.

Neglecting gravity effects means that (in the model) there is no segregation of oil and gas due to buoyancy (caused by density difference), and that liberation is unaffected by the hydrostatic head difference, just as if the reservoir was very thin - i.e., the oil and gas saturations are not functions of depth.

All these assumptions affect reservoir performance, with a severity varying from case to case. However, at an early stage when only a PVT report, a well test, and a log analysis for one or a few wells are known, the field description is rather insufficient, and this is likely to cause uncertainties in the reservoir performance of

the same magnitude or larger than the assumptions described above.

4.1.1 Flow Behaviour: Infinite Acting and Pseudosteady State

When the well is opened to flow, a pressure drop is propagated through the formation. The well is said to be infinite acting (IA) while this pressure transient is moving outwards from the well and before it has reached any no-flow boundary of the drainage volume. When the no-flow boundary is reached all over, the well is producing in the pseudosteady-state (PSS) period, which means that the rate of pressure decline is equal and constant throughout the whole reservoir. If the boundary is a constant-pressure boundary, the flow is steady state (SS), which means that the flow rate and pressure are constant in the whole reservoir. Different equations should be applied for the different flow regimes.

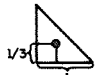
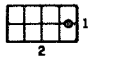
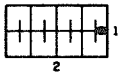
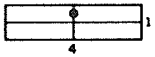
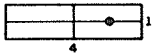
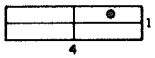
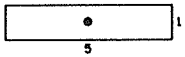
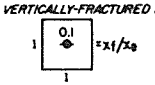
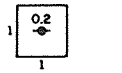
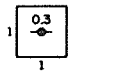
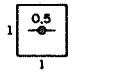
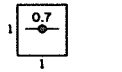
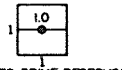
The GMS program is based on equations developed for the PSS period. The PSS period starts when the dimensionless time t_{DA} equals 0.1 (for a circular drainage area) (see Table 4.1). Expressed in time, this is

$$t = \frac{0.1\ \phi\mu c_t A}{k} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (4.1)$$

where t = time, s
(k/μ) = total mobility, $m^2/Pa\ s$
c_t = total compressibility, Pa^{-1}
ϕ = formation porosity, fraction
A = drainage area, m^2
k = permeability, m^2
μ = viscosity, Pa s

Earlougher[12] discusses the application of Eq. 4.1 to multiple-phase flow. The permeability is the most important parameter here, because it can vary within the range of 0.001 to 10,000 $10^{-15}\ m^2$, while the other parameters do not usually vary within such a large interval. As on can see, a small permeability would give a long IA period. During the IA period, the PSS equations yield pessimistic production rates. For plateau production this would be seen as a difference in plateau duration. Calculations are, however, also affected by the the

TABLE 4.1--SHAPE FACTORS FOR VARIOUS CLOSED SINGLE-WELL DRAINAGE AREAS. AFTER EARLOUGHER.[12]

IN BOUNDED RESERVOIRS	C_A	$\ln C_A$	$1/2 \ln\left(\frac{2.2458}{C_A}\right)$	EXACT FOR $t_{DA}>$	LESS THAN 1% ERROR FOR $t_{DA}>$	USE INFINITE SYSTEM SOLUTION WITH LESS THAN 1% ERROR FOR $t_{DA}<$
	31.62	3.4538	-1.3224	0.1	0.06	0.10
	31.6	3.4532	-1.3220	0.1	0.06	0.10
	27.6	3.3178	-1.2544	0.2	0.07	0.09
	27.1	3.2995	-1.2452	0.2	0.07	0.09
	21.9	3.0865	-1.1387	0.4	0.12	0.08
	0.098	-2.3227	+1.5659	0.9	0.60	0.015
	30.8828	3.4302	-1.3106	0.1	0.05	0.09
	12.9851	2.5638	-0.8774	0.7	0.25	0.03
	4.5132	1.5070	-0.3490	0.6	0.30	0.025
	3.3351	1.2045	-0.1977	0.7	0.25	0.01
	21.8369	3.0836	-1.1373	0.3	0.15	0.025
	10.8374	2.3830	-0.7870	0.4	0.15	0.025
	4.5141	1.5072	-0.3491	1.5	0.50	0.06
	2.0769	0.7309	+0.0391	1.7	0.50	0.02
	3.1573	1.1497	-0.1703	0.4	0.15	0.005
	0.5813	-0.5425	+0.6758	2.0	0.60	0.02
	0.1109	-2.1991	+1.5041	3.0	0.60	0.005
	5.3790	1.6825	-0.4367	0.8	0.30	0.01
	2.6896	0.9894	-0.0902	0.8	0.30	0.01
	0.2318	-1.4619	+1.1355	4.0	2.00	0.03
	0.1155	-2.1585	+1.4838	4.0	2.00	0.01
	2.3606	0.8589	-0.0249	1.0	0.40	0.025
IN VERTICALLY-FRACTURED RESERVOIRS	USE $(x_e/x_f)^2$ IN PLACE OF A/r_w^2 FOR FRACTURED SYSTEMS					
 $=x_f/x_e$	2.6541	0.9761	-0.0835	0.175	0.08	CANNOT USE
	2.0348	0.7104	+0.0493	0.175	0.09	CANNOT USE
	1.9986	0.6924	+0.0583	0.175	0.09	CANNOT USE
	1.6620	0.5080	+0.1505	0.175	0.09	CANNOT USE
	1.3127	0.2721	+0.2685	0.175	0.09	CANNOT USE
	0.7887	-0.2374	+0.5232	0.175	0.09	CANNOT USE
IN WATER-DRIVE RESERVOIRS						
	19.1	2.95	-1.07	—	—	—
IN RESERVOIRS OF UNKNOWN PRODUCTION CHARACTER						
	25.0	3.22	-1.20	—	—	—

assumption of a constant producing GOR throughout the formation (see Section 4.3) and the neglection of the saturation and relative permeability distributions in the reservoir, which results in the opposite effect (optimistic rates from GMS). This can be seen from comparisons with a simulation that uses a radial refined grid (see Sections 7.5.3 and 7.6).

If the superposition principle is applied, a change of the production rate is equal to the opening of an imaginary production or injection well at the same position as the old well, while the old well produces with unchanged rate. The equations are then used for each well separately, and the results are superpositioned. GMS does not perform any superposition when the production rate is changed - i.e., a variable-rate history is not accounted for. It should be noted that superposition would require more computing time.

4.1.2 Skin Factors and Drainage Area Shape

The skin factor[12] accounts for several altered flow conditions compared to the ideal case. The GMS program requires as input a "formation" skin factor, s, and a rate dependent skin term, D. These are composite quantities as given by Eqs. 4.2a and 4.2b:

$$s = s_c + s_A + s_G + s_{dp} + \left(\frac{h}{h_p}\right) s_p + \left(\frac{h}{h_p}\right) s_a \qquad (4.2a)$$

$$D = D_R + D_a + D_{dp} + D_G \qquad (4.2b)$$

where s = formation skin factor (not rate dependent), dimensionless

D = non-Darcy flow coefficient (rate dependent skin term), s/m^3

h = net formation thickness, m

h_p = height of perforated interval, m

and subscripts

c = partial penetration

A = drainage area shape

G = gravel pack

dp = damaged perforation

p = perforation

a = damage/stimulation
R = reservoir

The skin factor (s), and the non-Darcy flow coefficient multiplied by the production rate (D q) are dimensionless quantities.

For idealized conditions, all the skin factor components are zero. A positive skin factor means higher resistance to flow (e.g., a damaged zone around the well), while a negative skin factor indicates less resistance to flow (e.g., a stimulated well). Since the skin factor may change with time, it can be given as a function of time in the input to GMS. This also enables the investigation of the effect of stimulation (giving negative skin) of all the wells in the field.

The drainage-area-shape skin factor accounts for noncylindrical drainage area of the well and can be calculated as:

$$s_A = 0.5 \ln\left(\frac{31.62}{C_A}\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots (4.3)$$

where C_A = shape factor.

The shape factor is given by Table 4.1. A more detailed description of calculation procedures for these skin factor components is given by Golan and Whitson[15] (Chapter 3).

4.2 Developing the Equations

The traditional IPR equations for solution-gas drive oil reservoirs and depletion drive gas reservoirs are considered first, as they form the basis of the further developments. The pseudopressure concept is then introduced, and the equations are modified to give better results than the traditional approach for volatile oils and rich gases. The chapter concludes with a description of the calculation procedure.

4.2.1 Traditional Equations

Starting from Darcy's law in differential form, a relationship between the BHFP, average reservoir pressure, production rate, and pressure-dependent properties is developed. Darcy's law for radial flow of oil:

$$u_{of} = \frac{k k_{ro}}{\mu_o} \frac{\partial p}{\partial r} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.4)$$

where u_{of} = velocity of free reservoir oil (volumetric flux per unit area), m/s

k_{ro} = relative permeability to oil, fraction

μ_o = oil viscosity, Pa s

p = pressure, Pa

r = radial distance from the well, m

For the geometry considered here, the volumetric velocity (u_{of}) can be written in terms of the production rate at standard conditions (q_{of}) and formation volume factor (B_o) as:

$$u_{of} = \frac{q_{of} B_o}{2\pi r h} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.5)$$

where q_{of} = oil production rate from free reservoir oil, at standard conditions, Sm^3/s

B_o = oil formation volume factor, Rm^3/Sm^3

Combining Eqs. 4.4 and 4.5, eliminating the velocity u_{of} and integrating with respect to radial distance, r, from the well sandface to the outer drainage boundary leads to:

$$\int_{r_w}^{r_e} \frac{q_{of}\, B_o}{2\pi h\, r}\, dr = \int_{r_w}^{r_e} \frac{k k_{ro}}{\mu_o} \frac{\partial p}{\partial r}\, dr \qquad \ldots\ldots\ldots (4.6)$$

where r_w = wellbore radius, m

r_e = radius of drainage area, m

Since the pressure distribution throughout the reservoir is not known, Eq. 4.6 is modified to solve this problem and the result is given by Eq. 4.7:

$$q_{of} = \frac{2\pi kh}{\ln(r_e/r_w)} \int_{p_{wf}}^{p_e} \frac{k_{ro}}{\mu_o\, B_o}\, dp \qquad \ldots\ldots\ldots (4.7)$$

where p_e = pressure at external boundary of drainage area, Pa

p_{wf} = bottomhole flowing pressure, Pa

The theoretical basis for this simplification about the pressure distribution is discussed by Bøe *et. al*,[16] and Jones and Raghavan.[17] Eq. 4.7 is valid for steady-state, radial flow and constant production rate since it originates from an integration of Darcy's equation.[18,19] The following equation, where the skin factor is also included, applies for PSS flow:[20,21]

$$q_{of} = \frac{2\pi kh}{\ln(r_e/r_w) - 0.75 + s} \int_{p_{wf}}^{p_R} \frac{k_{ro}}{\mu_o\, B_o}\, dp \qquad \ldots\ldots (4.8)$$

where p_R = average reservoir pressure, Pa

If desired, one can include the rate dependent skin term, D, as well. This is done in Eq. 4.9 which is written in terms of the *pseudopressure function, m(p)*:

$$q_{of} = \frac{2\pi kh}{\ln(r_e/r_w) - 0.75 + s + Dq_{of}} \left[m(p_R) - m(p_{wf}) \right] \quad (4.9)$$

where $$m(p) = \int_0^p \frac{k_{ro}}{\mu_o B_o} dp \quad \ldots\ldots\ldots\ldots\ldots\ldots (4.10)$$

4.2.2 Modified IPR Equations (used with General PVT and Material-Balance Data)

The modification described by Bøe *et al.*[16] is based on the general PVT and MB formulations. With volatile oil reservoirs a considerable volume of oil might be produced from reservoir gas.[2] Since the oil rate measured at the surface is the total oil rate, it would be practical to have q_o instead of q_{of} in Eq. 4.9. This is achieved by modifying the pseudopressure correspondingly (see Eqs. 4.11, 4.12). The pseudopressure integrand is expanded with a term representing the additional oil originating from free reservoir gas.

$$q_o = \frac{2\pi kh}{\ln(r_e/r_w) - 0.75 + s + Dq_o} \left[m(p_R) - m(p_{wf}) \right] \quad (4.11)$$

and $$m(p) = \int_0^p \left(\frac{k_{ro}}{\mu_o B_o} + \frac{k_{rg}\, r_s}{\mu_g B_g} \right) dp \quad \ldots\ldots\ldots (4.12)$$

where q_o = total surface oil production rate from free reservoir oil and from solution in free reservoir gas, Sm^3/s

k_{rg} = relative permeability to gas, fraction

μ_g = gas viscosity, Pa s

B_g = gas formation volume factor, Rm^3/Sm^3

r_s = solution oil/gas ratio in gas, Sm^3/Sm^3

The amount of oil produced from free reservoir gas depends on the gas mobility and the solution oil/gas ratio in gas. These quantities are accounted for in Eqs. 4.11 and 4.12. The modification is general,

because for dry gas (evolved from oil), r_s is zero, and the equations reduce to the traditional ones. For gas the corresponding equation is

$$q_g = \frac{2\pi kh}{\ln(r_e/r_w) - 0.75 + s + Dq_g} \left[m(p_R) - m(p_{wf}) \right] \quad (4.13)$$

and

$$m(p) = \int_0^p \left(\frac{k_{rg}}{\mu_g B_g} + \frac{k_{ro} R_s}{\mu_o B_o} \right) dp \quad \ldots\ldots\ldots (4.14)$$

where q_g = total surface gas production rate from free reservoir gas and from solution in free reservoir oil, Sm^3/s

R_s = solution gas/oil ratio in oil, Sm^3/Sm^3

Flow conditions in a condensate reservoir can vary widely with time and fluid distribution and is strongly influenced by production history and initial parameters. Since uncertainties are often larger with condensate reservoirs than with oil reservoirs, Eqs. 4.13 - 4.14 might be not as satisfactory as their analogous oil equations.[22-24] It is also found that as the gas saturation increases, the analysis for oil becomes less accurate.[17]

4.3 Estimating the Pseudopressure Function

The pseudopressure function m(p) is a function of pressure (due to the pressure dependent fluid property variables) and saturation (due to the relative permeability variables). Both pressure and saturation are functions of the distance from the well. Hence, saturation is indirectly a function of pressure. By assuming a constant producing GOR throughout the reservoir,[6,10,21] this relationship can be found, and the pseudopressure computed. The calculation procedure for the pseudopressure function with the general formulation of the MB (see Eqs. 4.11 and 4.12) is described below. The producing GOR is approximated by:

$$R = \frac{\Delta G_p}{\Delta N_p} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.15)$$

where R is the producing gas/oil ratio, and ΔG_p and ΔN_p are incremental gas and oil production, Sm^3, at standard conditions. To calculate saturations, the mobility ratio of free gas to free oil in the reservoir must be estimated. This is done by dividing the production term of the general gas material balance (Eq. 3.44) by the production term of the corresponding oil equation (Eq. 3.43) and equating this to the producing GOR of Eq. 4.15 which is known from MB calculation of the current timestep. The mobility ratio, M_b, as defined below, is then isolated in the resulting equation.

$$\frac{\Delta N''_{pf}\ (M_b + R_s\ \varrho_g^*)}{\Delta N''_{pf}\ (1 + r_s\ \varrho_o^*\ M_b)} = R \qquad \ldots\ldots\ldots\ldots \quad (4.16)$$

Rearranging gives:

$$M_b = \frac{R - R_s\ \varrho_g^*}{1 - R\ r_s\ \varrho_o^*} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.17)$$

where M_b is defined by:

$$M_b = \frac{k_{rg}\mu_o B_o}{k_{ro}\mu_g B_g} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.18)$$

and $\Delta N''_{pf}$ = incremental oil production during the last timestep from free reservoir oil divided by reservoir bulk volume, dimensionless

ϱ_o^* and ϱ_g^* = dimensionless density ratios for oil and gas, defined by Eqs. 3.45 and 3.46.

Having calculated M_b, the relative permeability ratio is found from Eq. 4.18. Since RPR is only a monotonous function of saturation (e.g., gas saturation), this procedure enables gas saturation to be calculated as a function of pressure for each timestep. Finally, the relative permeabilities required by the pseudopressure function are found as functions of saturation, and the numerical integration can be performed. The calculation sequence is:

$$M_b = f(p,R), \quad \text{(see Eq. 4.17)} \qquad \ldots\ldots\ldots\ldots \quad (4.19)$$

$$\frac{k_{rg}}{k_{ro}} = f(M_b) \quad \text{(see Eq. 4.18)} \qquad \ldots\ldots\ldots\ldots \quad (4.20)$$

$$S_g = f\left(\frac{k_{rg}}{k_{ro}}\right) \quad \text{(from table or graph)} \qquad \ldots\ldots\ldots \quad (4.21)$$

$$k_{ro} \text{ and } k_{rg} = f(S_g) \quad \text{(from table or graph)} \qquad \ldots\ldots \quad (4.22)$$

4.4 IPR Calculation Procedure

Using the IPR equation on the present problem, BHFP is the only unknown variable. Rewriting Eq. 4.11 results in:

$$\int_{p_{wf}}^{p_R} \left(\frac{k_{ro}}{\mu_o B_o} + \frac{k_{rg}\, r_s}{\mu_g B_g}\right) dp = C_3 \qquad \ldots\ldots\ldots\ldots \quad (4.23)$$

$$C_3 \equiv q_o \frac{\ln(r_e/r_w) - 0.75 + s + Dq_o}{2\pi kh} \qquad \ldots\ldots\ldots \quad (4.24)$$

C_3 (defined by Eq. 4.24) is a constant for each timestep. The BHFP is estimated by numerical integration of the left-hand side of Eq. 4.23. GMS integrates using *Simpson's method*. A small "area" is added to the summation variable, and the cumulative area is checked for each new pressure step. When this area has exceeded the value of C_3, the solu-

tion to p_{wf} is found by a modified Newton-Raphson iteration technique which adds or subtracts small areas until convergence is achieved.

4.5 A Method to Compare IPR Equations

By modifying the IPR equations implemented in GMS and applying some simplifying assumptions, one arrives at a parameter suitable for comparing IPR's calculated by application of different formulations of the oil and gas flow equations (e.g., a fully implicit numerical model and GMS). Start with Eqs. 4.11 and 4.12, and assume that the pseudopressure integrand is a straight line ranging from $1/\mu_o B_o$ at the bubblepoint pressure to the origin. This assumption is acceptable for saturated oil.[15] Also, assume D=0. Then, the pseudopressure can be found analytically, resulting in:

$$q_o = C(p_R^2 - p_{wf}^2) \qquad \ldots\ldots\ldots\ldots\ldots\ldots (4.25)$$

where $$C \equiv \frac{2\pi kh}{2\,\mu_o\,B_o\,p_R\,[\ln(r_e/r_w) - 0.75 + s]} \qquad \ldots\ldots (4.26)$$

Rearranging Eq. 4.25 gives,

$$C = \frac{q_o}{(p_R^2 - p_{wf}^2)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (4.27)$$

The C variable (defined by Eqs. 4.26 and 4.27), which is called the performance coefficient, is an expression of difference in squared pressures normalized with respect to production rate. For oil, C is a function of average reservoir pressure, which again is a function of cumulative production (N_p). The right hand side of Eq. 4.27 is plotted versus N_p or versus time. For the evaluation of inflow-performance procedures one can also compare BHFP, production rate, and producing gas/oil ratio.

Chapter 5

PROGRAM DOCUMENTATION, USER'S GUIDE

5.0 Introduction

The program is called GMS which stands for: "A General Material-Balance and Inflow-Performance Simulation Model for Oil and Gas-Condensate Reservoirs". An entire hydrocarbon field, with multiple wells, can be simulated, and oil and gas rates (on a well and field basis), average reservoir pressure, bottomhole flowing pressure (BHFP) and wellhead pressure are reported as functions of time. The main objective of the GMS program is to serve as an easy-to-use and fast reservoir simulation model for preliminary predictions. The model is suitable for predictions of field performance at an early stage of the field development when data are scarce. It could also be combined with a model for the optimization of field-development strategies (after some extensions) since it is not so time consuming on the computer (see Sections 7.7 and 7.10).

Emphasis has been put on making the output easy to read. It was also borne in mind that the programmed code should be easily interpreted in case of future modifications. This chapter discusses the modelling and the major assumptions applied in the program at a higher level.

5.1 Modelling, Major Assumptions and Limitations

One of the basic ideas of the model is that all the wells are "equivalent", having identical IPR's and produce at the same average reservoir conditions. The reservoir is modelled zero-dimensionally with a MB procedure. Inflow to the well is estimated with IPR equations which give the BHFP as a function of the production rate, fluid properties, reservoir properties and average reservoir pressure. An artificial function is implemented for pressure loss in the production string (see Sections 6.2.6 and 7.11).

Multiple Wells

One of the benefits of assuming that all wells in the field have the same IPR is that execution time is not increased significantly by an increasing number of wells. The calculations are performed on one well, and the results are multiplied by the number of wells to determine field production quantities. The wells are assumed to have circular drainage areas and radial flow towards the wellbore. This is unlikely to be the case in a real reservoir during the PSS period. To account for irregular drainage area shapes and nonradial flow due to the reservoir geometry and well locations, the user can supply a drainage area skin factor. This skin factor was discussed in the IPR chapter previously.

The simulation starts with the average reservoir pressure being greater than or equal to bubblepoint pressure for oil reservoirs and greater than or equal to dewpoint pressure for gas-condensate reservoirs. Hence, there is only one hydrocarbon phase present initially. The water phase is assumed to be *immobile*, so it will not be produced. The drive mechanism is solution-gas drive for oil reservoirs and depletion drive for gas reservoirs. In both cases all the drive energy comes from the hydrocarbons in place. Injection and aquifer effects are not considered. The model does not handle gas or water coning. The user should be aware of the assumptions and limitations of the model and determine whether it could be applied for a given simulation problem or not.

5.2 Error Types and Messages

All the input data are checked in accordance with given restrictions. The control is performed just after reading each data item, and error messages are written to the output file immediately. If any errors are detected, the program terminates after having printed out the input data as usual.

The following tests are performed: Each data item is checked to see that it is within a permitted interval. The points of time in the well control table, the pressures in the PVT-data table and the gas saturations in the relative permeability table are checked for strict increases down the column. Since the PVT-data table is divided into

two sections, these are controlled to have an equal number of entries. The relative permeability table is tested to cover the necessary interval for the given interstitial water saturation, assuming in the first case zero gas saturation and in the second case zero oil saturation. The error reports show a message, a value and a permitted interval.

All the major subroutines have a section for messages. These messages start with the subroutine name and timestep number. Messages are written if errors are detected or just to inform the user about the run. If a subroutine detects an error, a message is written, the control is in most cases passed "upwards" to the main program, tables of results are written and the execution is terminated.

5.3 GMS Program System Data

The GMS program system is supplied on a diskette (enclosed for some copies of this report). The diskette which is formatted to 360K, works on IBM-PC/AT compatible computers.

The diskette contains the following files:

1. GMS.FOR	GMS program system source code, all in Standard ANSI 77 Fortran .....:	86K
2. GMS.EXE	GMS program in executable version .....:	146K
3. DEMO.DAT	Input file, oil system .....:	3K
4. COND.DAT	Input file, gas-condensate system .....:	3K
5. PLOT-GMS.FOR	Program for preparation of plot files for the program PLOT (ND computer).	
6. PLOT-GMS.TXT	Texts necessary for running PLOT-GMS.	

The GMS program on file GMS.FOR is divided into 14 routines and contains 2560 Fortran lines, of which 950 are comment lines. The maximum number of timesteps is 500 and maximum number of lines in input tables is 100.

GMS is executed as an ordinary Fortran program. Input and output file names are prompted from the keyboard.

5.4 Communication

The program communicates with one input data file, one output file for results (see Appendix B) and the keyboard and screen (standard I/O device).

5.4.1 Input Data File Description

General description.

The first line on the input file is the "job identification". Below this line there are two kinds of lines (cards), (1) data lines and (2) comment lines. Any line, which starts with a number (0-9), a decimal point (.) or the signs (+ -) in the first nonblank position, is treated as a data line. All other lines are regarded as comment lines and *ignored* by GMS. One may arbitrarily have comment lines between the data lines. The data lines, as well as the data items on each line, have to follow a given sequence. The format on each line is *"list directed"* Fortran format (e.g., READ (n,*) VAR) so the data items should be separated by a comma and/or one or more spaces.

File structure.

The first data line below the job identification contains integer data controlling the execution mode. The two next data lines contain single real parameters specifying the timestep and reservoir parameters. The last section of the file enters four tables, (1) well control, (2) pressure dependent properties of oil, (3) pressure dependent properties of gas, and (4) relative permeability. The input variables are described in the GMS program listing and the User's Input Manual (Appendices A.1 and C).

Unit systems.

There are two unit systems available, "Metric" units and "Oil Field" units. In the input file one of the two unit systems is chosen. All input must be consistent with the indicated unit system. The output is written in both unit systems.

5.4.2 Output

The first part of the output is a review of the input data. The final results are written as tables at the end of program execution (see Appendix B.4). Output of several variables to the screen each timestep can be specified. This option is intended for debugging purposes.

5.4.3 Parameter Lists

The variables that appear in parameter lists for the transfer of data between program modules are sorted from left to right in accordance with specific rules. The sorting is done on three levels, with the first level as the most significant one: (1) input to the subroutine, output from the subroutine; (2) double precision, integer, character, logical; (3) arrays, single variables. An example of this is given in Fig 5.1. No variables are assigned both for input and output. This is to avoid confusion. (There is one exception: the error counter.)

```
      CALL SUB (AR1,B,C,IAR1,I,J,ZA,ZB,Q1,Q1,X,Y,Z,K,Z,QS)

input/output     IIIIIIIIIIIIIIIIIIIIIIIII OOOOOOOOOOO
real/int/chr/log xxxxxxx iiiiiii zzzzz qqqqq xxxxx i z qq
array/single     aaa sss aaaa sss sssss sssss sssss s s ss
```

Fig. 5.1--Example of the sorting of parameter lists for subroutine calls. I=Input to the subroutine, O=output from the subroutine, x=double precision, i=integer, z=character, q=logical, a=array, s=single variable.

Chapter 6

PROGRAM ARCHITECTURE

6.0 Introduction

The architecture of the GMS program is described by (1) a program listing and a flowchart - presented in Appendices A.1 and A.2, and (2) by a "call tree" and a description of each program module - located in this chapter.

6.1 Program Structure and Call Hierarchy

The program consists of the main program and 13 subroutines or functions. Table 6.1 gives the name of these routines with a short explanation. The TUBING subroutine is included merely as a preparation for future development.

TABLE 6.1 - GMS SUBROUTINE AND FUNCTION NAMES WITH EXPLANATION

Module name	*Explanation*
MAIN	This is the main program
RATE	Determines production rate
WHPRS	Determines wellhead pressure
RESPRS	Determines reservoir pressure
MATBAL	Calculates material-balance error
IPR	Calculates the inflow-performance relationship
FNPRS	Calculates IPR pressure function
TUBING	Calculates pressure loss in tubing
INTPL	Performs linear interpolation
ISGN	Finds the sign (-1, 0, +1) of a variable
SKIP	Skips text lines in data files
ITEST	Tests input data
TEST	Tests input data
TESTGE	Tests input data

These routines constitute a call tree as illustrated in Fig. 6.1. (The auxiliary routines INTPL, SKIP, ISGN, ITEST, TEST and TESTGE are not included in this figure.)

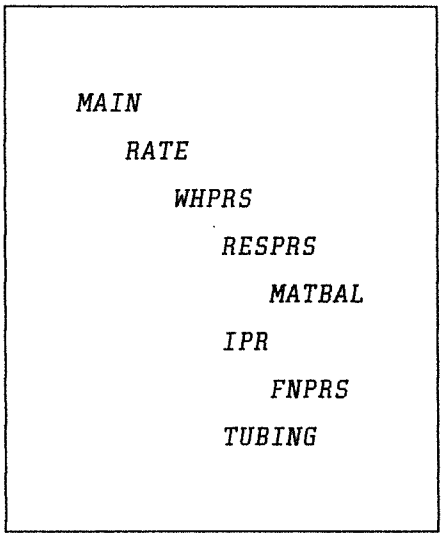


Fig. 6.1--Call tree of the GMS program.

6.2 Description of Each Program Module

The description gives an introduction to the qualitative performance of the main program and the subroutines presented in Fig. 6.1, and to the flow of control. No variable names are presented in this section since this is intended to be a general survey. If the GMS program listing, flow-chart and variable explanation (Appendices A.1 - A.3) are examined at the same time, it will be easier to get thoroughly into the system. The program listing is commented from the top.

6.2.1 GMS (MAIN)

The MAIN routine starts with reading the input file. If the input is supplied in Oil Field Units, it is converted to Metric Units since this is the unit system that is used for calculations by GMS. All output, as well as the "echo" of input data, are written in both unit systems. Variables are initialized, both local variables for the MAIN routine and variables belonging to common blocks for use in other modules. Some quantities, such as initial volumes of hydrocarbons in place and geometrical properties, are calculated and printed out.

The well and time control checks for well control specifications and takes care of variations in the number of wells, target and minimum rates, minimum bottomhole or wellhead pressure, and timestep length as functions of time. As a special feature, reports are made at all integer multiples of the timestep length up to maximum time in addition to the points of time specified in the well control input (see Section 7.4, point 4). If zero wells are specified, the run terminates. (The program makes its own specification of zero wells at maximum time, and this serves as the normal termination switch.) The reservoir pressure, BHFP, wellhead pressure, and production rate are then calculated by calling subroutine RATE. Variables for the next timestep are updated. Detailed output is written if the print option is in the debug mode. At the end of the timestep loop there is a check if the rate approaches zero. In that case calculation is terminated. The output and format sections are situated below.

6.2.2 RATE

The RATE subroutine determines the oil and gas production rates. This is done so that the rate of the preferred phase is as high as possible without any violation of the specified target (maximum) rate or the specified minimum wellhead pressure.

If the calculated wellhead pressure is too low after the first calculation, the rate is reduced until the wellhead pressure is equal to the specified minimum. This is done first by a stepwise search to establish a rate interval with a solution. If an interval is found, the rate is calculated by a modified chord method. If an interval is *not* found, control is passed to the main program and execution is terminated. If the calculated wellhead pressure is *higher* than the minimum (after the first calculation), and the rate is unchanged by the

RESPRS and IPR subroutines, then everything is satisfactory, and control is returned to the main program. On the other hand, if the wellhead pressure is higher than the specified minimum *and* the rate has been reduced by RESPRS or IPR, this means that PVT data are needed for lower pressures than what is supplied in the input PVT tables. (Note: No extrapolation is performed on tabulated data, so this situation interrupts the normal calculation procedure. In the text this is called "lack of PVT data".) In this case, lack of PVT data controls the rate, so the results from this timestep are disregarded. A message is written in addition to the ordinary tables of results, and the execution is terminated.

6.2.3 WHPRS

The WHPRS subroutine calculates the wellhead pressure as a function of rate. This requires the calculation of the average reservoir pressure, the BHFP, and pressure loss in tubing by calls to RESPRS, IPR and TUBING (see Section 6.2.6), respectively. The average reservoir pressure calculated by RESPRS is given as input to IPR without any averaging over the timestep.

The RESPRS and IPR may reduce the rate due to lack of PVT data. If such a rate reduction is done by the RESPRS subroutine, nothing special happens then, except the setting of a logical flag to inform the RATE subroutine, but if the IPR subroutine reduces the rate, then adjustments are required. This reduced rate will not match with the previous MB calculations, so RESPRS and IPR must be called again. To overcome this problem, a function is defined, which is the the difference between the output rate from RESPRS and the output rate from IPR. The input rate to RESPRS is the free variable of this function. Iterations are performed to find the input to RESPRS which makes the function equal to zero. This problem is solved by a sequential search to find a subinterval with a solution and then, if an interval is found, by the application of a modified chord method. It should be noted that the input rate to IPR is set equal to the timestep target rate. This is to ensure that the IPR subroutine will reduce the rate due to lack of PVT data at each call after the solution process has started. This reduced rate is indirectly a function of the input rate to RESPRS because of the average reservoir pressure. The process is considered to be convergent when the rate interval containing the solution is small enough (see Apppendix A.5).

6.2.4 RESPRS

RESPRS calculates the average reservoir pressure at the end of the current timestep. This is done by making the material-balance error, which is calculated by the subroutine MATBAL, approach zero. RESPRS receives a pressure interval and a rate. The pressure interval ranges from the minimum PVT-data pressure to a pressure slightly higher than that of the last timestep. The highest pressure is tried first as input to MATBAL, and the pressure is lowered until the material-balance error is zero. This is done first by a stepwise search to find an interval with a solution. If an interval is found, the pressure is calculated by a modified chord method. If an interval is *not* found, the minimum PVT-data pressure is assigned to the pressure variable, and the *rate* is reduced instead of the pressure. A rate which solves the material balance is calculated by using the *same* modified chord subroutine, but this time with the *rate* as the free variable. The initial rate interval ranges from zero to the rate initially given as input to RESPRS. This manipulation with the rate is necessary to get a solution so that the program execution may continue. The program must *not* be stopped on this level. This is because even though the rate can be reduced by RESPRS due to the lack of PVT data, the wellhead pessure calculated by WHPRS after RESPRS has finished processing might be lower than the specified minimum, which would cause the rate to be further reduced by the RATE sub-routine, and WHPRS and RESPRS to be called again. Consequently, the specified minimum wellhead pressure rather than the lack of PVT data would then be controlling the rate, which is normal during the decline period.

6.2.5 IPR

The IPR subroutine is called from WHPRS and calculates the pressure at the bottom of the well. This pressure is the only unknown in a given equation and appears as the lower integration limit in an integral in that equation. The integral equals a calculated constant. Integration is done by stepwise summation of "areas" calculated by Simpson's method until the sum is equal to the constant. In fact, the last sum is greater than the constant and the second last sum is less. A Newton-Raphson solution technique is applied to determine the pressure more accurately. Small areas are added or subtracted until

the sum equals the constant. The corresponding integration limit is the BHFP. If the rate is too large, the area will not be large enough because integration will stop at the minimum PVT-data pressure. The rate corresponding to *this* area is calculated instead and passed as output to the calling subroutine (WHPRS). The combination of rate and other parameters will then not match with material-balance calculations, so iterations must be performed, and the IPR subroutine called again (see Section 6.2.3 WHPRS).

6.2.6 TUBING

An artificial pressure loss function has been implemented. Note: This has been done merely as a preparation of the program structure for future developments (see Section 7.11). The function, which calculates the pressure loss by multiplying the rate by a constant, should be used for program testing only.

6.2.7 INTPL

Only linear interpolation is performed. The gas formation volume factor (B_g) and the relative permeability ratio (RPR), k_{rg}/k_{ro}, are found from interpolation in precalculated tables of $1/B_g$ and log(RPR), respectively. Using precalculated tables saves time compared to repeated calculation of $1/B_g$ and log(RPR) for each interpolation. During testing of the program it was found that a considerable amount of processing time could be saved by reducing the number of calls to the interpolation subroutine and performing interpolation in the calling subroutines instead. When a series of interpolations is needed (e.g., for calculation of pressure-dependent properties) INTPL performs the first interpolation including the search in tables and then returns information which enables the calling subroutine to continue (see Appendix A.4).

6.3 Data Structure

6.3.1 Variables

The variable names in GMS comply with the SPE standard[25-27] with a few exceptions (see Appendix A.3). The variable *type* is defined by the first letter of the variable name as listed in Table 6.2. The allocation of arrays and variables is static with arrays permitting 500 timesteps and 100 lines in each input table (PVT data and relative permeability).

TABLE 6.2--GMS DATA TYPE DEFINITIONS

FIRST LETTER OF VARIABLE NAME	*TYPE*
I-N	INTEGER
Z	CHARACTER
Q	LOGICAL
ALL OTHERS	DOUBLE-PRECISION

6.3.2 Common Blocks

The use of common blocks has been restricted to some well defined applications as given by Table 6.3. This table shows whether the variables of the common blocks are used for the read only, the write only, or both, by each subroutine.

TABLE 6.3--COMMON BLOCK LOCATIONS OF THE GMS PROGRAM R=READ ONLY, W=WRITE ONLY, X=READ AND WRITE

		COMMON BLOCK						
		PROP	MBAL1	MBAL2	MBAL3	IPR1	TUB	ICOUNT
SUBROUTINE	GMS	W	W	R	R	W	W	X
	RATE							X
	WHPRS							X
	RESPRS							X
	MATBAL	R	R	W	W			X
	IPR					R		X
	FNPRS	R						X
	TUBING						R	X
	ISGN							X
	INTPL							X

Chapter 7

RESULTS AND DISCUSSION

7.0 Introduction

The main result of this thesis is the development of a material-balance and inflow-performance model for oil and gas-condensate reservoirs. The model is implemented as a Fortran 77 program and called GMS. Test cases have been run with GMS and compared with results from other programs (ECLIPSE, TARNER and DRYGAS) and other GMS cases. A "post processor" program for the preparation of plot files has also been made.

7.1 The GMS Model

The GMS model can simulate production from an entire oil and gas field with multiple wells. All the wells are assumed to be "equivalent" and produce at the same average reservoir conditions, and have the same inflow-performance relationship. Thus, the calculations are performed on a well-basis which is multiplied by the number of wells to obtain field production quantities. The number of wells, field target and minimum production rates of the preferred phase, and minimum bottomhole or wellhead pressure control the execution. These are specified on the input as functions of time. The GMS model was described in more detail in the preceding chapters of this report.

The post-processor program called PLOT-GMS reads output files from GMS and prepares input files for the plotting program PLOT.* PLOT-GMS is listed in Appendix A.7.

* PLOT is a plotting program based on GPGS-F (a graphics package developed at RUNIT, U. of Trondheim).

7.2 Summary of Test Runs

Objectives

The test runs presented in the report were performed for the purpose of (1) demonstrating the well and time control facilities of GMS, (2) verifying the GMS MB-calculation procedure, (3) comparing the inflow-performance calculations of GMS with other models, (4) showing examples of sensitivity to timestep length and permeability variations, (5) finding effects of applying different PVT formulations, and (6) giving examples of the processing speed of GMS compared with other models.

Data sets

The following data sets were given mnemonic names: (1) BASE - the base case data set, (2) LTS - long timestep data set, (3) HPRM - high permeability data set, (4) CONV - conventional PVT formulation data set, and (5) GEN - general PVT formulation data set. The PVT relations for all these data sets refer to the same oil fluid system (see Section 7.3). The difference in PVT data is caused by the formulation applied to calculate the black-oil parameters. GEN utilized the general PVT formulation, having solution gas/oil ratio in oil, solution oil/gas ratio in gas, and surface densities of (1) the oil from solution in gas, (2) the oil from free reservoir oil, (3) the gas from solution in oil, and (4) the gas from free reservoir gas, as functions of reservoir pressure (see Section 2.3.2). BASE, LTS and HPRM used the same PVT data as GEN, except for the density ratios [(1)/(2) and (3)/(4) above], which were assumed to be equal to unity (see Section 2.3.3). The PVT data of CONV were calculated by the conventional formulation (see Section 2.3.1), having a solution oil/gas ratio equal to zero, density ratios equal to unity, and solution gas/oil ratio and formation volume factors different from the data sets previously mentioned.

Some points should be noted about these data sets. They all (1) have the same relative permeability data (see Section 7.3), (2) have a simple well and time control scheme - only one specification, and only one well in the field, and (3) have many data in common with the BASE data set. Some important data from the BASE data set are listed in Table 7.1 (see Appendix B.1 for the entire BASE data set). However,

three of the parameters in Table 7.1: hydrocarbon pore volume, initial porosity, and well radius, are too large to represent a real well. The differences between BASE and each of the other data sets (apart from the PVT data) are presented in Table 7.2. This table indicates that whereas GMS was run with all the data sets, ECLIPSE,* was only run for four of them. This was both as a monoblock model (ECL 1) and a one-dimensional radial model with 20 gridblocks (of equal length on a logarithmic scale) (ECL 20). To allow for comparisons with ECLIPSE, the density ratios were set equal to unity because ECLIPSE does not consider surface densities as functions of the reservoir pressure.

* ECLIPSE is a commercial, general, three-dimensional, fully implicit reservoir simulator.

TABLE 7.1 - VALUES OF SOME IMPORTANT INPUT VARIABLES (BASE DATA SET)

Variable Name in GMS	*Value*	*Explanation*
IHC	1	preferred phase is oil
DELTIM	1/24 years	timestep length
HCPV	9.0 10^{7} m^{3}	hydrocarbon pore volume
PORI	0.40	initial porosity
SATWI	0.30	initial water saturation (connate)
CMPF	0.0 kPa^{-1}	formation compressibility
PRM	14.0 10^{-15} m^{2}	permeability (≈14 md)
THK	50.0 m	reservoir thickness
RADW	0.20 m	well radius
SKN	0.0	skin factor
DSKN	0.0	rate dependent skin term
NWELLS	1	number of wells
TRTEFM	12.0 m^{3}/D	field minimum production rate
TRTEFT	1200.0 m^{3}/D	field target production rate
TPWMIN	1.0 10^{5} kPa	minimum wellhead pressure (i.e., in this case minimum BHFP since TF=0.)

TABLE 7.2 - KEY PARAMETERS FOR TEST RUNS OF GMS AND ECLIPSE

RUN ID.	Δt	ϱ^*	r_s	k	*EXPLANATION*
GMS and ECLIPSE:					
BASE	1/24	1.0	f(p)	14.0	Base Case
LTS	1/2	1.0	f(p)	14.0	Long Timesteps
HPRM	1/24	1.0	f(p)	100.0	High Permeability
CONV	1/24	1.0	0.0	14.0	Conventional PVT formulation
GMS only:					
GEN	1/24	f(p)	f(p)	14.0	General formulation

Note: For CONV, the PVT data are based on the conventional formulation, giving different B_g, B_o, R_s and r_s

Δt = timestep length, years

ϱ^* = surface density ratios, dimensionless

r_s = solution oil/gas ratio, Sm^3/Sm^3

k = permeability, $10^{-15} m^2$ ($\approx$ md)

f(p) = "the quantity is a function of pressure"

Another case was run to demonstrate *the well control facilities* of GMS. This case, which applies a more complex control scheme, is described in Section 7.4.

7.3 Origin of Data Used for Program Runs

Relative permeability data were calculated by the COREY program made by C. H. Whitson. [This program applies the Corey *et al.*[28,29] model based on (1) irreducible water saturation, (2) pore-size distribution, (3) a saturation variable and (4) relative permeability of oil or gas at irreducible water saturation.] The same relative permeability data were used in all runs of GMS, ECLIPSE, DRYGAS and TARNER (see Appendix B.1 or B.2). Relative permeability curves for drainage were used for solution-gas-drive calculations because the oil is drained while the gas saturation develops.

For *PVT-data calculations*, three programs were employed: PVTX, FLASH and CVD (by C. H. Whitson). PVTX, which is a differential-liberation simulator, was used on a given oil composition of unknown origin. The resulting data were used as input to the subsequent calculations.

1. For the calculation of general PVT data, oil and gas were flashed separately to standard conditions by the multistage FLASH simulation program (see Section 2.3.2). [Output from FLASH was: B_o, B_g, μ_o, μ_g, R_s, r_s, ϱ_{og}^{STC}, ϱ_{oo}^{STC}, ϱ_{go}^{STC}, ϱ_{gg}^{STC} as defined in Chapter 3. Note that the densities are used only as ratios (ϱ_o^* and ϱ_g^*) by GMS.] The constant-surface-density PVT data are just a modification of the general PVT data.

2. Conventional PVT data were calculated by applying the equations of Section 2.3.1. (The oil and gas viscosities were taken from the FLASH run previously mentioned.)

For a gas-condensate composition of unknown origin, the CVD program took care of the CVD and flash calculations necessary for the calculation of the gas-condensate data set by the general formulation (see Section 2.3.2 and Appendix B.3).

7.4 Examples of Well and Time Control in GMS

The calculations of GMS are controlled by the target and minimum production rates of the preferred phase, as well as the minimum wellhead pressure or BHFP, and the number of wells. An example (the DEMO case) was run to show how this can work in practice. Plots of the output from GMS are presented in Figs. 7.1a - 7.1f, and the printed output is listed in Appendix B.4.

Explanation to Figs. 7.1a - 7.1f (DEMO case).
(Refer to the corresponding marks on the figures.)

1. Production starts with one well. The well is able to produce at the target rate.

2. The number of wells is increased to two, and the field target production rate is increased from 225 m^3/D to 450 m^3/D.

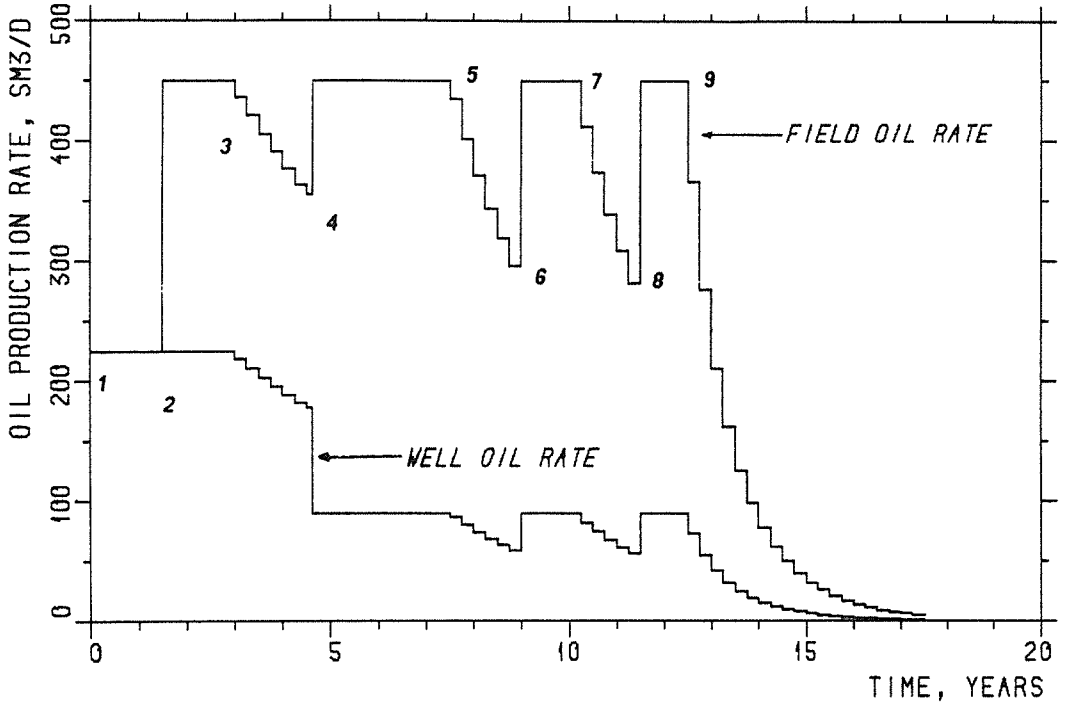


Fig. 7.1a--Field and well oil production rates vs. time. Demo case.

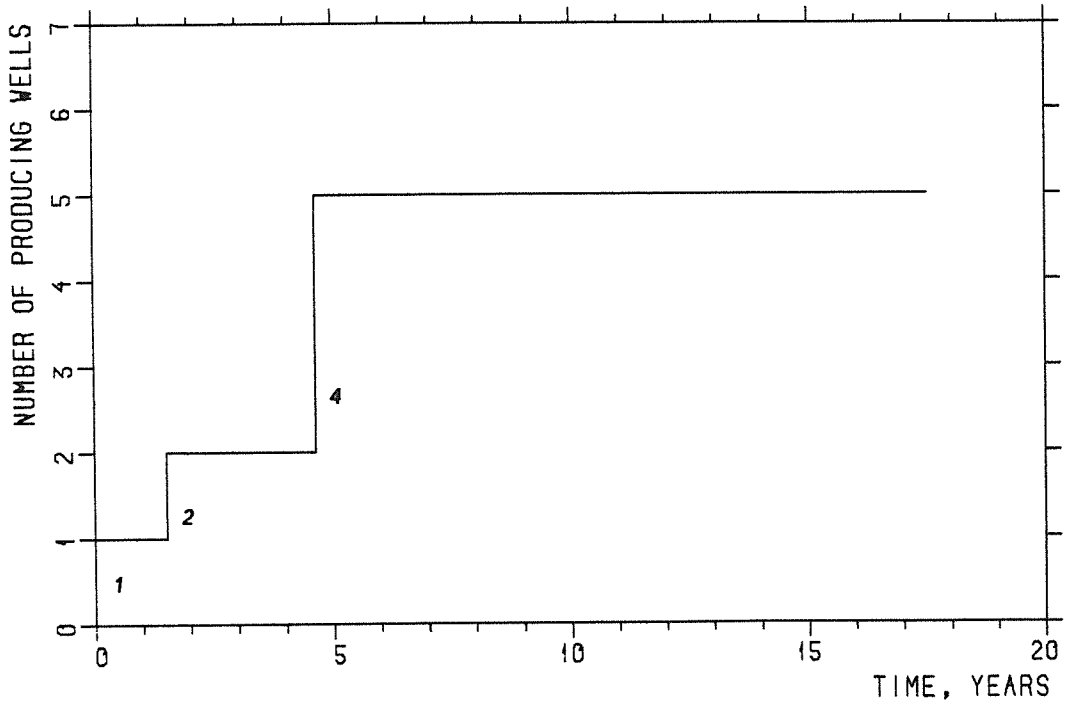


Fig. 7.1b--Number of producing wells vs. time. Demo case.

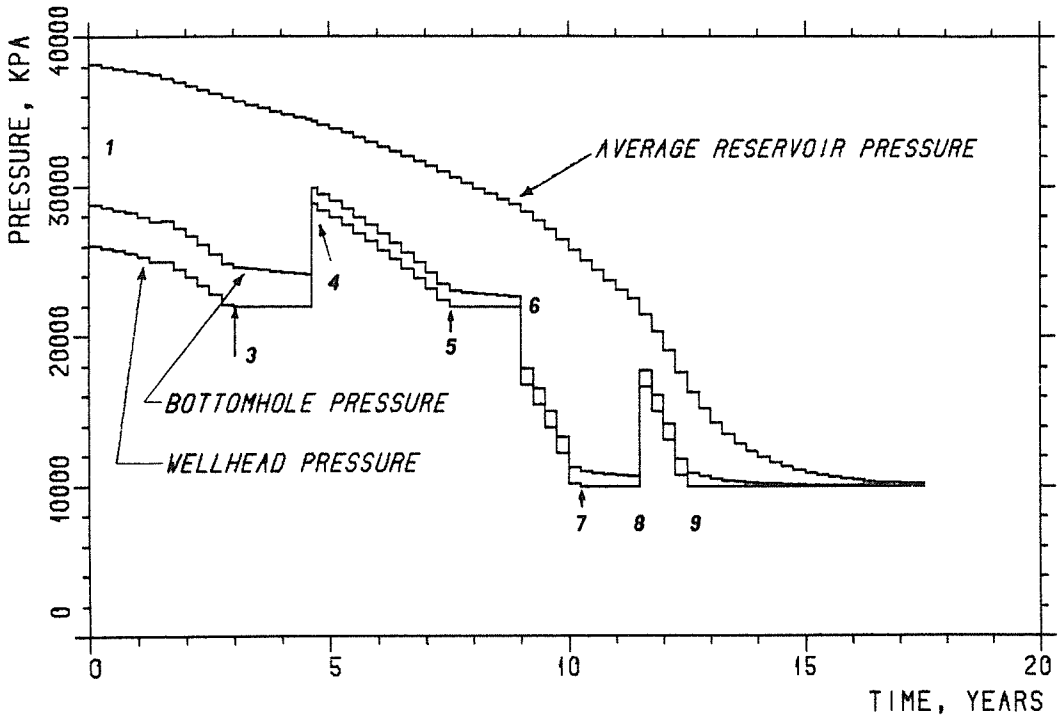


Fig. 7.1c--Average reservoir pressure, bottomhole pressure and wellhead pressure vs. time. Demo case.

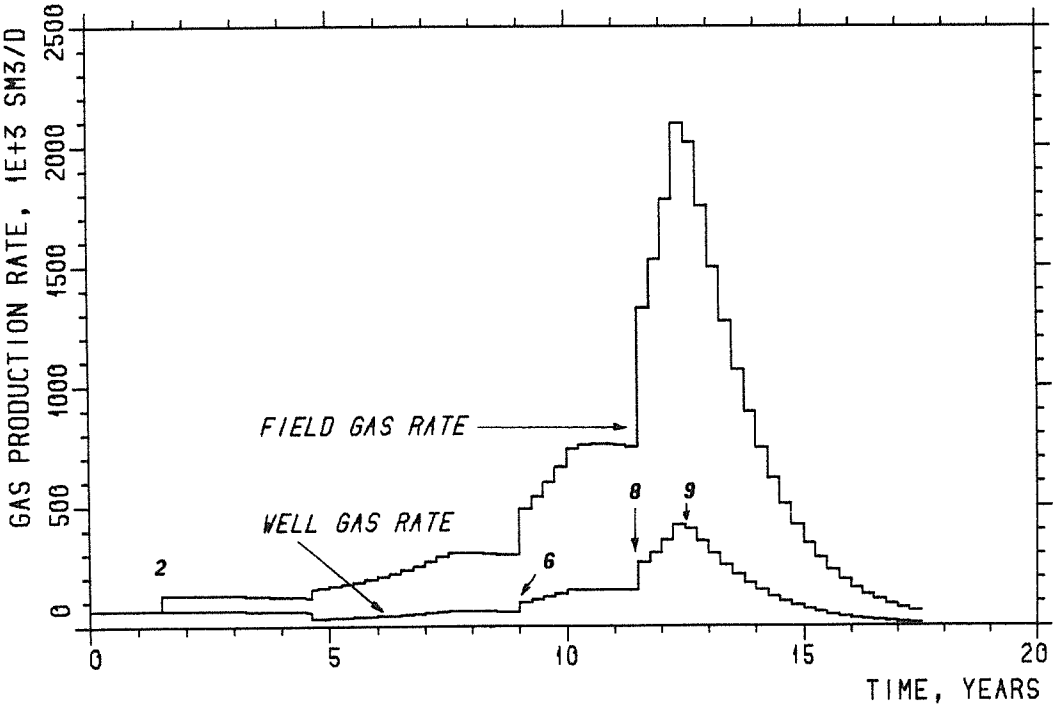


Fig. 7.1d--Field and well gas production rates vs. time. Demo case.

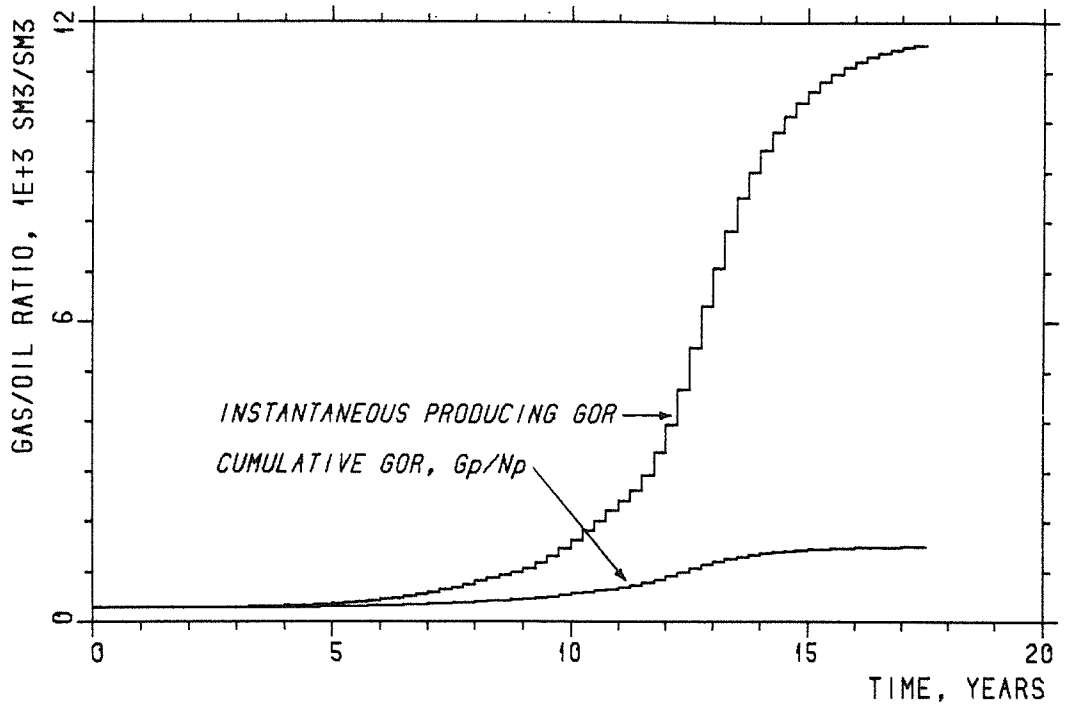


Fig. 7.1e--Instantaneous producing gas/oil ratio vs. time and ratio of field cumulative gas production to field cumulative oil production (cumulative GOR) vs. time. Demo case.

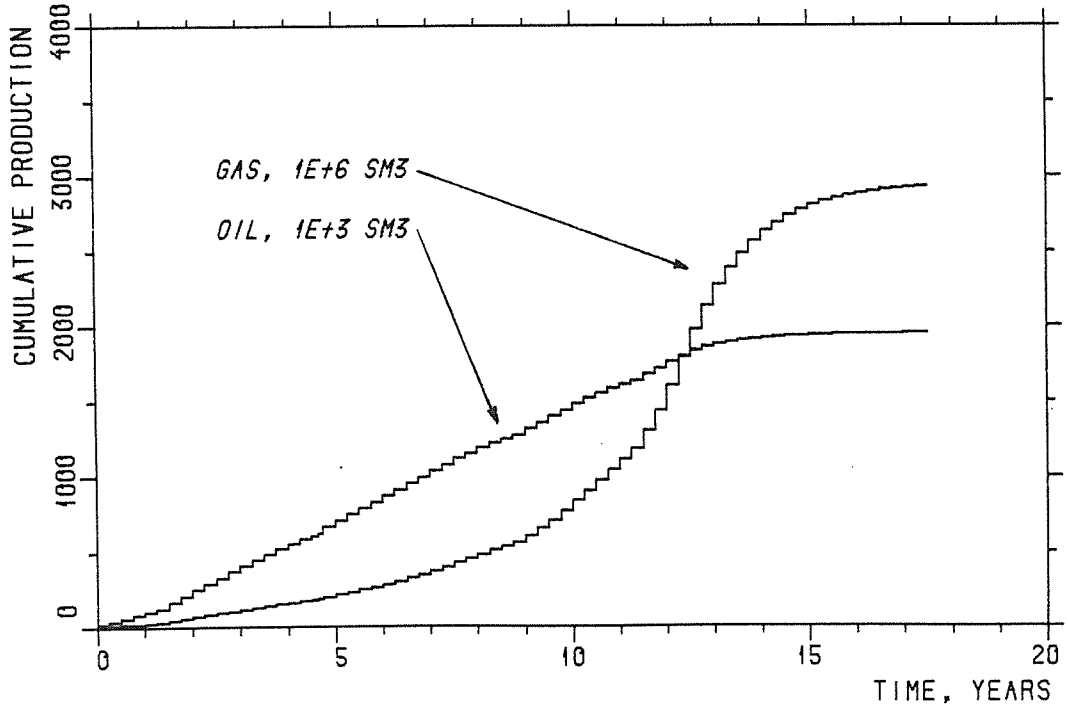


Fig. 7.1f--Cumulative oil production and cumulative gas production vs. time. Demo case.

3. The target rate is now too high, so the production rate is lowered by GMS to keep the wellhead pressure at the minimum level.

4. The number of wells is increased to five while the field target rate and minimum wellhead pressure remain unchanged. The field target can be obtained because the target rate for each well is smaller. Note that the length of the last timestep of this period is shorter. This is because reports are made at the points of time when changes in well control are specified. These reports are in addition to to the reports at all integer multiples of the timestep length.

5. Same as 3. above.

6. The minimum wellhead pressure is lowered from 22000 kPa to 10000 kPa; the wells can again produce at the target rate.

7. Same as 3. above.

8. A negative skin of -6 is introduced (e.g., from stimulation of all the wells in the field). This means that the inflow to the well causes a smaller pressure drop, and the target rate can be held.

9. Final decline period starts. The wellhead pressure is kept constant at the minimum.

7.5 Testing the Material-Balance Procedure of GMS

The material-balance procedure of GMS was checked against three other programs, TARNER, DRYGAS and ECLIPSE. The two former programs were made only for this test purpose, whereas the latter is a commercial, general, three-dimensional reservoir simulator.

7.5.1 Dry Gas

The DRYGAS program was based on the dry-gas MB, as described in Section 3.1. The gas-condensate data set was used after being modified to represent a dry gas by setting the solution oil/gas ratio equal to zero and density ratios equal to unity. GMS and DRYGAS calculated the average reservoir pressure as a function of gas recovery exactly equally (see Fig. 7.2), indicating that GMS handles the dry-gas case correctly. Owing to its simple form, the dry-gas MB was compared only by means of the average reservoir pressure.

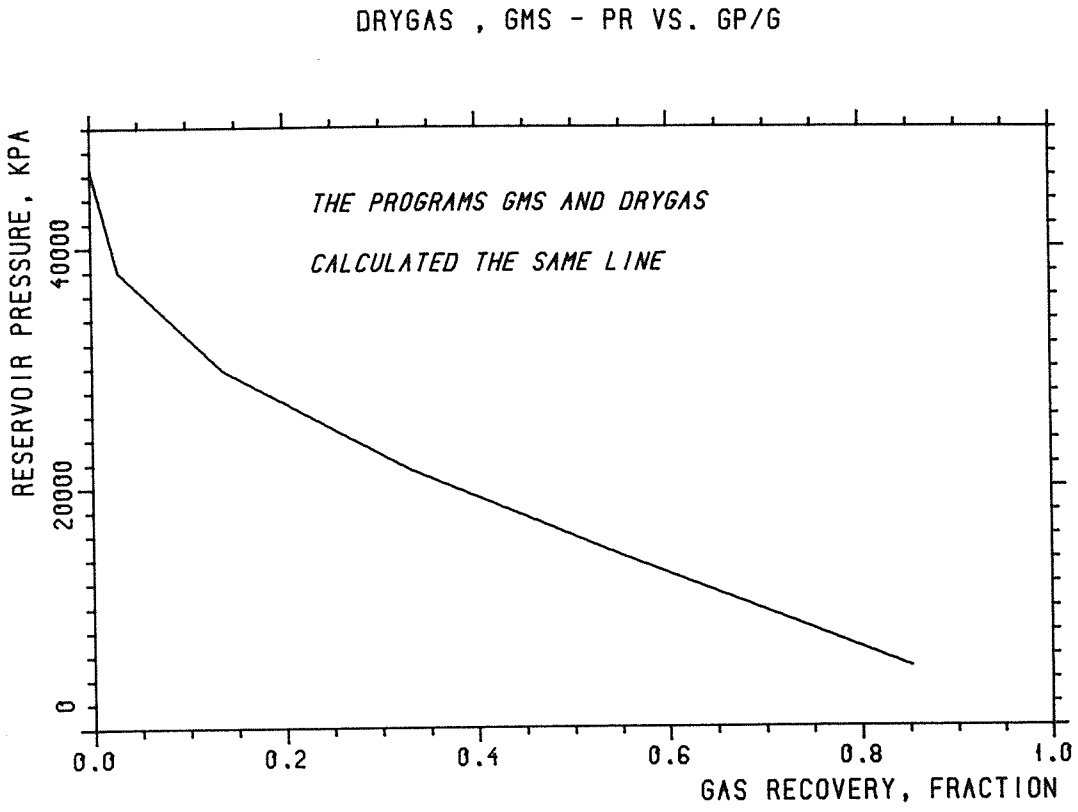


Fig. 7.2--Average reservoir pressure vs. gas recovery calculated by GMS and DRYGAS for dry-gas PVT data.

7.5.2 Tarner

As another test, GMS was compared with the TARNER program developed in accordance with the Tarner procedure of Section 3.2. The BASE data set was used, but with one modification: the gas was considered to be dry ($r_s = 0$). For average reservoir pressure and producing GOR, the curves from GMS and TARNER were identical (see Figs. 7.3a and 7.3b).

7.5.3 ECLIPSE

The comparison with ECLIPSE was done with the BASE data set. In this data set, the solution OGR is a function of pressure, but the density ratios (ϱ^*) are treated as constants equal to unity because of limitations in ECLIPSE. Compared to the Tarner formulation, this was one additional step towards the *general* formulation. ECLIPSE was run both with one block (ECL 1) and 20 blocks (ECL 20). A comparison of the MB of GMS and ECLIPSE gave interesting results. GMS and ECL 1 were very close, whereas ECL 20 showed a distinct deviation. As an example, it could be mentioned that at a cumulative oil production of four million Sm^3, the average reservoir pressure and the producing GOR of ECL 20 were 6.7% less and 24% greater, respectively, than that of the two monoblock models which were rather close to each other (see Figs. 7.4f and 7.4g). A similar effect was observed for the other test cases, too. The difference between the models seen from the plots of the average reservoir pressure versus time and versus cumulative oil production should also be noted (Figs. 7.4b and 7.4f). These differences have come into being because the production versus time is not equal for the three models.

ECL 20 calculates an earlier development of mobile gas. This can be understood by considering the pressure and saturation distribution in the reservoir and the shape of the relative permeability curves. The monoblock models operate with uniform saturation and pressure throughout the reservoir, while ECL 20 approximates the real distributions better using a refined radial grid. Obviously, the pressure is lower than the average at the wellbore and higher than the average at the outer boundary. For gas saturation it is the other way around, higher gas saturation near the wellbore and lower gas saturation at the outer boundaries. The higher gas saturation at the wellbore means a higher relative gas permeability and a reduced oil relative permea-

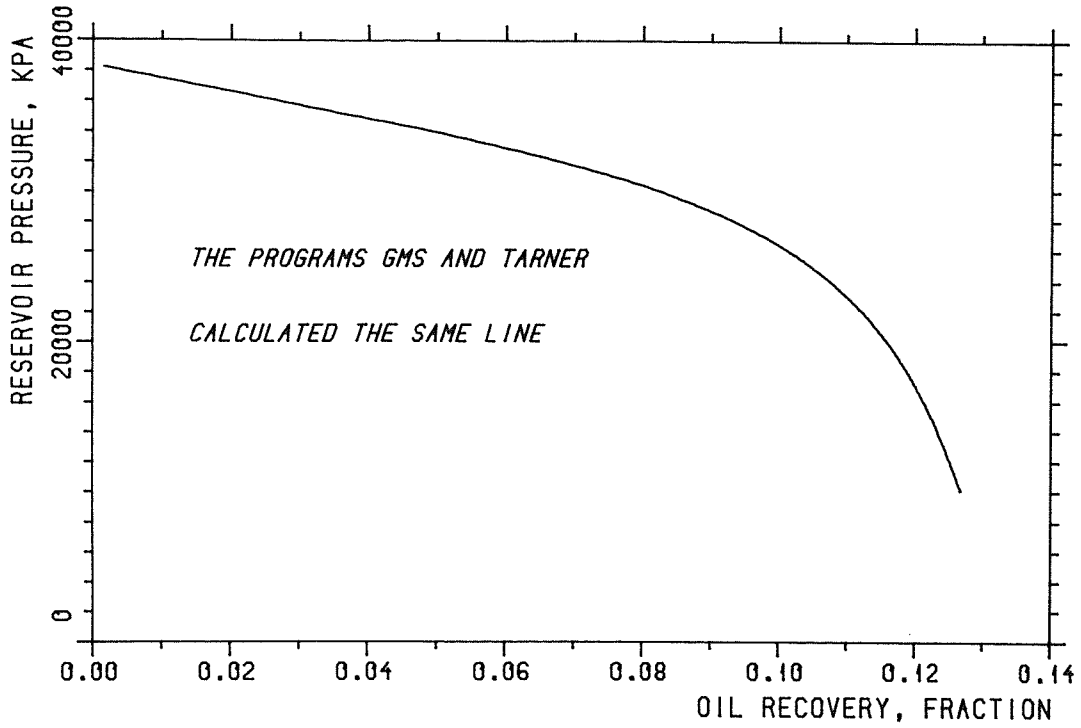


Fig. 7.3a--Average reservoir pressure vs. oil recovery calculated by GMS and TARNER for oil PVT data with surface gravity ratios equal to one and solution oil/gas ratio in gas equal to zero.

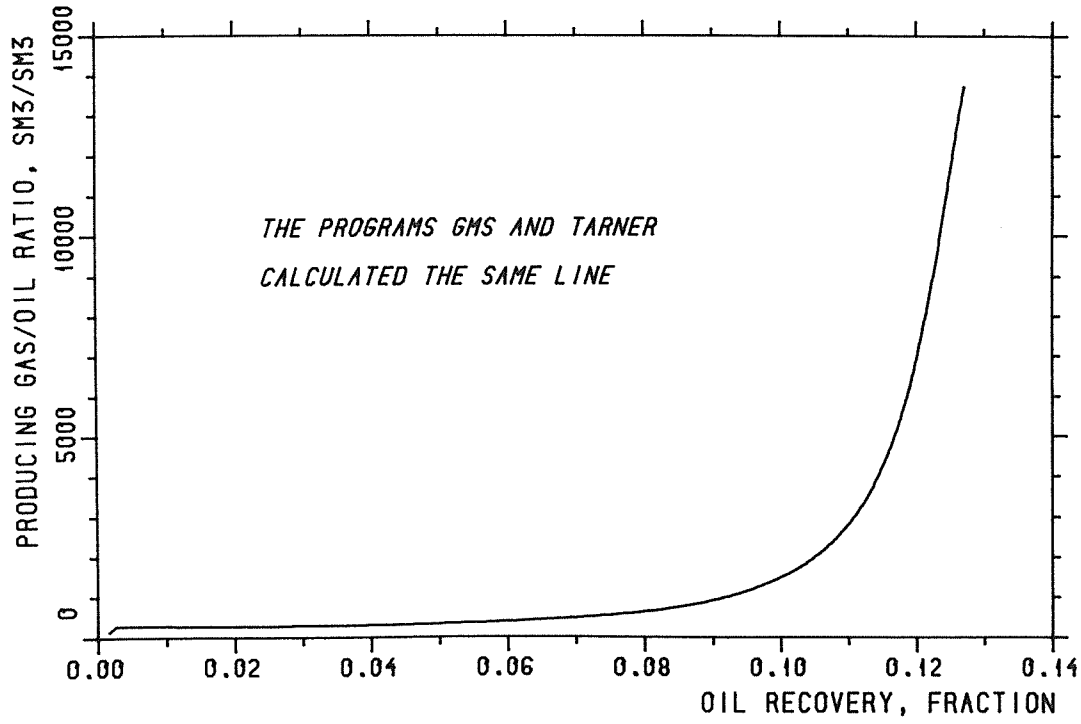


Fig. 7.3b--Producing gas/oil ratio vs. oil recovery calculated by GMS and TARNER for oil PVT data with surface gravity ratios equal to one and solution oil/gas ratio in gas equal to zero.

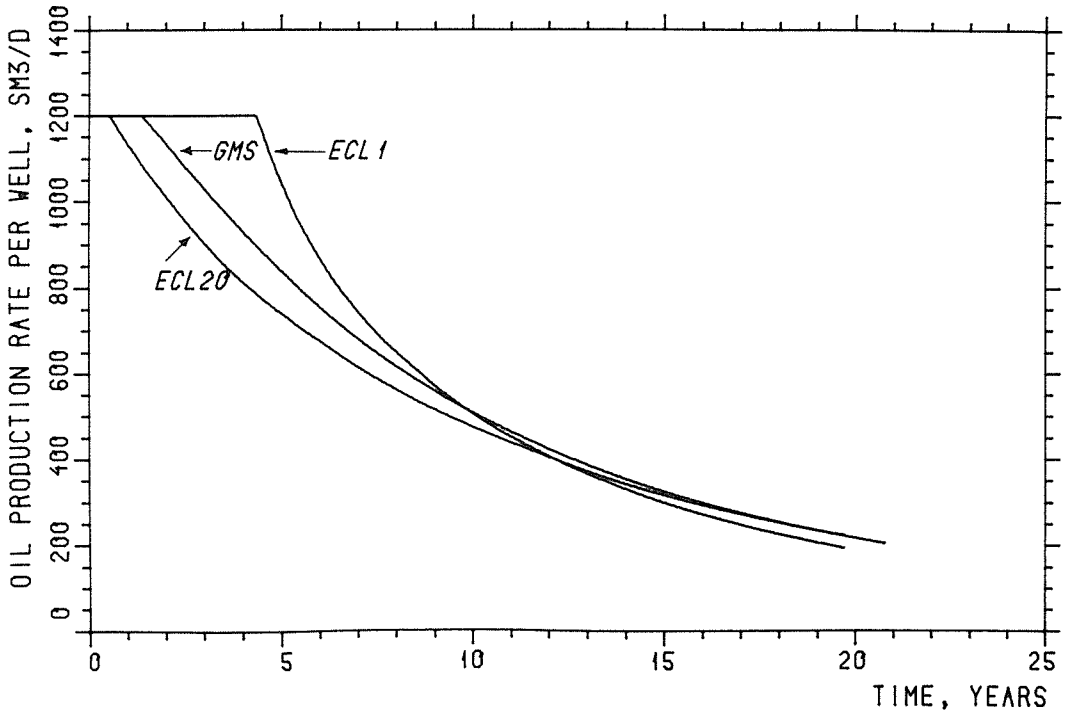


Fig. 7.4a--BASE case oil production rate vs. time for GMS, ECLIPSE with one gridblock (ECL1), and ECLIPSE with 20 gridblocks (ECL20).

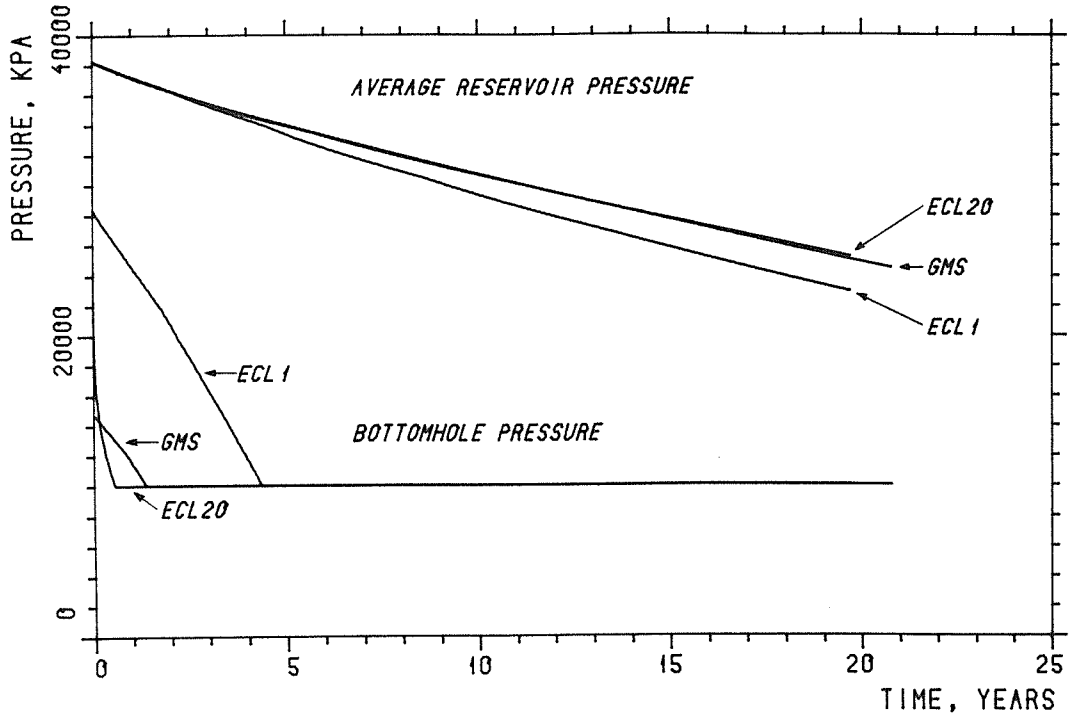


Fig. 7.4b--BASE case average reservoir pressure and bottomhole pressure vs. time for GMS, ECLIPSE with one gridblock (ECL1), and ECLIPSE with 20 gridblocks (ECL20).

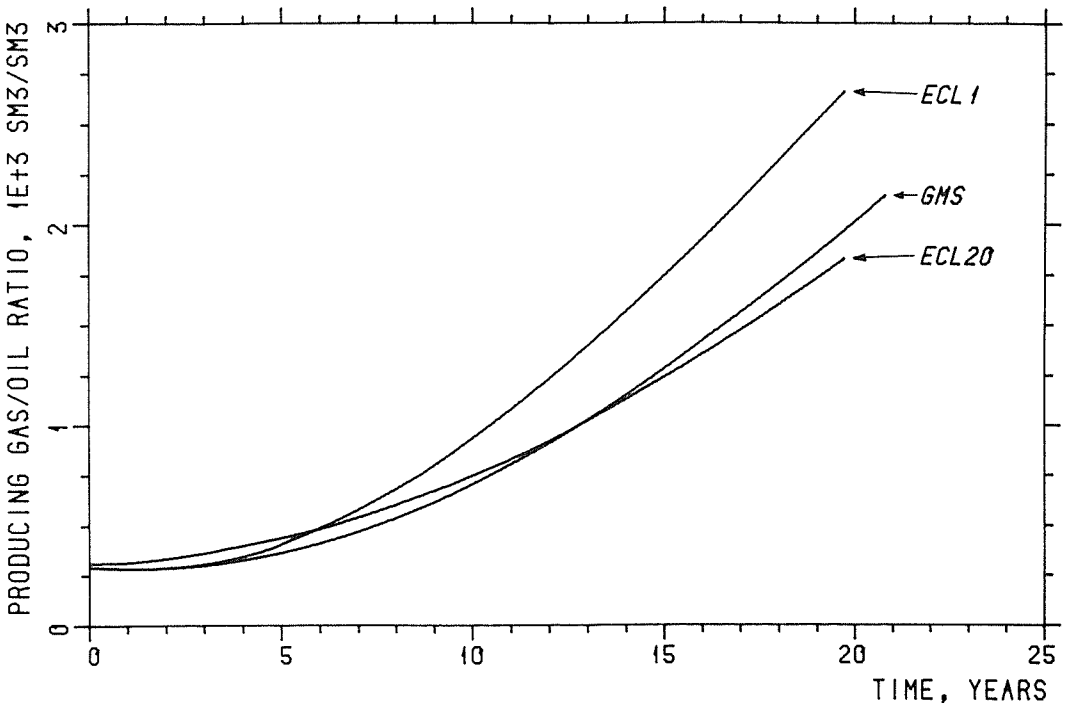


Fig. 7.4c--BASE case producing gas/oil ratio vs. time for GMS, ECLIPSE with one gridblock (ECL1), and ECLIPSE with 20 gridblocks (ECL20).

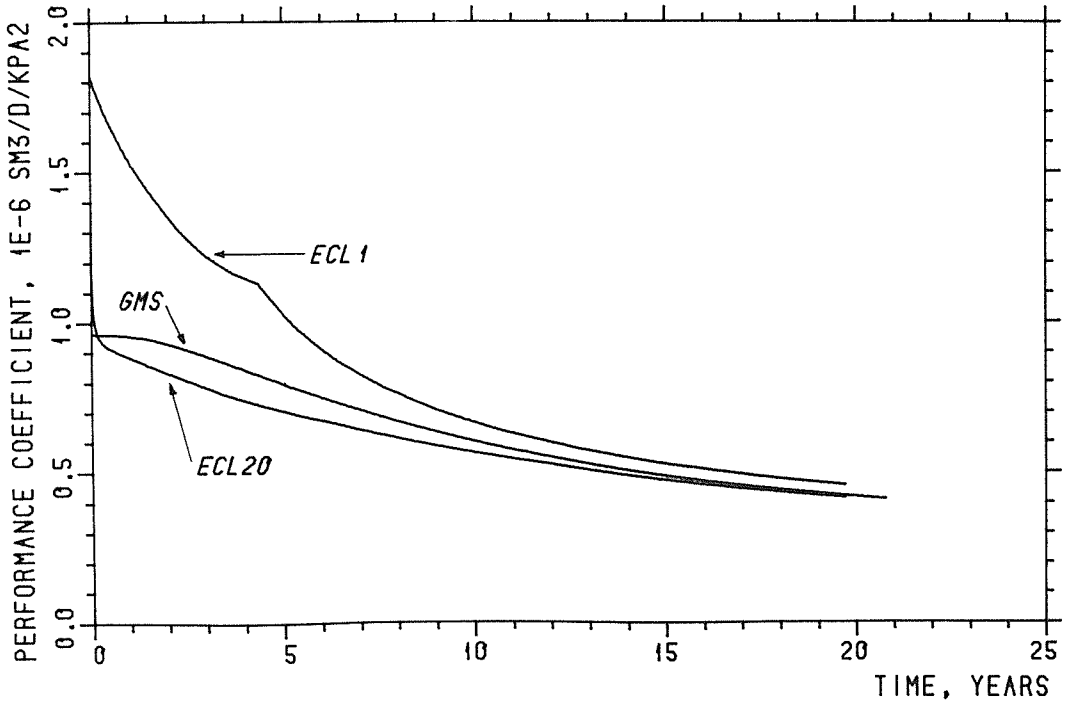


Fig. 7.4d--BASE case performance coefficient vs. time for GMS, ECLIPSE with one gridblock (ECL1), and ECLIPSE with 20 gridblocks (ECL20).

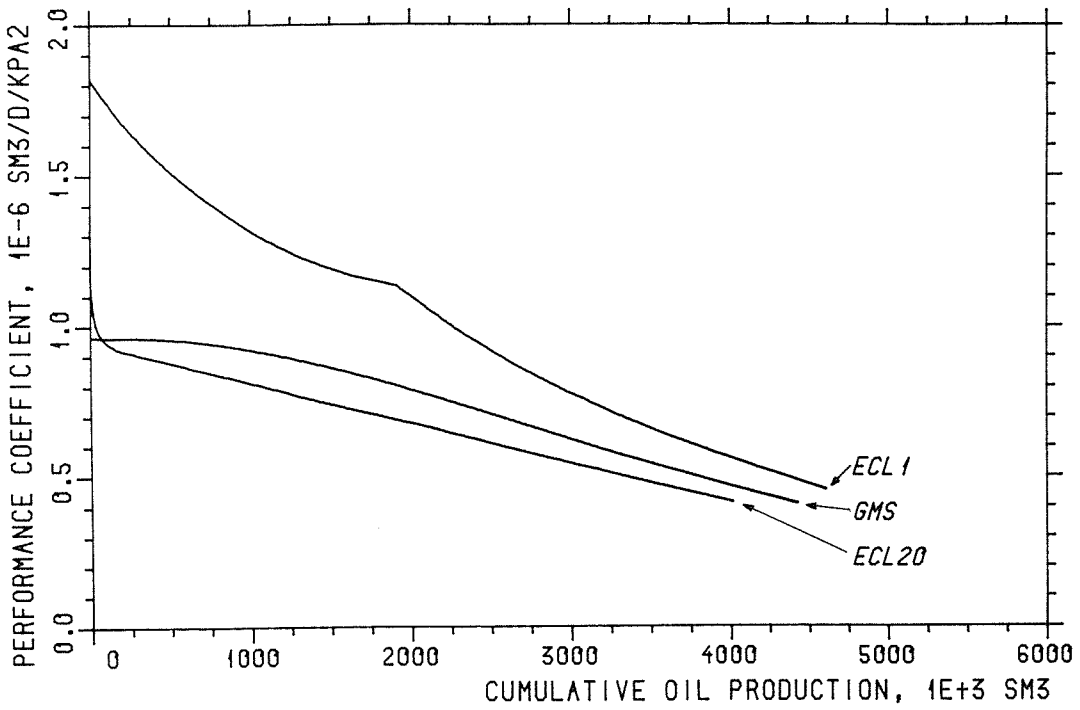


Fig. 7.4e--BASE case performance coefficient vs. cumulative oil production for GMS, ECLIPSE with one gridblock (ECL1), and ECLIPSE with 20 gridblocks (ECL20).

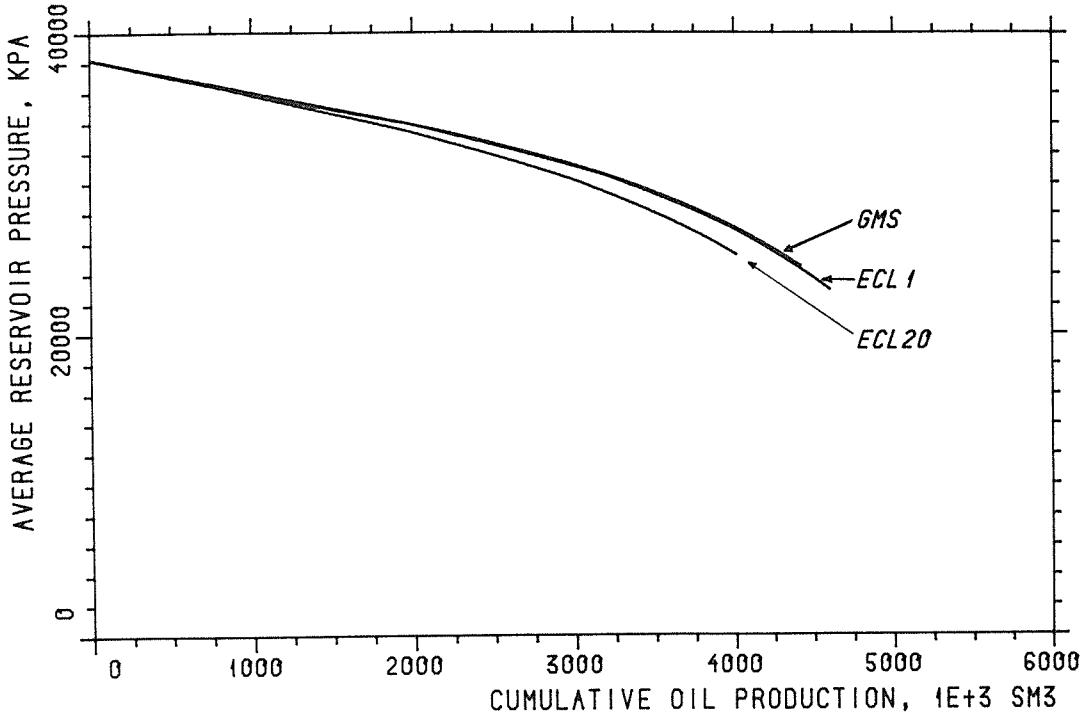


Fig. 7.4f--BASE case average reservoir pressure vs. cumulative oil production for GMS, ECLIPSE with one gridblock (ECL1), and ECLIPSE with 20 gridblocks (ECL20).

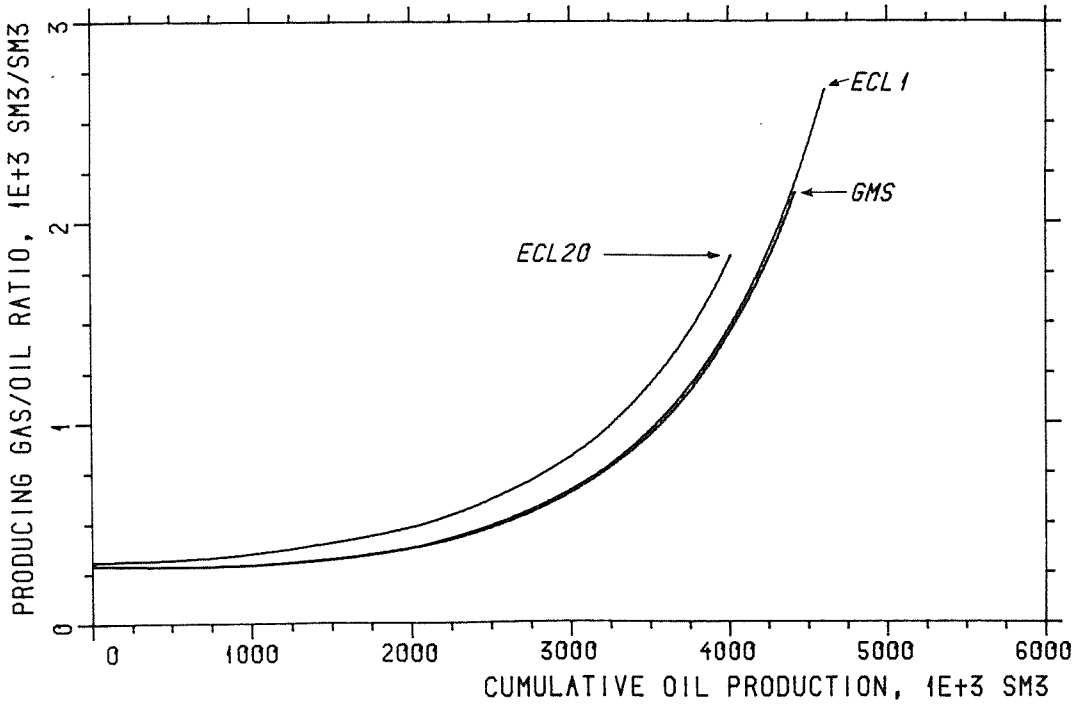


Fig. 7.4g--BASE case producing gas/oil ratio vs. cumulative oil production for GMS, ECLIPSE with one gridblock (ECL1), and ECLIPSE with 20 gridblocks (ECL20).

bility, which results in a higher producing GOR and a larger pressure drop per produced unit volume of oil.

These tests do not say how GMS responds to variable surface densities. Nevertheless, the two monoblock models are very close with respect to MB calculations in the tests performed.

7.6 Comparing IPR of GMS and ECLIPSE

The IPR is the relationship between the average reservoir pressure, bottomhole flowing pressure (BHFP) and production rate. The aim of this comparison was to investigate with which accuracy GMS performs IPR calculations. ECL 20 was used as a reference because it was thought to give the most correct results. Though the IPR routine of ECLIPSE is less sofisticated than the GMS IPR, with ECL 20 the cell that is connected to the well is so small that a simple procedure is satisfactory. (ECL 1, on the other hand, which has only one cell, would suffer from this simplification.) The GMS approach to the IPR problem is to utilize the pseudopressure concept (with numerical integration) instead of multiple reservoir cells.

The BASE data set was used. The relatively low permeability in BASE was chosen to get a large pressure drawdown. This also resulted in a short plateau production period and quite a long decline period (see Figs. 7.4a - 7.4c). The large drawdown obtained would enhance the difference between the models with respect to IPR. (With a too small drawdown, only the material-balance calculations would have been tested.) GMS and ECLIPSE did not calculate equal average reservoir pressures and production rates as functions of time, so a better approach than just comparing the BHFP's (Fig. 7.4b) would be to consider an expression including all these quantities. The right-hand side of Eq. 4.27 (below) was chosen as the parameter to be plotted. (The theory behind this choice is given in Section 4.5).

$$C = \frac{q_o}{(p_R^2 - p_{wf}^2)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4.27)$$

An observation from Figs. 7.4d and 7.4e shows that C from ECL 20 is approximately 13% less than C from GMS at the point of maximum devi-

ation. For a case with smaller pressure drawdown, such as the high permeability (HRPM) case, the differences in C were a lot smaller (see Fig. 7.6d). Another important quantity is the plateau rate duration. For the BASE case, GMS is a bit more optimistic than ECL 20, but still far behind ECL 1 (Fig. 7.4a).

The ECL 20 calculates the fastest drawdown (see Fig. 7.4b). This might be because of an early development of gas close to the wellbore, which results in a reduced relative permeability to oil and a larger pressure drop (see Section 7.5.3).

7.7 Sensitivity to Timestep Length

Increased timestep length is an effective way of decreasing processing time on the computer (see Table 7.3 below). Since this may lead to a loss of accuracy, the "longer timestep" (LTS) case was compared to the BASE case to give an indication of the timestep sensitivity of GMS.

Comparisons with the BASE case showed equal plateau production duration and a slightly larger oil production rate (1.5%) for LTS during the decline period (see Fig. 7.5). The timestep could be increased from 1/24 to 1/2 years with only a small loss of accuracy. This is no more than an indication, because another data set might give another result.

7.8 High Permeability Case

For GMS, the permeability has an indirect influence on the processing time on the computer through its effect on the production profile. A common effect of a small permeability is that the plateau production time is decreased and the decline period is increased. Calculations during the decline period require at least one more iteration level (subroutine RATE) or even two (subroutines RATE and WHPRS) and thereby execute slower per timestep than plateau production calculations. The change in production characteristics is seen from Figs. 7.6a - 7.6d. The three models were a lot closer for this case than for the BASE case. The main trend is that GMS plots between the two other models. A reason for this is the smaller drawdown, giving

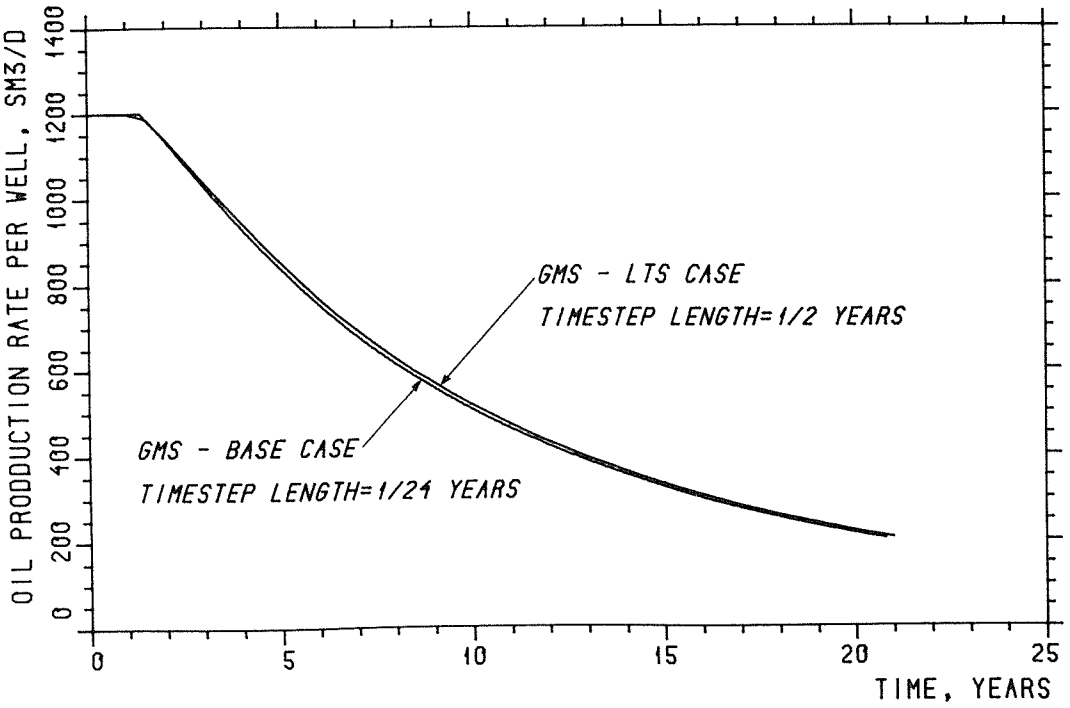


Fig. 7.5--Oil production rate vs. time for the BASE and LTS data sets simulated with GMS.

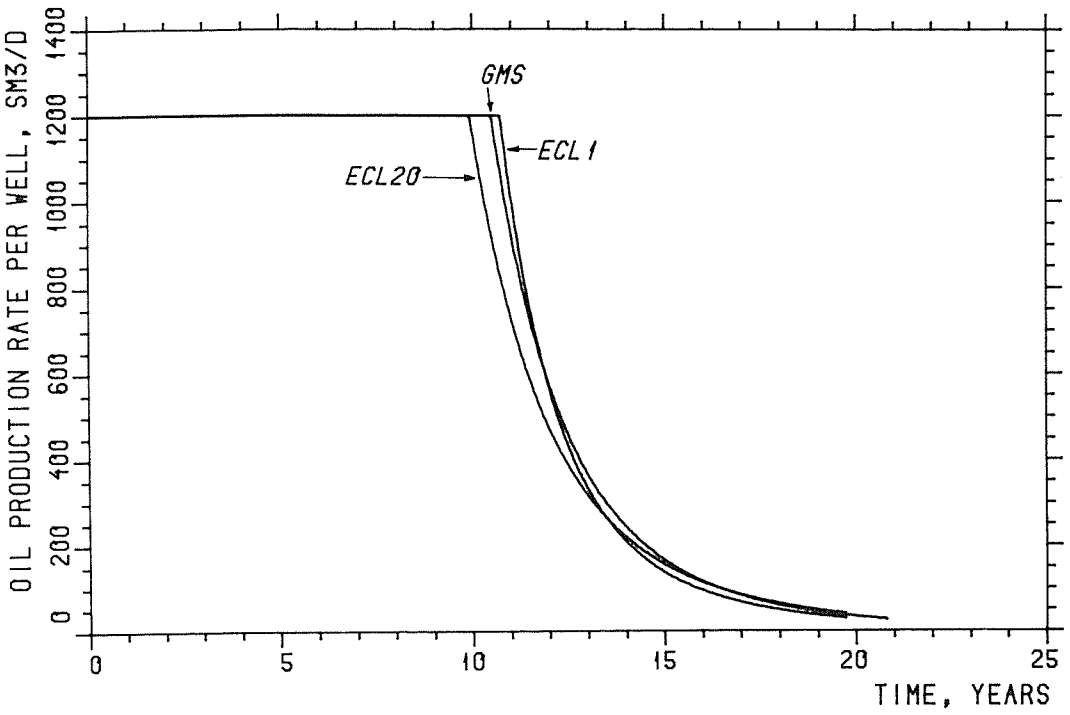


Fig. 7.6a--HPRM case oil production rate vs. time for GMS, ECLIPSE with one gridblock (ECL1), and ECLIPSE with 20 gridblocks (ECL20).

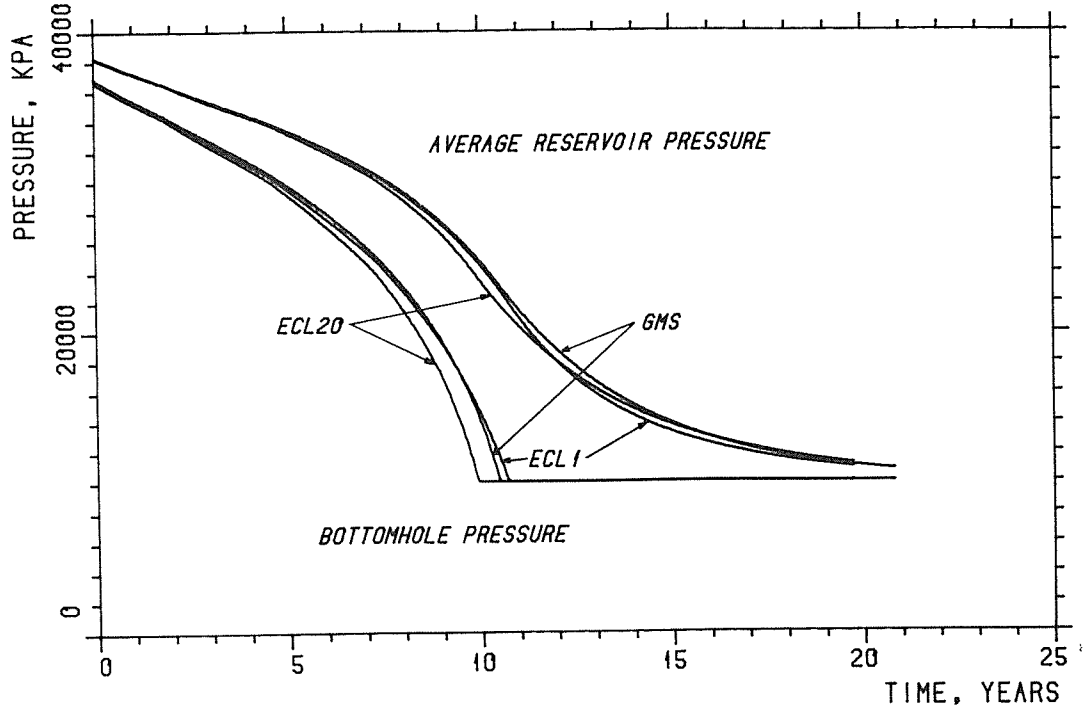


Fig. 7.6b--HPRM case average reservoir pressure and bottomhole pressure vs. time for GMS, ECLIPSE with one gridblock (ECL1), and ECLIPSE with 20 gridblocks (ECL20).

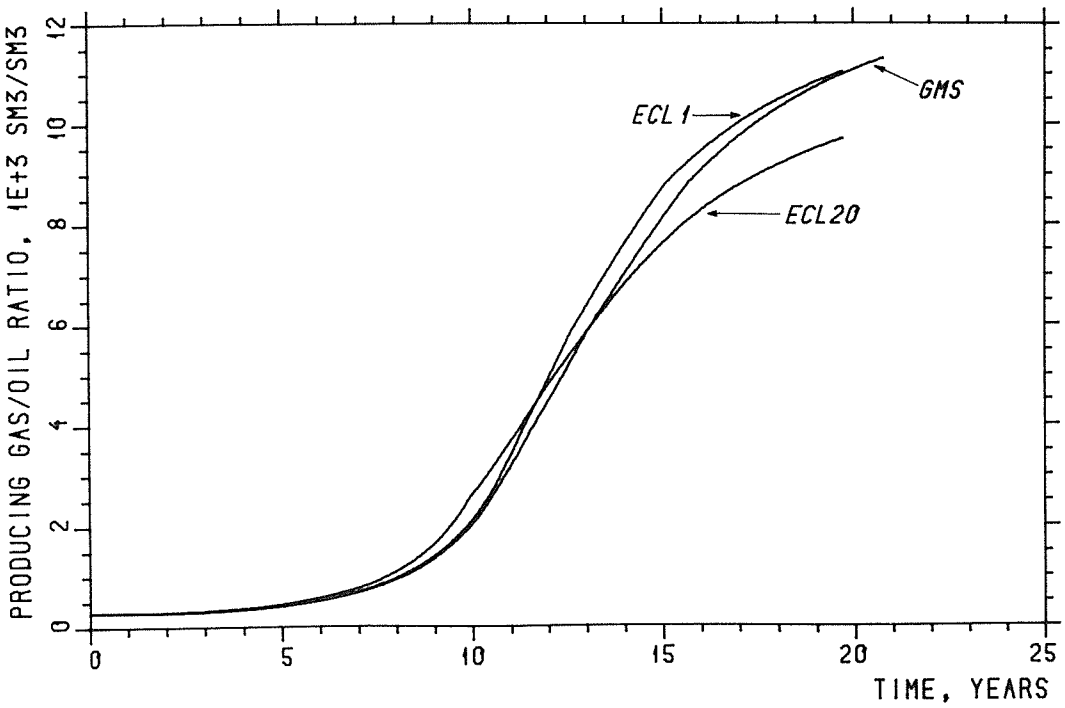


Fig. 7.6c--HPRM case producing gas/oil ratio vs. time for GMS, ECLIPSE with one gridblock (ECL1), and ECLIPSE with 20 gridblocks (ECL20).

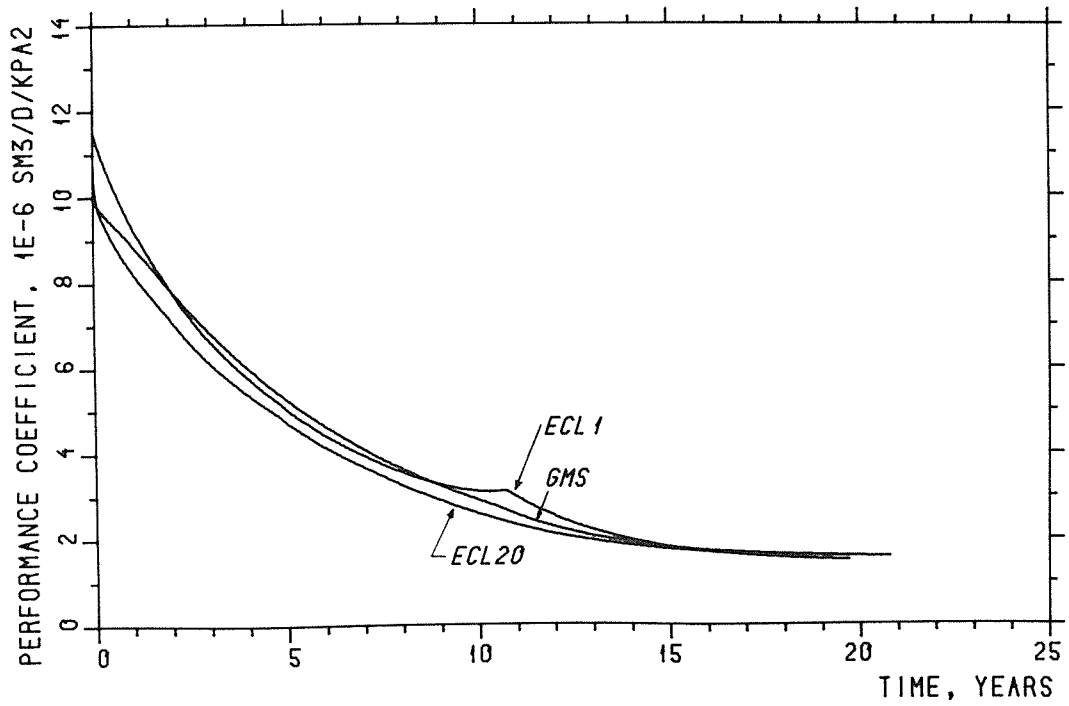


Fig. 7.6d--HPRM case performance coefficient vs. time for GMS, ECLIPSE with one gridblock (ECL1), and ECLIPSE with 20 gridblocks (ECL20).

less significance to the inflow calculations. The smaller drawdown also contributes to reduced processing time through its reduction of the pressure interval for numerical IPR integration (see Table 7.3 below).

7.9 Applying Different PVT Formulations

One of the potentials of the GMS program was to compare the effect on reservoir performance from applying different PVT formulations. In this work, one test of this kind was performed. General quantitative conlusions could not be drawn from this limited material. It does, however, convey the impression that the selection of PVT formulation is significant with regards to simulation results. Since the MB and IPR formulations of GMS are general, all the PVT formulations described in Chapter 2 are applicable.

The GEN, BASE and CONV data sets, being different in PVT data only, were used for this comparison. The general impression from the simulation results is that GEN and BASE are rather close, with GEN as the pessimistic one, while the CONV case is even more pessimistic (see Figs. 7.7a - 7.7g). These deviations are caused solely by the difference in PVT data due to the different PVT formulations, showing that a proper choice of PVT formulation is important.

7.10 Tuning, Accuracy and CPU Time Consumption

The tuning of the models is often a compromise between the accuracy of the results and the computing time needed. For example, if too few iterations are requested, the results will be in error, but the program will be fast. On the other hand, superfluous iterations will slow down the execution. This is an optimization problem.

GMS was first run with strict tolerances and then tuned to increase efficiency without having unacceptable deviation in the results. However, one tuning parameter, which was left for the user to specify on the input, is the pressure interval in integration (DPINT) in subroutine IPR. For the cases considered here, DPINT was set equal to 1500 kPa. This gave a maximum error in the pressures of 0.3% and in the rates of 0.01% compared to another case with DPINT

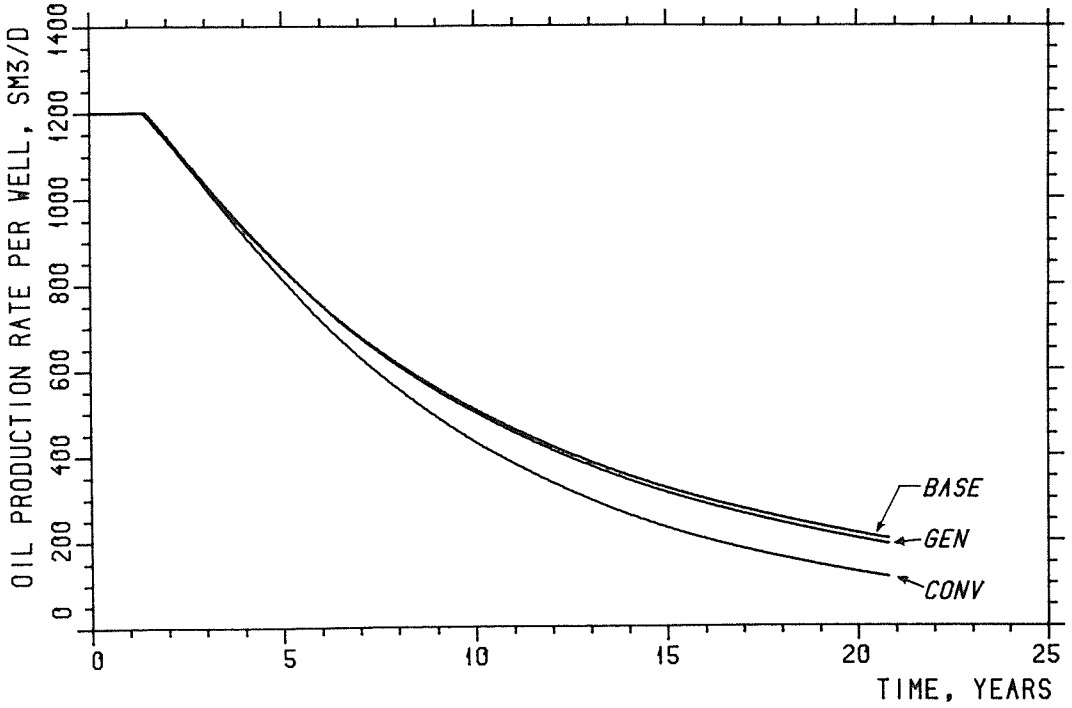


Fig. 7.7a--Oil production rate vs. time calculated by GMS for the general (GEN), constant-surface-gravity (BASE), and conventional (CONV) PVT formulation.

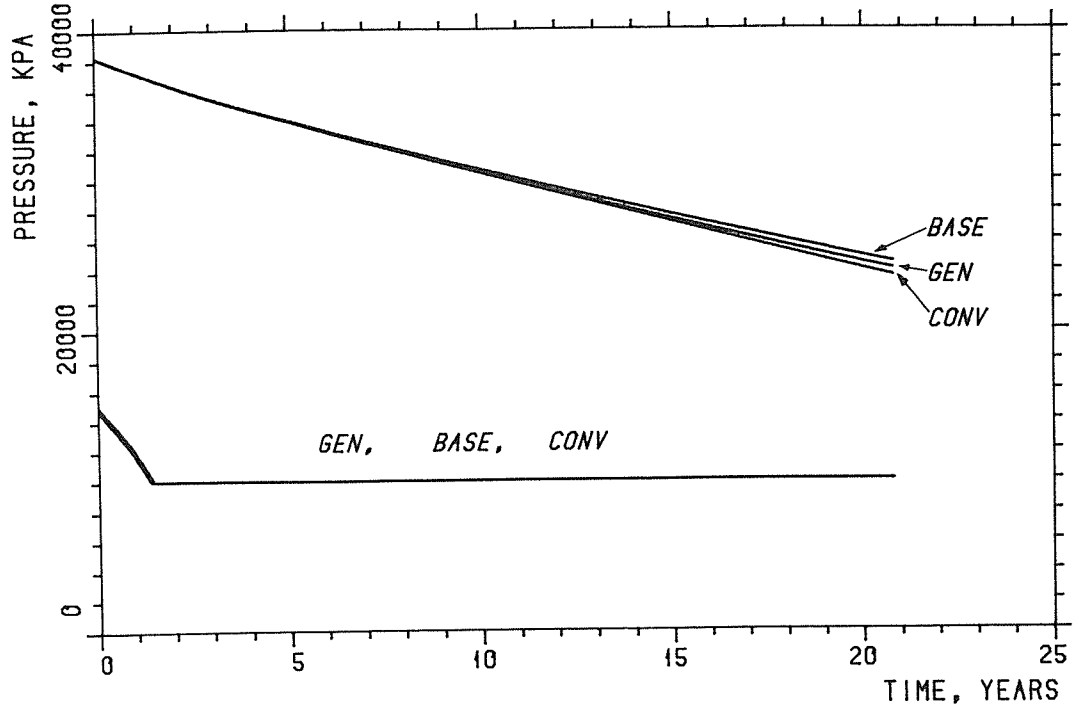


Fig. 7.7b--Average reservoir pressure and bottomhole pressure vs. time calculated by GMS for the general (GEN), constant-surface-gravity (BASE), and conventional (CONV) PVT formulation.

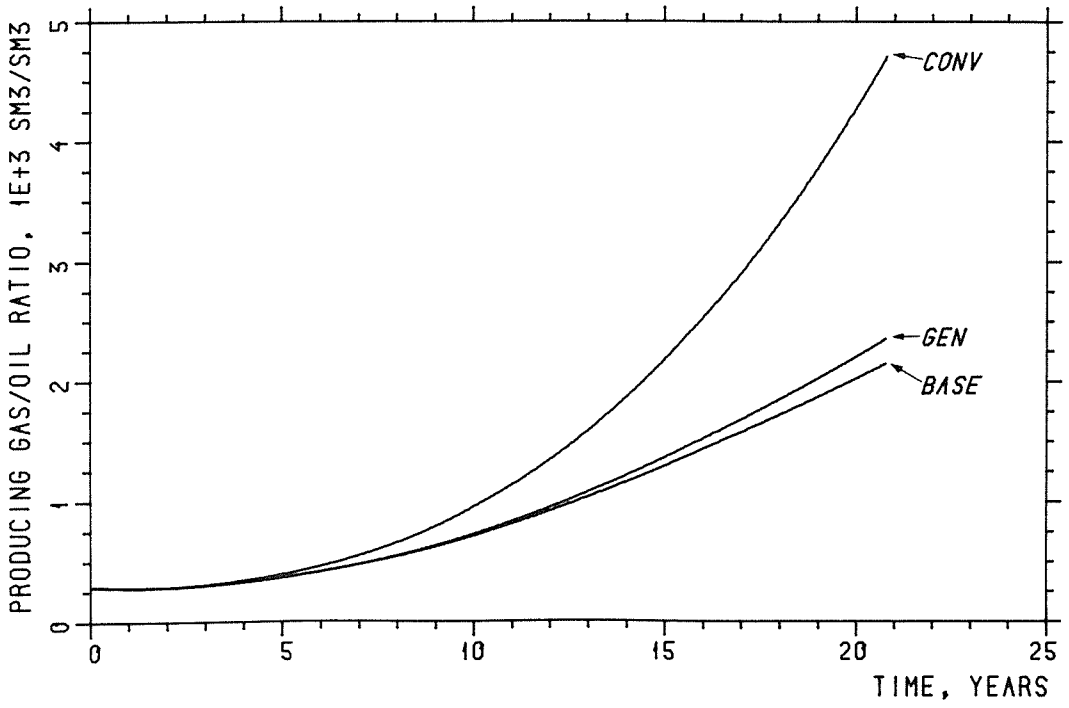


Fig. 7.7c--Producing gas/oil ratio vs. time calculated by GMS for the general (GEN), constant-surface-gravity (BASE), and conventional (CONV) PVT formulation.

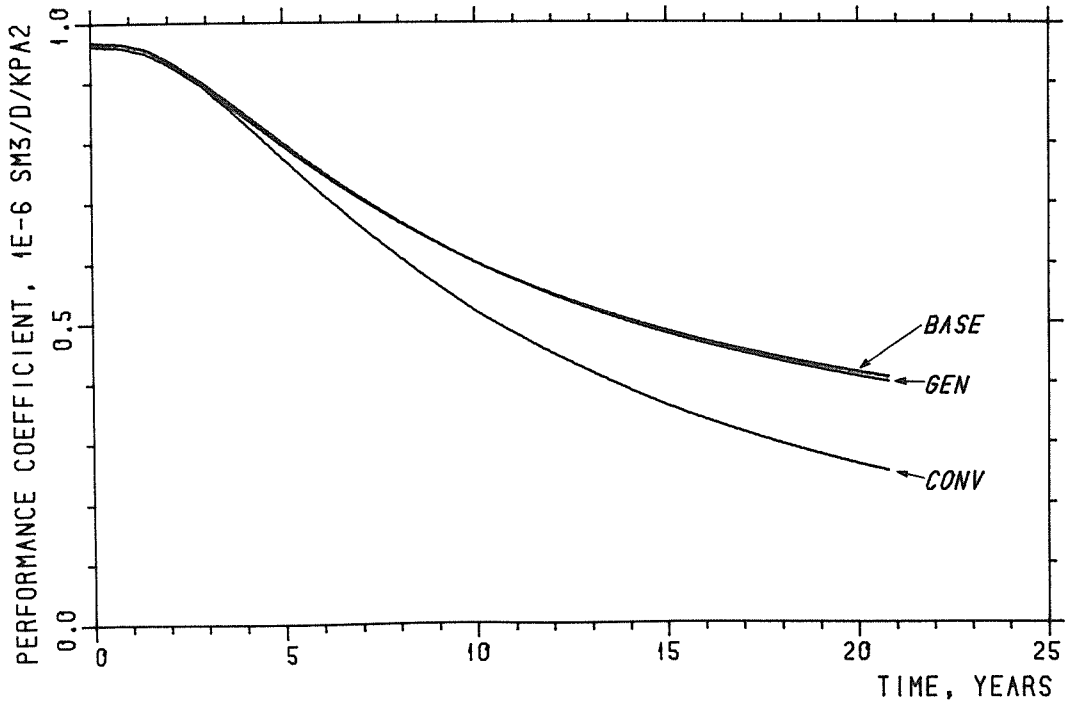


Fig. 7.7d--Performance coefficient vs. time calculated by GMS for the general (GEN), constant-surface-gravity (BASE), and conventional (CONV) PVT formulation.

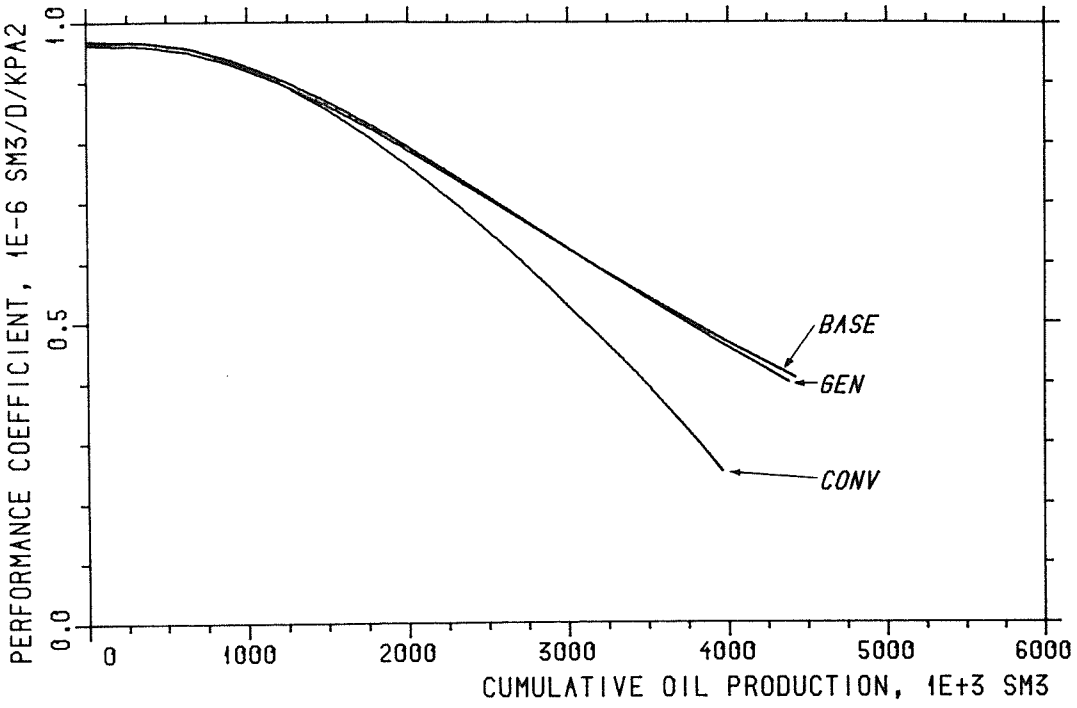


Fig. 7.7e--Performance coefficient vs. cumulative oil production calculated by GMS for the general (GEN), constant-surface-gravity (BASE), and conventional (CONV) PVT formulation.

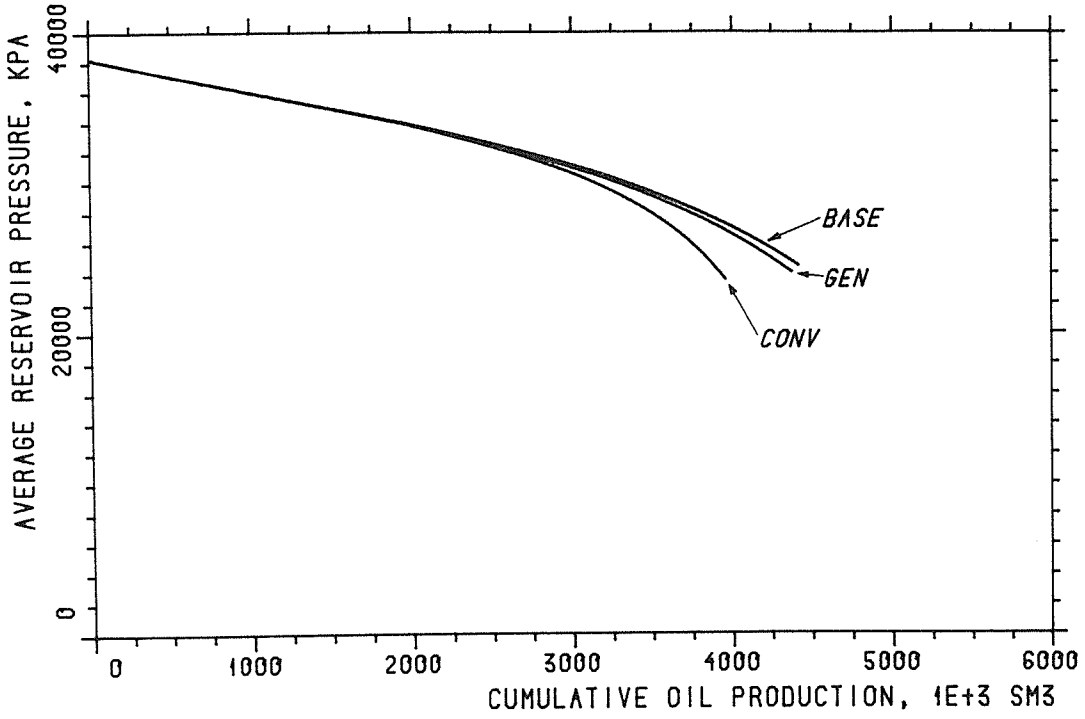


Fig. 7.7f--Average reservoir pressure vs. cumulative oil production calculated by GMS for the general (GEN), constant-surface-gravity (BASE), and conventional (CONV) PVT formulation.

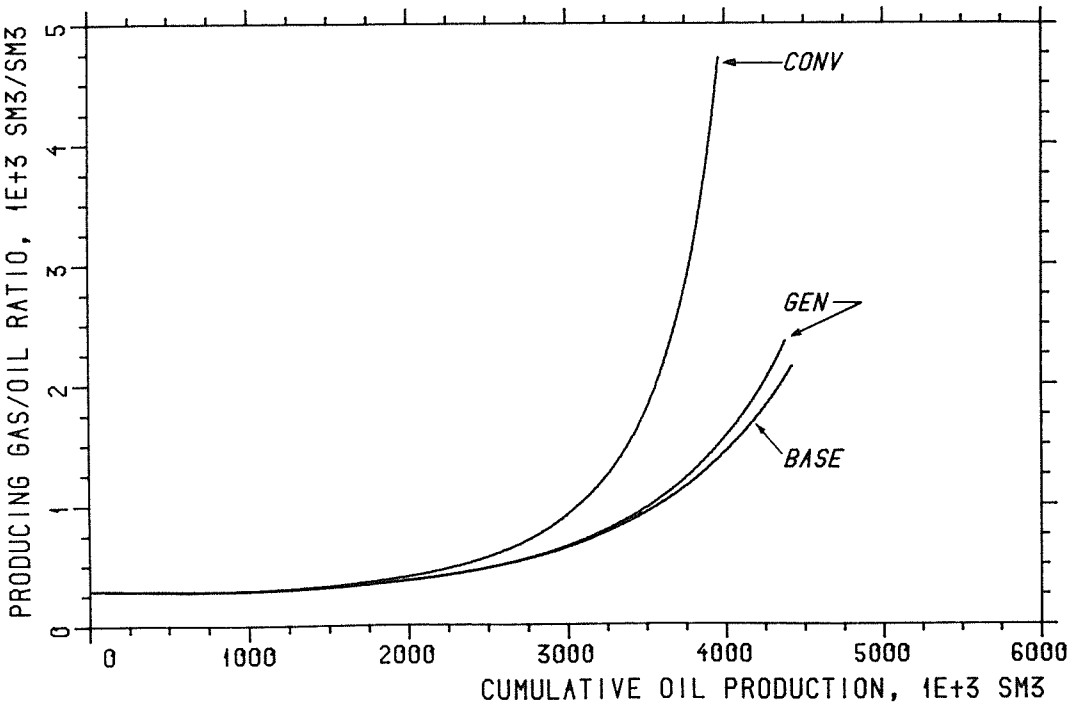


Fig. 7.7g--Producing gas/oil ratio vs. cumulative oil production calculated by GMS for the general (GEN), constant-surface-gravity (BASE), and conventional (CONV) PVT formulation.

equal to 100 kPa. The iteration tolerances were set equal to: pressure, 0.5 kPa [0.073 psi]; and production rate, 0.0005 multiplied by the target rate (see Appendix A.5). ECLIPSE was run with defaulted tuning parameters only. Table 7.3 compares the computer's central processing unit (CPU) time consumption for GMS, ECL1 and ECL 20. It should be noted that GMS consumes considerably less time than the others.

TABLE 7.3--CPU TIME CONSUMPTION FOR GMS AND ECLIPSE ON ND-500 FOR SIMULATION OF 21 YEARS OF PRODUCTION. TIME UNIT IS SECONDS

	MODEL		
DATA SET	*GMS*	*ECL 1*	*ECL 20*
BASE	*33*	*119*	*160*
HPRM	*21*	*64*	*168*
LTS	*6*	*15*	*25*

The total execution time on an IBM-PC/AT is about 20 *times longer* than the times given in Table 7.3.

Discussion of the time consumption

One can reckon the time consumption for ordinary GMS simulations to be in the range of 5 to 20 ND-500 CPU seconds, depending on the production time to be simulated, the timestep length, and the number of iterations required at each timestep (depending on the problem severity) (see Section 7.8). A timestep length of 1/24 years (BASE and HPRM) is probably in most cases shorter than necessary (see Section 7.7), which means that the CPU time can be decreased compared to these cases. Connected to an economic model, some time could be saved by reducing the amount of output. This approach depends on the interface connecting the models. On the IBM-PC/AT, about 11% of the execution time was used for writing to file.

It will also be possible to save computing time by increasing the convergence tests tolerances (located in the well and time control of the main program), and increasing the pressure step in integration (by

altering "DPINT" in the input file). This would probably be at the expense of calculation accuracy.

7.11 Future Developments of GMS

The GMS model provides a good basis for further developments, and some possible extensions are suggested here. The interaction with or implementation of a tubing model should be provided. In its simplest form this could be interpolation in precalculated tables given as input. This would be a fast-processing solution. The development of an interface with a total field development model for economic and strategic planning could be considered. This would be necessary for the total model to be able to perform an automatic optimization process. The range of drive mechanisms implemented in GMS is limited to the depletion of in-situ hydrocarbons (solution-gas drive for oil and depletion drive for gas reservoirs). This could be extended to take into account gas-cap, injection and aquifer drives. Coning problems are also of interest. Further, the calculation of skin components from permeability, geometric and other input data could be implemented.

Chapter 8

CONCLUSIONS

The development and testing of the material-balance (MB) and inflow-performance model for oil and gas-condensate reservoirs led to the following conclusions.

1. A model, named GMS, for the simulation of oil and gas production from a field with multiple wells has been developed. The program can utilize PVT data from the general PVT formulation and is based on (1) a general formulation of the reservoir MB, and (2) an inflow-performance relationship based on the pseudopressure concept, incorporating both the solution GOR in oil and the solution OGR in gas.

2. An example demonstrates the well and time control facilities of the GMS model. Minimum and target production rates of the preferred phase, minimum required wellhead pressure, and the number of wells can be specified as functions of time in the input file; these quantities control the simulation.

3. GMS was compared with three other programs to verify its MB calculations. For each comparison, the same PVT data were used for GMS and the other program in question. The three programs were (1) a dry-gas program (used with PVT data for a dry gas), (2) a Tarner MB program (used with oil PVT data as required by the Tarner MB), and (3) the commercial, fully implicit, three-dimensional simulator ECLIPSE, run as a monoblock model (used with PVT data as calculated with the general MB formulation, modified by setting the surface density ratios equal to one). An exact match was achieved for the quantities compared. This indicates that GMS should be correct with respect to MB calculations as far as these tests show.

4. ECLIPSE was also run as a one-dimensional, one-well model with 20 gridblocks in a radial refined grid. ECLIPSE with 20 gridblocks showed a higher producing GOR than GMS. This might be because the monoblock models (GMS, and ECLIPSE with one gridblock) fail to model the pressure, saturation, and relative permeability distri-

butions in the reservoir correctly.

5. The inflow-performance calculations of GMS were evaluated by considering the performance coefficient of Eq. 4.27. The deviation between GMS and ECLIPSE run with 20 gridblocks (ECL 20) increased with increasing pressure drawdown. However, GMS plots closer to ECL 20 than ECLIPSE can manage when run as a *monoblock model*. In many cases, it is believed that GMS could yield the required accuracy.

6. Simulations performed with PVT data generated from the conventional and the general formulations show distinct disparity, indicating that the choice of PVT formulation can have a significant influence on the simulation results.

7. GMS provides a good basis for further developments. Some possible extensions are tubing-performance calculations, interface to an economic model, other drive mechanisms than the depletion of in-situ hydrocarbons, coning considerations and the calculation of skin.

8. The processing of GMS is faster per timestep during the plateau-production period than during the decline period. This is because one, or often two, more iteration levels are active for the decline period calculations.

9. GMS consumes considerably less processing time on the computer than ECLIPSE, for the cases considered (ECLIPSE run with either 1 or 20 gridblocks).

NOMENCLATURE

English symbols

A = drainage area, m^2

B_g = gas formation volume factor, Rm^3/Sm^3

B_o = oil formation volume factor, Rm^3/Sm^3

B_{od} = oil volume (Rm^3) at reservoir pressure required to yield one Sm^3 of stock-tank oil when differentially liberated to stock-tank conditions, Rm^3/Sm^3

B_{odb} = volume of bubblepoint oil (Rm^3) required to yield one Sm^3 of stock-tank oil when differentially liberated to stock-tank conditions, Rm^3/Sm^3

B_{ofb} = volume of bubblepoint oil (Rm^3) required to yield one Sm^3 of stock-tank oil when flashed through the separator system to stock-tank conditions, Rm^3/Sm^3

C = performance coefficient, defined by Eqs. 4.26 and 4.27

C_A = shape factor.

C_1 = constant defined by Eq. 3.37

C_2 = constant defined by Eq. 3.38

C_3 = constant defined by Eq. 4.24

c_t = total compressibility, Pa^{-1}

D = non-Darcy flow coefficient (total rate dependent skin term), s/m^3

G = initial gas volume in place, Sm^3

G_p = cumulative gas production, Sm^3

G'_p = variable defined by Eq. 3.6b

ΔG_p = incremental gas production, Sm^3

ΔG_{pf} = incremental gas production during the last timestep from free reservoir gas, Sm^3

h = net formation thickness, m

h_p = height of perforated interval, m

k = permeability, m^2

k_{rg} = relative permeability to gas, fraction

k_{ro} = relative permeability to oil, fraction

M_b = mobility ratio as defined by Eq. 4.18

m_g = total mass of gas at STC from both free oil and free gas, kg

m_{gg} = mass of gas at STC existing in the reservoir as free gas, kg

m_{go} = mass of gas at STC existing in the reservoir as free oil, kg

m_o = total mass of oil at STC from both free oil and free gas, kg

m_{og} = mass of oil at STC existing in the reservoir as free gas, kg

m_{oo} = mass of oil at STC existing in the reservoir as free oil, kg

m_p = mass of oil and gas in the reservoir, kg

N = initial oil volume in place, Sm^3

N_p = cumulative oil production, Sm^3

N_p' = recovery of oil, fraction

ΔN_p = incremental oil production, Sm^3

ΔN_{pf} = incremental oil production during the last timestep from free reservoir oil, Sm^3

p = pressure, Pa

p_e = pressure at external boundary of drainage area, Pa

p_R = average reservoir pressure, Pa

p_{wf} = bottomhole flowing pressure, Pa

q_g = total surface gas production rate from free reservoir gas and from solution in free reservoir oil, Sm^3/s

q_{gf} = gas production rate from free reservoir gas, at standard conditions, Sm^3/s

$\check{q}_g$ = total surface gas mass flux, kg/s

$\check{q}_{gf}$ = gas mass flux from free reservoir gas, kg/s

$\check{q}_{gs}$ = gas mass flux from solution in free reservoir oil, kg/s

q_o = total surface oil production rate from free reservoir oil and from solution in free reservoir gas, Sm^3/s

q_{of} = oil production rate from free reservoir oil, at standard conditions, Sm^3/s

$\check{q}_o$ = total surface oil mass flux, kg/s

$\check{q}_{of}$ = oil mass flux from free reservoir oil, kg/s

$\check{q}_{os}$ = oil mass flux from solution in free reservoir gas, kg/s

$\check{q}_p$ = mass production rate from the reservoir, kg/s

r = radial distance from the well, m

R = producing gas/oil ratio, Sm^3/Sm^3

r_e = radius of drainage area, m

$(R_L)_{st}$ = standard volume (Sm^3) of gas liberated by differential liberation from the initial bubblepoint pressure to another reservoir pressure, referred to a Sm^3 of liquid at standard conditions, Sm^3/Sm^3

R_s = solution gas/oil ratio in oil, Sm^3/Sm^3

r_s = solution oil/gas ratio in gas (oil solubility in free reservoir gas), Sm^3/Sm^3

R_{sp} = gas volume (Sm^3) liberated at the separator per stock-tank Sm^3 of oil by flashing bubblepoint oil, Sm^3/Sm^3

r_w = wellbore radius, m

s = total "formation" skin factor (not rate dependent), dimensionless

S_g = gas saturation, fraction

S_o = oil saturation, fraction

S_w = water saturation, fraction

T = temperature, K

t = time, s

Δt = timestep length, s

u_{of} = velocity of free reservoir oil (volumetric flux per unit area), m/s

V_b = reservoir bulk volume, m^3

V_{gg}^{STC} = stock-tank gas volume from flash separation of the free reservoir gas (V_g^R), Sm^3

V_{go}^{STC} = stock-tank gas volume from flash separation of the free reservoir oil (V_g^R), Sm^3

V_g^R = volume of free reservoir gas, Rm^3

V_{og}^{STC} = stock-tank oil volume from flash separation of the free reservoir gas (V_g^R), Sm^3

V_{oo}^{STC} = stock-tank oil volume from flash separation of the free reservoir oil (V_o^R), Sm^3

V_o^R = volume of free reservoir oil, Rm^3

z = compressibility factor (real gas deviation factor), dimensionless

Greek symbols

μ = viscosity, Pa s

μ_g = gas viscosity, Pa s

μ_o = oil viscosity, Pa s

ϱ = density, kg/m^3

ϱ_g^* = gas density ratio (specific gravity ratio) as defined by Eq. 3.46, dimensionless

ϱ_{gg}^{STC} = density of gas from free reservoir gas, kg/m^3

ϱ_{go}^{STC} = density of gas from free reservoir oil, kg/m^3

ρ_o^* = oil density ratio (specific gravity ratio) as defined by Eq. 3.45, dimensionless

ρ_{og}^{STC} = density of oil from free reservoir gas, kg/m^3

ρ_{oo}^{STC} = density of oil from free reservoir oil, kg/m^3

ϕ = formation porosity, fraction

ϕ_n = constant defined by Eq. 3.4, dimensionless

ϕ_g = constant defined by Eq. 3.5, dimensionless

Subscripts and superscripts

a = damage/stimulation
A = drainage area shape
avg = average
b = bubblepoint
b = bulk
v = partial penetration
d = differential liberation
dp = damaged perforation
e = external boundary
f = flash
f = free phase in the reservoir
G = gravel pack
g = gas
gg = gas from free reservoir gas
go = gas from free reservoir oil
i = initial
j = current timestep
k = next timestep, timestep counter
L = liberated
o = oil
og = oil from free reservoir gas
oo = oil from free reservoir oil
p = perforation
p = produced
r = relative

R = reservoir
res = reservoir
s = solution
sp = separator
st = standard conditions.
STC = standard conditions.
stc = standard conditions.
w = water
w = wellbore
wf = well flowing
" = divided by V_b
~ = mass instead of volume

Mathematical operators

∂ = partial derivative
∇ = gradient, m^{-1}
$\nabla\cdot$ = divergence, m^{-1}
Δ = difference

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Appendix A

THE GMS PROGRAM SYSTEM

A.0 Introduction

The GMS program is in this appendix described by a program listing, flowcharts, and lists of variable names with a short explanation. Below this, one can find sections about program efficiency and convergence criteria for GMS. The post-processor program PLOT-GMS for the preparation of plot files is listed in the last section. This program is not further documented in this report.

A.1 GMS Program Listing

```
C TAB F; () 7,72;
C * * * * * A GENERAL MATERIAL BALANCE AND INFLOW PERFORMANCE * * * * *
C * * * * SIMULATION MODEL FOR OIL AND GAS CONDENSATE RESERVOIRS  * * *
C * * * * * * * * * * * * * * * * GMS * * * * * * * * * * * * * * * * *
C * * * * * * * * * * * * * * * MAIN PROGRAM  * * * * * * * * * * * * * *
C
C TITLE .......:  GMS, MAIN PROGRAM
C AUTHOR ......:  GUNNAR BORTHNE
C DATE ........:  APRIL 1986
C VERSION .....:  1.0
C LANGUAGE ....:  FORTRAN 77
C
C FUNCTION ....:  This program is a material balance and inflow
C     performance simulation model for oil and gas-condensate
C     reservoirs.  The GMS formulations can utilize PVT data from the
C     general PVT formulation which is based on flash separation of the
C     oil  and  gas,  separately,  to  stock-tank conditions (STC). (For
C     these data, flash has been done  from  each  pressure  step  in  a
C     differential-liberation or constant-volume depletion process.  The
C     gas/oil ratio in oil, oil/gas ratio in gas, and densities  at  STC
C     are functions of the feed pressure to the flash process.)
C          The inflow-performance procedure utilizes the pseudopressure
C     concept with numerical integration of a pressure function.
C     (Simpson's integration method is used.)
C          A field with multiple wells can be simulated.  The field
C     target and minimum production rates, minimum bottomhole or
C     wellhead pressure, and the number of wells should be specified on
C     the input as functions of time. All the wells are considered to be
```

```
C     "equivalent" and produce at the same average reservoir conditions
C     and have the same inflow-performance relationship.  Calculations
C     are performed on a well-basis and multiplied by the number of
C     wells to get field quantities.
C
C          For more information, see diploma thesis by Gunnar Borthne,
C     NTH, 1986.
C
C OUT-CALLS ...:  RATE, INTPL, SKIP, ITEST, TEST, TESTGE
C
C*********************************************************************
C
C     DESCRIPTION OF INPUT DATA
C     -------------------------
C
C---- FORMAT    : TEXT STRING (1 LINE)
C
C     1. JOBID .: JOB IDENTIFICATION
C
C
C
C---- FORMAT    : 4 INTEGERS (1 LINE)
C
C     1. IHC    : HYDROCARBON TYPE
C                   = 0 : GAS CONDENSATE
C                   = 1 : OIL
C     2. IUNIN  : UNITS IDENTIFIER FOR INPUT DATA
C                   = 0 : METRIC UNITS
C                   = 1 : OIL FIELD UNITS
C     3. IPRT   : PRINT OPTION
C                   = 0 : TABLES OF RESULTS ONLY
C                   = 1 : + ECHO OF INPUT DATA
C                   = 2 : + ITERATION REPORT
C                   = 3 : + RESULTS PRINTED TO THE SCREEN EACH TIMESTEP
C                   = 4 : + A MESSAGE FROM EACH ROUTINE
C     4. IEXE   : EXECUTION MODE
C                   = 0 : MATERIAL BALANCE ONLY
C                   = 1 : MATERIAL BALANCE AND IPR
C                   = 2 : MATERIAL BALANCE, IPR AND TUBING
C
C
C     ** NOTE : SEPARATE VARIABLES WITH A COMMA
C               AND/OR ONE OR MORE SPACES
C
C     ** NOTE : USE ONLY THE UNIT SYSTEM                          OIL
C               CHOSEN WITH IUNIN                  METRIC      FIELD
C                                                   UNITS      UNITS
C                                                  -------   --------
```

```
C---- FORMAT    : 6 DOUBLEPRECISION VARIABLES (1 LINE)
C
C     1. DELTIM : TIMESTEP LENGTH ..................:  YEARS      YEARS
C     2. XMXTIM : LENGTH OF SIMULATION .............:  YEARS      YEARS
C     3. HCPV   : HYDROCARBON PORE VOLUME ..........:    M3        BBL
C     4. PORI   : INITIAL POROSITY .................:    (FRACTION)
C     5. SATWI  : INITIAL WATER SATURATION .........:    (FRACTION)
C     6. CMPF   : FORMATION COMPRESSIBILITY ........:  1/KPA      1/PSI
C
C
C
C---- FORMAT    : 6 DOUBLEPRECISION VARIABLES (1 LINE)
C
C     1. PRM ...: PERMEABILITY .....................:    uM2         MD
C     2. THK ...: RESERVOIR THICKNESS ..............:     M          FT
C     3. RADW ..: WELLBORE RADIUS ..................:     M          FT
C     4. DSKN ..: NON-DARCY FLOW COEFFICIENT
C                 (RATE DEPENDENT SKIN TERM)
C                              ** IF IHC=0 (GAS) ...:  D/SM3      D/SCF
C                              ** IF IHC=1 (OIL) ...:  D/SM3      D/STB
C     5. DPINT  : PRESSURE INCREMENT IN SIMPSON-
C                 INTEGRATION, IPR ROUTINE .........:    KPA         PSI
C     6. TF     : "TUBING FACTOR" (NO PHYSICAL MEANING,
C                 USED ONLY IN TEMPORARY TUBING ROUTINE)
C                                       ..........:    DIMENSIONLESS
C
C
C
C
C---- TABLE OF WELL CONTROL SPECIFICATIONS
C---- FORMAT    : 1 DOUBLEPRECISION + 1 INTEGER + 4 DOUBLEPRECISION
C                 ON EACH LINE
C                 (REPEAT LINES, END WITH -1)
C
C     1. TTIM   : TIME FOR WELL CONTROL ............:  YEARS      YEARS
C     2. NWELLS : NUMBER OF WELLS ..................:
C     3. TRETFM : FIELD MINIMUM PRODUCTION RATE
C                              ** IF IHC=0 (GAS) ...:  SM3/D      SCF/D
C                              ** IF IHC=1 (OIL) ...:  SM3/D      STB/D
C     4. TRTEFT : FIELD TARGET  PRODUCTION RATE
C                              ** IF IHC=0 (GAS) ...:  SM3/D      SCF/D
C                              ** IF IHC=1 (OIL) ...:  SM3/D      STB/D
C     5. TPWMIN : MINIMUM WELLHEAD PRESSURE ........:    KPA       PSIA
C     6. TSKN ..: TOTAL SKIN (EXCEPT RATE DEPENDENT) .:    DIMENSIONLESS
C
C     ** NOTE: - TTIM MUST INCREASE DOWN THE COLUMN.
C              - TO END THE TABLE, PUT:  -1  ON THE NEXT LINE.
C
```

```
C
C
C
C---- TABLE OF PVT DATA FOR THE OIL PHASE
C---- FORMAT    : 5 DOUBLEPRECISION VARIABLES ON EACH LINE
C                 (REPEAT LINES, END WITH -1)
C
C     1. TPRS   : PRESSURE FOR PVT DATA .............:       KPA       PSIA
C     2. TVISO  : OIL VISCOSITY .....................:     PA S         CP
C     3. TGORS  : SOLUTION GAS/OIL RATIO,
C                 IN OIL PHASE ......................:  SM3/SM3   SCF/BBL
C     4. TDENRO : DENSITY RATIO (GRAVITY RATIO),
C                 OIL-FROM-GAS / OIL-FROM-OIL .......:     DIMENSIONLESS
C     5. TFVFO  : OIL FORMATION VOLUME FACTOR .......:  (RES.VOL/STD.VOL)
C
C     ** NOTE: - TPRS MUST INCREASE DOWN THE COLUMN.
C              - TO END THE TABLE, PUT:  -1  ON THE NEXT LINE.
C
C
C
C
C---- TABLE OF PVT DATA FOR THE GAS PHASE
C---- FORMAT    : 4 DOUBLEPRECISION VARIABLES ON EACH LINE
C                 (REPEAT LINES, END WITH -1)
C                 ** NOTE : SAME PRESSURES AS ABOVE
C
C     1. TVISG  : GAS VISCOSITY .....................:     PA S         CP
C     2. TOGRS  : SOLUTION OIL/GAS RATIO,
C                 IN GAS PHASE ......................:  SM3/SM3 STB/MMSCF
C     3. TDENRG : DENSITY RATIO (GRAVITY RATIO),
C                 GAS-FROM-OIL / GAS-FROM-GAS .......:    DIMENSIONLESS
C     4. TFVFG  : GAS FORMATION VOLUME FACTOR .......:  (RES.VOL/STD.VOL)
C
C     ** NOTE: TO END THE TABLE, PUT:  -1  ON THE NEXT LINE
C
C
C
C
C---- TABLE OF RELATIVE PERMEABILITY VS. SATURATION
C---- FORMAT    : 3 DOUBLEPRECISION VARIABLES ON EACH LINE
C                 (REPEAT LINES, END WITH -1)
C
C     1. TSATG  : GAS SATURATION ....................:       (FRACTION)
C     2. TPRMRO : RELATIVE PERMEABILITY TO OIL .....:       (FRACTION)
C     3. TPRMRG : RELATIVE PERMEABILITY TO GAS .....:       (FRACTION)
C
C     ** NOTE: - TSATG MUST INCREASE DOWN THE COLUMN.
C              - TO END THE TABLE, PUT:  -1  ON THE NEXT LINE.
```

```
C
C*********************************************************************
C
      PROGRAM GMS
C
C---- VARIABLES AND CONSTANTS
C
      INTEGER N1, N2
      PARAMETER (N1=100, N2=500)
C
      INTEGER IVNWEL(0:N2), NWELLS(N1), I, IERR, IEXE, IHC, IPRT,
     .    IUNIN, IWCTR, J, K, NSTEP, NWELL, NWT
C
      DOUBLEPRECISION TPWMIN(N1), TRTEFM(N1), TRTEFT(N1), TSKN(N1),
     .    TTIM(N1), VGASP(0:N2), VGOR(0:N2), VOILP(0:N2), VPRSR(0:N2),
     .    VPRSWF(0:N2), VPRSWH(0:N2), VRTEG(0:N2), VRTEO(0:N2), AN(8),
     .    VTIME(0:N2), AREA, DELTIM, DENRGI, DENROI, DGASP, DGASPS,
     .    DGORP, DOILP, DOILPS, EPSPRS, EPSRTE, FRAC, FVFGI, FVFOI,
     .    GASTI, GORSI, HCPV, OGRSI, OILTI, PI, PRMGOI, PRS, PRSHI,
     .    PRSWF, PRSWH, PVTMAX, PVTMIN, PWHMIN, RADE, RADW, RTEHI,
     .    RTELO, RTEMAX, RTEW, SATGI, SATOI, VISGI, VISOI, VOLB, X0, X1,
     .    X10, X2, X3, X4, X5, X6, X7, X8, X9, XMOBR, XMXTIM, Y
C
      CHARACTER ZJOBID*60, ZINPFL*32, ZOUTFL*32, ZC(8)*6
C     (Variable ZC is initialized in DATA below)
C
      LOGICAL QWCTR, QSTOP
C
C---- COMMON BLOCKS
C
      COMMON /PROP/ TDENRG, TDENRO, TFVFG, TFVFGX, TFVFO, TGORS,
     .    TOGRS, TPRMRG, TPRMRO, PRMLGO, TPRS, TSATG, TVISG, TVISO,
     .    NPVT, NRP
      DOUBLEPRECISION TDENRG(100), TDENRO(100), TFVFG(100), TFVFGX(100),
     .    TFVFO(100), TGORS(100), TOGRS(100), TPRMRG(100), TPRMRO(100),
     .    PRMLGO(100), TPRS(100), TSATG(100), TVISG(100), TVISO(100)
      INTEGER NPVT, NRP
      COMMON /MBAL1/  AG1, AO1, CMPF, DTIM, PORI, PRSI, RG1, RO1, SATWI,
     .    VOLBW
      DOUBLEPRECISION AG1, AO1, CMPF, DTIM, PORI, PRSI, RG1, RO1, SATWI,
     .    VOLBW
      COMMON /MBAL2/  AO2, AG2, RO2, RG2, RGAV
      DOUBLEPRECISION AO2, AG2, RO2, RG2, RGAV
      COMMON /MBAL3/  DENRG, DENRO, FVFG, FVFO, GORS, OGRS, POR, PRMGO,
     .    SATG1, SATO1, VISG, VISO, XMBAL1
      DOUBLEPRECISION DENRG, DENRO, FVFG, FVFO, GORS, OGRS, POR, PRMGO,
     .    SATG1, SATO1, VISG, VISO, XMBAL1
      COMMON /IPR1/   DPINT, DSKN, PRM, RADEQ, SKN, THK
```

```
      DOUBLEPRECISION DPINT, DSKN, PRM, RADEQ, SKN, THK
      COMMON /TUB/    TF
      DOUBLEPRECISION TF
      COMMON /ICOUNT/ IC, IT
      INTEGER         IC(8), IT(8)
C
C---- CONVERSION FACTORS WITH UNITS
C
      DOUBLEPRECISION C1,C2,C3,C4,C5,C6,C7,C8
      CHARACTER*20    Z1,Z2,Z3,Z4,Z5,Z6,Z7,Z8
      DATA C1, Z1  /.100000E-02, 'Pa s/cp '/,
     .     C2, Z2  /.404686E+04, 'm2/acre '/,
     .     C3, Z3  /.304800E+00, 'm/ft    '/,
     .     C4, Z4  /.689476E+01, 'kPa/psi '/,
     .     C5, Z5  /.986923E-03, 'um2/md  '/,
     .     C6, Z6  /.158987E+00, 'm3/bbl  '/,
     .     C7, Z7  /.561458E+01, 'ft3/bbl '/,
     .     C8, Z8  /.283169E-01, 'm3/ft3  '/
C
C---- DATA STATEMENTS
C
      DATA ZC /'RATE', 'WHPRS', 'RESPRS', 'MATBAL', 'IPR', 'FNPRS',
     .         'ISGN', 'INTPL'/
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                                           C
C                         START EXECUTION                                   C
C                                                                           C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      PRINT *,'                        GMS                                '
      PRINT *,'  A GENERAL MATERIAL BALANCE AND INFLOW PERFORMANCE         '
      PRINT *,'SIMULATION MODEL FOR OIL AND GAS CONDENSATE RESERVOIRS      '
      PRINT *,'          AUTHOR: GUNNAR BORTHNE, NTH, 1986                '
      PRINT *,'                     VERSION 1.0                           '
      PRINT *
      PRINT *,'INPUT DATA FILE NAME  :'
      PRINT *
      READ  1500,ZINPFL
      PRINT *,'OUTPUT DATA FILE NAME  :'
      PRINT *,'(Output to screen on ND      write: TERMINAL,'
      PRINT *,'                   on IBM-PC  write: CON)'
      PRINT *
      READ  1500,ZOUTFL
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                                           C
```

```
C                       READ INPUT DATA FROM FILE,                      C
C                        CONVERT TO METRIC UNITS                        C
C                     TEST INPUT DATA IN METRIC UNITS                   C
C                                                                       C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      OPEN (2, FILE=ZINPFL)
      OPEN (3, FILE=ZOUTFL)
      IERR=0
      PRINT *,'Reading and testing input data...'
      PRINT *
C
C---- READ DATA LINE 1, JOB IDENTIFICATION
C
      READ (2,1500) ZJOBID
C
C---- READ AND TEST DATA LINE 2
C
      CALL SKIP(2)
      READ (2,*) IHC,IUNIN,IPRT,IEXE
      CALL ITEST(IHC,0,1,'IHC',IERR)
      CALL ITEST(IUNIN,0,1,'IUNIN',IERR)
      CALL ITEST(IPRT,0,4,'IPRT',IERR)
      CALL ITEST(IEXE,0,2,'IEXE',IERR)
C
C---- READ AND TEST DATA LINE 3
C
      CALL SKIP(2)
      READ (2,*) DELTIM,XMXTIM,HCPV,PORI,SATWI,CMPF
      IF (IUNIN.EQ.1) THEN
          HCPV=HCPV*C6
          CMPF=CMPF/C4
      ENDIF
      CALL TEST(DELTIM,0D+0,1D+0,'DELTIM',IERR)
      CALL TEST(XMXTIM,0D+0,400D+0,'XMXTIM',IERR)
      CALL TEST(HCPV,0D+0,1D+20,'HCPV',IERR)
      CALL TEST(PORI,0D+0,1D+0,'PORI',IERR)
      CALL TEST(SATWI,0D+0,1D+0,'SATWI',IERR)
      CALL TEST(CMPF,0D+0,1D-1,'CMPF',IERR)
      DELTIM=DELTIM*365.
      XMXTIM=XMXTIM*365.
C
C---- READ AND TEST DATA LINE 4
C
      CALL SKIP(2)
      READ (2,*) PRM,THK,RADW,DSKN,DPINT,TF
      IF (IUNIN.EQ.1) THEN
          PRM=PRM*C5
```

```
          THK=THK*C3
          RADW=RADW*C3
          IF (IHC.EQ.0) DSKN=DSKN/C8
          IF (IHC.EQ.1) DSKN=DSKN/C6
          DPINT=DPINT*C4
      ENDIF
      CALL TEST(PRM,0D+0,10000D+0,'PRM',IERR)
      CALL TEST(THK,0D+0,1000D+0,'THK',IERR)
      CALL TEST(RADW,0D+0,3D+1,'RADW',IERR)
      CALL TEST(DPINT,10D+0,10000D+0,'DPINT',IERR)
C
C---- READ AND TEST DATA TABLE 1
C
      I=0
  100 CONTINUE
          I=I+1
          CALL SKIP(2)
          READ (2,*) X0
          IF (X0.LT.0.) GOTO 109
          BACKSPACE (2)
          READ (2,*) TTIM(I),NWELLS(I),TRTEFM(I),TRTEFT(I),TPWMIN(I),
     .         TSKN(I)
C         Note: Input time in years, internal time in days.
          TTIM(I)=TTIM(I)*365
          NWT=I
          X1=C8
          IF (IHC.EQ.1) X1=C6
          IF (IUNIN.EQ.1) THEN
              TRTEFM(I)=TRTEFM(I)*X1
              TRTEFT(I)=TRTEFT(I)*X1
              TPWMIN(I)=TPWMIN(I)*C4
          ENDIF
          CALL TEST(TTIM(I)/365,0D+0,400D+0,'TTIM',IERR)
          IF (I.GT.1) CALL TESTGE(TTIM(I-1)/365,TTIM(I)/365,'TTIM',IERR)
          CALL ITEST(NWELLS(I),1,500,'NWELLS',IERR)
          CALL TEST(TRTEFM(I),0D+0,1D+7,'TRTEFM',IERR)
          CALL TEST(TRTEFT(I),0D+0,2D+9,'TRTEFT',IERR)
          CALL TEST(TPWMIN(I),0D+0,1D+5,'TPWMIN',IERR)
          CALL TEST(TSKN(I),-1D+2,1D+2,'TSKN',IERR)
      GOTO 100
  109 CONTINUE
      CALL TEST(TTIM(1)/365,0D+0,0D+0,'TTIM(1)',IERR)
      CALL ITEST(NWT,1,N1-1,'NWT >= N1',IERR)
C
C---- READ AND TEST DATA TABLE 2
C
      I=0
  110 CONTINUE
```

```
          I=I+1
          CALL SKIP(2)
          READ (2,*) X0
          IF (X0.LT.0.) GOTO 119
          BACKSPACE (2)
          READ (2,*) TPRS(I),TVISO(I),TGORS(I),TDENRO(I),TFVFO(I)
          NPVT=I
          IF (IUNIN.EQ.1) THEN
              TPRS(I)=TPRS(I)*C4
              TVISO(I)=TVISO(I)*C1
              TGORS(I)=TGORS(I)/C7
          ENDIF
          CALL TEST(TPRS(I),0D+0,5D+5,'TPRS',IERR)
          IF (I.GT.1) CALL TESTGE(TPRS(I-1),TPRS(I),'TPRS',IERR)
          CALL TEST(TVISO(I),0D+0,.1D+0,'TVISO',IERR)
          CALL TEST(TGORS(I),0D+0,5000D+0,'TGORS',IERR)
          CALL TEST(TDENRO(I),0D+0,10D+0,'TDENRO',IERR)
          CALL TEST(TFVFO(I),0D+0,10D+0,'TFVFO',IERR)
          GOTO 110
  119 CONTINUE
C
C---- READ AND TEST DATA TABLE 3
C
      I=0
  120 CONTINUE
          I=I+1
          CALL SKIP(2)
          READ (2,*) X0
          IF (X0.LT.0.) GOTO 129
          BACKSPACE (2)
          READ (2,*) TVISG(I),TOGRS(I),TDENRG(I),TFVFG(I)
          TFVFGX(I)=1/TFVFG(I)
          IF (IUNIN.EQ.1) THEN
              TVISG(I)=TVISG(I)*C1
              TOGRS(I)=TOGRS(I)*C7/1E+6
          ENDIF
          CALL TEST(TVISG(I),0D+0,.01D+0,'TVISG',IERR)
          CALL TEST(TOGRS(I),0D+0,1D+0,'TOGRS',IERR)
          CALL TEST(TDENRG(I),0D+0,10D+0,'TDENRG',IERR)
          CALL TEST(TFVFG(I),0D+0,2D+0,'TFVFG',IERR)
      GOTO 120
  129 CONTINUE
      CALL ITEST(NPVT,I-1,I-1,'NPVT TABLES DIFFERENT LENGTH',IERR)
      CALL ITEST(NPVT,2,N1,'NPVT',IERR)
C
C---- READ AND TEST DATA TABLE 4
C
      I=0
```

```
 130 CONTINUE
         I=I+1
         CALL SKIP(2)
         READ (2,*) X0
         IF (X0.LT.0.) GOTO 139
         BACKSPACE (2)
         READ (2,*) TSATG(I),TPRMRO(I),TPRMRG(I)
         NRP=I
         CALL TEST(TSATG(I),0D+0,1D+0,'TSATG',IERR)
         IF (I.GT.1) CALL TESTGE(TSATG(I-1),TSATG(I),'TSATG',IERR)
         CALL TEST(TPRMRO(I),0D+0,1D+0,'TPRMRO',IERR)
         CALL TEST(TPRMRG(I),0D+0,1D+0,'TPRMRG',IERR)
      GOTO 130
 139 CONTINUE
      CALL ITEST(NRP,2,N1,'NRP',IERR)
      CALL TEST(TSATG(1),0D+0,0D+0,'TSATG, FIRST VALUE',IERR)
      CALL TEST(TSATG(NRP),1D+0-SATWI,1D+0,'TSATG, LAST VALUE',IERR)
C
      CLOSE (2)
      TTIM(NWT+1)=XMXTIM
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                                           C
C                          WRITE INPUT DATA,                                C
C               (BOTH METRIC UNITS AND OIL FIELD UNITS)                     C
C                                                                           C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      WRITE (3,2000)
      IF (IPRT.EQ.0) GOTO 300
      PRINT *,'Writing...'
      PRINT *
      WRITE (3,2010) 'REVIEW OF INPUT DATA'
      WRITE (3,*   ) '--------------------'
C
C---- WRITE DATA LINE 1 AND 2
C
      WRITE (3,2020) ZJOBID,IHC,IUNIN
      WRITE (3,2022) IPRT,IEXE
      WRITE (3,2025) NWT,NPVT,NRP
      X1=DELTIM/365.
C
C---- WRITE DATA LINE 3
C
      X2=XMXTIM/365.
      X3=HCPV/C6
      X4=CMPF*C4
      WRITE (3,2030) X1,X2,HCPV,X3,PORI,SATWI,CMPF,X4
```

```
C
C---- WRITE DATA LINE 4
C
      X1=PRM/C5
      X2=THK/C3
      X3=RADW/C3
      X4=DSKN*C8
      X5=DSKN*C6
      X6=DPINT/C4
      WRITE (3,2040) PRM,X1,THK,X2,RADW,X3,DSKN,X4,X5,
     .    DPINT,X6,TF
C
C---- WRITE DATA TABLE 2
C
      WRITE (3,2050) ZJOBID
      DO 208 I=1,NPVT
          X1=TPRS(I)/C4
          X2=TVISO(I)/C1
          X3=TGORS(I)*C7
          WRITE (3,2060) I,TPRS(I),X1,TVISO(I),X2,
     .         TGORS(I),X3,TDENRO(I),TFVFO(I)
  208 CONTINUE
      WRITE (3,2101)
C
C---- WRITE DATA TABLE 3
C
      WRITE (3,2090) ZJOBID
      DO 218 I=1,NPVT
          X1=TPRS(I)/C4
          X2=TVISG(I)/C1
          X3=TOGRS(I)*1E+6/C7
          WRITE (3,2100) I,TPRS(I),X1,TVISG(I),X2,
     .         TOGRS(I),X3,TDENRG(I),TFVFG(I)
  218 CONTINUE
      WRITE (3,2101)
C
C---- WRITE DATA TABLE 4
C
      WRITE (3,2130) ZJOBID
      DO 228 I=1,NRP
          WRITE (3,2140) I,TSATG(I),TPRMRO(I),TPRMRG(I)
  228 CONTINUE
      WRITE (3,2039)
C
C---- WRITE DATA TABLE 1
C
      IF (IHC.EQ.0) THEN
          WRITE (3,2150) ZJOBID
```

```
            X0=1./C8
        ELSEIF (IHC.EQ.1) THEN
            WRITE (3,2160) ZJOBID
            X0=1./C6
        ENDIF
        DO 238 I=1,NWT
            X1=TTIM(I)/365.
            X2=TTIM(I+1)/365.
            X3=TRTEFM(I)*X0
            X4=TRTEFT(I)*X0
            X5=TPWMIN(I)/C4
            WRITE (3,2170) I,TTIM(I),TTIM(I+1),X1,X2,NWELLS(I),
     .          TRTEFM(I),X3,TRTEFT(I),X4,TPWMIN(I),X5,TSKN(I)
  238 CONTINUE
        WRITE (3,2126)
C
C---- IF ERRORS ARE DETECTED: WRITE MESSAGE AND STOP RUN
C
  300 CONTINUE
        IF (IERR.GT.0) THEN
            WRITE (3,*)
            WRITE (3,*) IERR,' INPUT DATA ERROR(S) DETECTED'
            PRINT *,    IERR,' INPUT DATA ERROR(S) DETECTED'
            STOP
        ENDIF
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                                      C
C                              INITIALIZE                              C
C                                                                      C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C---- INITIALIZE VARIABLES
C
        K=0
        IWCTR=1
        QWCTR=.TRUE.
        QSTOP=.FALSE.
        PI=3.141592654
        NWELLS(NWT+1)=0
        PVTMIN=MIN(TPRS(1),TPRS(NPVT))
        PVTMAX=MAX(TPRS(1),TPRS(NPVT))
        PRSI=PVTMAX
        VOLB=HCPV/PORI/(1-SATWI)
        AREA=VOLB/THK
        RADE=SQRT(AREA/PI+RADW*RADW)
C
C---- INITIALIZE PRECALCULATED ARRAY OF LOG (REL.PERM. RATIO)
```

```
C
      DO 408 I=1,NRP
          IF (TPRMRO(I).LT.1E-50) THEN
              PRMLGO(I)=115.
          ELSEIF (TPRMRG(I).EQ.0.) THEN
              PRMLGO(I)=-115.
          ELSE
              PRMLGO(I)=LOG(TPRMRG(I)/TPRMRO(I))
          ENDIF
          IF (PRMLGO(I).GT.115.) PRMLGO(I)=115.
  408 CONTINUE
C
C---- INITIALIZE VARIABLES TO BE USED BY MBAL
C
      CALL INTPL(TPRS,TGORS,PRSI,1,NPVT,GORSI,FRAC,J)
      FVFOI=TFVFO(J)+FRAC*(TFVFO(J+1)-TFVFO(J))
      VISOI=TVISO(J)+FRAC*(TVISO(J+1)-TVISO(J))
      OGRSI=TOGRS(J)+FRAC*(TOGRS(J+1)-TOGRS(J))
      VISGI=TVISG(J)+FRAC*(TVISG(J+1)-TVISG(J))
      DENROI=TDENRO(J)+FRAC*(TDENRO(J+1)-TDENRO(J))
      DENRGI=TDENRG(J)+FRAC*(TDENRG(J+1)-TDENRG(J))
C
C---- PRECALCULATE ARRAY OF RECIPROCAL OF FVFG
C
      FVFGI=1/(TFVFGX(J)+FRAC*(TFVFGX(J+1)-TFVFGX(J)))
C
      IF (IHC.EQ.0) SATOI=0.
      IF (IHC.EQ.1) SATOI=1-SATWI
      SATGI=1-SATWI-SATOI
      CALL INTPL(TSATG,PRMLGO,SATGI,1,NRP,Y,FRAC,J)
      PRMGOI=EXP(Y)
      XMOBR=PRMGOI*VISOI/VISGI
      AO1=PORI*(SATOI/FVFOI + SATGI*OGRSI*DENROI/FVFGI)
      AG1=PORI*(SATGI/FVFGI + SATOI*GORSI*DENRGI/FVFOI)
      RO1=(1. + OGRSI*DENROI*XMOBR*FVFOI/FVFGI)
      RG1=GORSI*DENRGI + XMOBR*FVFOI/FVFGI
C
C---- CALCULATE INITIAL GAS AND OIL IN PLACE
C
      GASTI=0.
      OILTI=0.
      IF (IHC.EQ.0) GASTI=HCPV/FVFGI
      IF (IHC.EQ.1) OILTI=HCPV/FVFOI
C
C---- INITIALIZE REPORT ARRAYS
C
      VTIME(0)=0.
      VTIME(1)=DELTIM
```

```
      VPRSR(0)=PRSI
      VPRSWF(0)=0.
      VPRSWH(0)=0.
      VGOR(0)=0.
      VGASP(0)=0.
      VOILP(0)=0.
C
C---- INITIALIZE ITERATION COUNTERS
C
      DO 418 I=1,8
          IC(I)=0
          IT(I)=0
          AN(I)=0.
  418 CONTINUE
C
C---- WRITE SOME RESULTS
C
      WRITE (3,2001)
      WRITE (3,*    ) 'CALCULATED RESULTS'
      WRITE (3,*    ) '------------------'
      IF (IHC.EQ.0) THEN
          X1=PRSI/C4
          X2=GASTI/C8
          WRITE (3,3000) PRSI,X1,GASTI,X2
      ELSEIF (IHC.EQ.1) THEN
          X1=PRSI/C4
          X2=OILTI/C6
          WRITE (3,3010) PRSI,X1,OILTI,X2
      ENDIF
      X1=VOLB/C6
      X2=AREA/C2
      X3=RADE/C3
      WRITE (3,3020) SATOI,SATGI,VOLB,X1,AREA/1000.,X2,RADE,X3
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                                          C
C                       START TIMESTEP LOOP                                C
C                                                                          C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      PRINT *,'Processing timestep :'
      PRINT *
 1000 CONTINUE
          K=K+1
          IF (IPRT.LT.3) PRINT 1530,K
          IF (K.GE.N2) GOTO 999
C
C---- WELL CONTROL
```

```
C
          IF (QWCTR) THEN
              NWELL=NWELLS(IWCTR)
              IF (NWELL .EQ. 0) THEN
C                 (It's time to stop execution)
                  GOTO 999
              ENDIF
              RTELO=TRTEFM(IWCTR)/NWELL
              RTEMAX=TRTEFT(IWCTR)/NWELL
              RTEW=RTEMAX
              EPSRTE=RTEW*0.0005
              EPSPRS=0.5
              VOLBW=VOLB/NWELL
              RADE=SQRT(RADW**2 + VOLBW/PI/THK)
              RADEQ=RADE/RADW
              PWHMIN=TPWMIN(IWCTR)
              SKN=TSKN(IWCTR)
              IWCTR=IWCTR+1
              QWCTR=.FALSE.
          ENDIF
C
C---- TIME CONTROL
C
          IF (VTIME(K) .GT. TTIM(IWCTR)) THEN
              QWCTR=.TRUE.
              VTIME(K+1)=VTIME(K)
              VTIME(K)=TTIM(IWCTR)
          ELSEIF (VTIME(K) .EQ. TTIM(IWCTR)) THEN
              QWCTR=.TRUE.
              VTIME(K+1)=VTIME(K)+DELTIM
          ELSE
              VTIME(K+1)=VTIME(K)+DELTIM
          ENDIF
          DTIM=VTIME(K)-VTIME(K-1)
C
C---- Assume that the average reservoir pressure and the rate will not
C     increase from one timestep to another unless well control is
C     changed. Since XMBAL usually is not identically zero after a time-
C     step, PRSHI is set > VPRSR(K-1)  to avoid problems when the rate
C     is zero.  Shrink the rate interval which will be used for
C     calculations.
C
          PRSHI=MIN(VPRSR(K-1)*1.0001,PVTMAX)
          RTEHI=MIN(RTEW*1.0001,RTEMAX)
C
C---- CALCULATE RATE, RESERVOIR PRESSURE, BOTTOMHOLE PRESSURE AND
C     WELLHEAD PRESSURE
C
```

```
          CALL RATE (PRSHI, PVTMIN, PWHMIN, RTEHI, RTELO, EPSPRS,
     .         EPSRTE, K, IPRT, IEXE, IHC, PRS, PRSWF, PRSWH, RTEW,
     .         DGASP, DOILP, DGORP, QSTOP)
          IF (QSTOP) GOTO 999
C
C---- UNPHYSICAL SATURATIONS ?
C
          IF (SATO1.LT.0. .OR. SATG1.LT.0.) THEN
              WRITE (3,*)'MAIN.  TIMESTEP:',K
              WRITE (3,*)'** ERROR **'
              WRITE (3,*)'UNPHYSICAL SATURATION'
              WRITE (3,*)'SATG1, SATO1', SATG1, SATO1
              WRITE (3,*)
              STOP
          ENDIF
C
C---- UPDATE VARIABLES
C
          DGASPS=DGASP*NWELL
          DOILPS=DOILP*NWELL
C         (Volumes on field basis:)
          VGASP(K)=VGASP(K-1) + DGASPS
          VOILP(K)=VOILP(K-1) + DOILPS
C         (Rates on well basis:)
          VRTEG(K)=DGASP/DTIM
          VRTEO(K)=DOILP/DTIM
          VGOR(K)=DGORP
          VPRSR(K)=PRS
          VPRSWF(K)=PRSWF
          VPRSWH(K)=PRSWH
          IVNWEL(K)=NWELL
          AO1=AO2
          AG1=AG2
          RO1=RO2
          RG1=RG2
C
C---- WRITE INTERMEDIATE RESULTS IF REQUESTED
C
          IF (IPRT.GE.3) THEN
              WRITE (3,*)
              WRITE (3,2075)
              WRITE (3,1510)'TIMESTEP NUMBER : ',K,'TIME : ',VTIME(K)
              WRITE (3,2075)
              WRITE (3,*)
              WRITE (3,1520) 'VGASP(K)', VGASP(K),    'FVFO',     FVFO
              WRITE (3,1520) 'VOILP(K)', VOILP(K),    'VISG',     VISG
              WRITE (3,1520) 'PRS',      PRS,         'OGRS',     OGRS
              WRITE (3,1520) 'PRSWF',    PRSWF,       'DENRG',    DENRG
```

```
            WRITE (3,1520) 'PRSWH',     PRSWH,       'FVFG',     FVFG
            WRITE (3,1520) 'DGORP',     DGORP,       'POR',      POR
            WRITE (3,1520) 'VRTEG(K)', VRTEG(K),     'SATO1',    SATO1
            WRITE (3,1520) 'VRTEO(K)', VRTEO(K),     'SATG1',    SATG1
            WRITE (3,1520) 'PRSHI',     PRSHI,       'XMBAL1',   XMBAL1
            WRITE (3,1520) 'PVTMIN',    PVTMIN,      'PRMGO',    PRMGO
            WRITE (3,1520) 'PWHMIN',    PWHMIN,      'VOLBW',    VOLBW
            WRITE (3,1520) 'RTEHI',     RTEHI,       'RADEQ',    RADEQ
            WRITE (3,1520) 'RTELO',     RTELO,       'RADE',     RADE
            WRITE (3,1520) 'SKN',       SKN,         'AO2',      AO2
            WRITE (3,1520) 'VISO',      VISO,        'AG2',      AG2
            WRITE (3,1520) 'GORS',      GORS,        'RO2',      RO2
            WRITE (3,1520) 'DENRO',     DENRO,       'RG2',      RG2
            WRITE (3,1521) 'IVNWEL(K)',IVNWEL(K)
            WRITE (3,*)
            WRITE (3,2076)
            WRITE (3,*)
         ENDIF
C
C---- CHECK STOP CONDITIONS
C
         IF (RTEW.LT.0.01 .AND. RTEW.LT.RTEHI) GOTO 999
         IF (PRS.GT.VPRSR(K-1)) GOTO 999

C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                                             C
C                       END TIMESTEP LOOP                                     C
C                                                                             C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      GOTO 1000
C
C
C---- WRITE MESSAGES
C
  999 CONTINUE
      IF (K.GE.N2) THEN
          WRITE (3,*)'MAIN.  TIMESTEP:',K
          WRITE (3,*)'ATTEMPT TO RUN TOO MANY TIMESTEPS.'
          WRITE (3,*)'EXECUTION STOPS.'
          WRITE (3,*)
      ENDIF
      IF (RTEW.LT.0.01 .AND. RTEW.LT.RTEHI) THEN
          WRITE (3,*)
          WRITE (3,*)'MAIN.  TIMESTEP:',K
          WRITE (3,*)'THE RATE (RTEW) IS APPROXIMATELY ZERO.'
          WRITE (3,*)'EXECUTION STOPS.'
```

```
          WRITE (3,*)
      ENDIF
      IF (PRS.GT.VPRSR(K-1)) THEN
          WRITE (3,*)'MAIN.  TIMESTEP:',K
          WRITE (3,*)'PRS > VPRSR(K-1)'
          WRITE (3,*)
      ENDIF
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                                              C
C                            WRITE RESULTS                                     C
C                                                                              C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      PRINT *
      PRINT *,'Writing results...'
      PRINT *
      NSTEP=K-1
C
C---- WRITE TABLE OF CUMULATIVE PRODUCTION
C
      WRITE (3,3200) ZJOBID
      DO 608 I=1,NSTEP
          X1=VTIME(I)/365.
          X2=VGASP(I)/1E+6
          X3=VGASP(I)/C8/1E+6
          X4=VOILP(I)/1E+3
          X5=VOILP(I)/C6/1E+3
          X6=0.
          IF (X4.NE.0.) X6=X2/X4
          X7=0.
          IF (X5.NE.0.) X7=X3/X5
          IF (IHC.EQ.0) X8=VGASP(I)/GASTI
          IF (IHC.EQ.1) X8=VOILP(I)/OILTI
          WRITE (3,3210) I,VTIME(I),X1,X2,X3,X4,X5,X6,X7,X8
  608 CONTINUE
      WRITE (3,2108)
C
C---- WRITE TABLE OF PRESSURES AND PRODUCING GOR
C
      WRITE (3,3300) ZJOBID
      DO 618 I=1,NSTEP
          X1=VTIME(I)/365.
          X2=VPRSR(I)/C4
          X3=VPRSWF(I)/C4
          X4=VPRSWH(I)/C4
          X5=VGOR(I)/1E+3
          X6=VGOR(I)*C7/1E+3
```

```
          WRITE (3,3310) I,VTIME(I),X1,VPRSR(I),X2,VPRSWF(I),X3,
     .         VPRSWH(I),X4,X5,X6
  618 CONTINUE
      WRITE (3,2120)
C
C---- WRITE TABLE OF PRODUCTION RATES
C
      WRITE (3,3400) ZJOBID
      WRITE (3,3405)
      DO 628 I=1,NSTEP
          X1=VTIME(I-1)/365.
          X2=VTIME(I)/365.
          X3=VRTEG(I)/1E+3
          X4=VRTEG(I)/C8/1E+6
          X5=X3*IVNWEL(I)
          X6=X4*IVNWEL(I)
          X7=VRTEO(I)
          X8=VRTEO(I)/C6
          X9=X7*IVNWEL(I)
          X10=X8*IVNWEL(I)
          WRITE (3,3410) I,VTIME(I-1),VTIME(I),X1,X2,IVNWEL(I),
     .         X3,X4,X5,X6,X7,X8,X9,X10
  628 CONTINUE
      WRITE (3,2132)
C
C---- CALCULATE AND WRITE ITERATION REPORT
C
      IF (IPRT.GE.2) THEN
          DO 638 I=1,3
              X1=IC(I+1)-IC(I)+IT(I)
              IF (IT(I).NE.0) AN(I)=X1/IT(I)
  638     CONTINUE
          X1=IC(5)
          AN(5)=IC(6)/X1
C
          WRITE (3,3500)
          DO 648 I=1,8
              WRITE (3,3510) ZC(I),IC(I),IT(I),AN(I)
  648     CONTINUE
          WRITE (3,3520)
      ENDIF
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                                              C
C                          FORMAT STATEMENTS                                   C
C                                                                              C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
```

```
1500 FORMAT (A)
1510 FORMAT (1X,A,I5,5X,A,F16.4)
1520 FORMAT (1X,4(A16,E17.10))
1521 FORMAT (1X,4(A16,I17))
1530 FORMAT ('+',I13)
1550 FORMAT (1X,A10,F6.1)
2000 FORMAT ('1',
    .1X,'*****************************************************************'/
    .1X,'*****************************************************************'/
    .1X,'**                                                             **'/
    .1X,'**                                                             **'/
    .1X,'**          ********       **          *       ********        **'/
    .1X,'**         **       **     **         **     **       **        **'/
    .1X,'**         **              ***      * *     **                 **'/
    .1X,'**         **              ** *    *  *      ********          **'/
    .1X,'**         **    *****     **   * *    *              **        **'/
    .1X,'**         **        *     **    *     *      **       **        **'/
    .1X,'**          *********     **          *       ********        **'/
    .1X,'**                                                             **'/
    .1X,'**                                                             **'/
    .1X,'**** A GENERAL MATERIAL-BALANCE AND INFLOW-PERFORMANCE *****'/
    .1X,'** SIMULATION MODEL FOR OIL AND GAS-CONDENSATE RESERVOIRS **'/
    .1X,'****************** AUTHOR: GUNNAR BORTHNE ********************')
2001 FORMAT ('1')
2027 FORMAT (1X,27('-'))
2039 FORMAT (1X,39('-'))
2051 FORMAT (1X,51('-'))
2063 FORMAT (1X,63('-'))
2075 FORMAT (1X,75('-'))
2076 FORMAT (1X,75('='))
2096 FORMAT (1X,96('-'))
2099 FORMAT (1X,99('-'))
2101 FORMAT (1X,100('-'))
2108 FORMAT (1X,108('-'))
2111 FORMAT (1X,111('-'))
2114 FORMAT (1X,114('-'))
2120 FORMAT (1X,120('-'))
2126 FORMAT (1X,126('-'))
2132 FORMAT (1X,132('-'))
2010 FORMAT (//,1X,A)
2020 FORMAT (///
    .1X,'JOB IDENTIFICATION : ',A60//
    .1X,'IHC    : HYDROCARBON TYPE .....................: ',I5/
    .1X,'           = 0 : GAS CONDENSATE '/
    .1X,'           = 1 : OIL '/
    .1X,'IUNIN  : UNITS IDENTIFIER FOR INPUT DATA .......: ',I5/
    .1X,'           = 0 : METRIC UNITS '/
    .1X,'           = 1 : OIL FIELD UNITS ')
```

```
 2022 FORMAT (
     .1X,'IPRT   : PRINT OPTION ..........................: ',I5/
     .1X,'         = 0 : TABLES OF RESULTS ONLY '/
     .1X,'         = 1 : + ECHO OF INPUT DATA '/
     .1X,'         = 2 : + ITERATION REPORT '/
     .1X,'         = 3 : + RESULTS PRINTED TO THE SCREEN EACH TIMESTEP'/
     .1X,'         = 4 : + A MESSAGE FROM EACH ROUTINE '/
     .1X,'IEXE   : EXECUTION MODE ........................: ',I5/
     .1X,'         = 0 : MATERIAL BALANCE ONLY '/
     .1X,'         = 1 : MATERIAL BALANCE AND IPR '/
     .1X,'         = 2 : MATERIAL BALANCE, IPR AND TUBING ')
 2025 FORMAT (
     .1X,'NWT    : NUMBER OF WELL CONTROL SPECIFICATIONS ..: ',I5/
     .1X,'NPVT   : NUMBER OF PVT DATA INPUT LINES .........: ',I5/
     .1X,'NRP    : NUMBER OF REL. PERM. DATA INPUT LINES ..: ',I5)
C
 2030 FORMAT (
     .1X,'DELTIM : TIMESTEP LENGTH (YEARS) ................: ',G12.5/
     .1X,'XMXTIM : LENGTH OF SIMULATION (YEARS) ...........: ',G12.5/
     .1X,'HCPV   : HYDROCARBON PORE VOLUME (M3) ...........: ',G12.5/
     .1X,'                                  (BBL) ...........: ',G12.5/
     .1X,'PORI   : INITIAL POROSITY (FRACTION) ............: ',G12.5/
     .1X,'SATWI  : INITIAL WATER SATURATION (FRACTION) ....: ',G12.5/
     .1X,'CMPF   : FORMATION COMPRESSIBILITY (1/KPA) ......: ',G12.5/
     .1X,'                                  (1/PSI) ......: ',G12.5)
 2040 FORMAT (//
     .1X,'PRM    : PERMEABILITY (uM2) .....................: ',G12.5/
     .1X,'                     (MD) .... .................: ',G12.5/
     .1X,'THK    : RESERVOIR THICKNESS (M) ................: ',G12.5/
     .1X,'                           (FT) ................: ',G12.5/
     .1X,'RADW   : WELLBORE RADIUS  (M) ...................: ',G12.5/
     .1X,'                        (FT) ...................: ',G12.5/
     .1X,'DSKN   : NON-DARCY FLOW COEFFICIENT (D/M3) ......: ',G12.5/
     .1X,'                                  (D/FT3) ......: ',G12.5/
     .1X,'                                  (D/BBL) ......: ',G12.5/
     .1X,'DPINT  : PRESSURE INCREMENT IN SIMPSON- '/
     .1X,'         INTEGRATION (KPA) ......................: ',F11.0/
     .1X,'                    (PSI) ......................: ',F12.1/
     .1X,'TF     : "TUBING FACTOR" (NO PHYSICAL MEANING,'/
     .1X,'         USED ONLY IN TEMPORARY TUBING ROUTINE) .: ',G12.5)
C
 2050 FORMAT ('1'/
     .1X,'JOB IDENTIFICATION : ',A60//
     .1X,'PRESSURE-DEPENDENT PROPERTIES, OIL'/
     .1X,100('-')/
     .1X,'            PRESSURE              OIL VISCOSITY    ',
     .      '  SOLUTION GAS/OIL RATIO    SPECIFIC    OIL FVF  '/
     .1X,'     ---------------------  ---------------------',
```

```
     .      ' ----------------------     GRAVITY  -----------'/
     .1X,'NO.      KPA         PSIA         PA S          CP     ',
     .      '    SM3/SM3      SCF/BBL     RATIO,OIL  RES/STD VOL'/
     .1X,'---  ----------  ----------  ----------  ----------',
     .      ' ----------  ----------  ----------  -----------')
 2060 FORMAT (1X,I3,F12.0,F12.1,6G12.5)
C
 2090 FORMAT ('1'/
     .1X,'JOB IDENTIFICATION : ',A60//
     .1X,'PRESSURE-DEPENDENT PROPERTIES, GAS'/
     .1X,100('-')/
     .1X,'             PRESSURE              GAS VICOSITY      ',
     .      '  SOLUTION OIL/GAS RATIO    SPECIFIC    GAS FVF  '/
     .1X,'      ----------------------  ----------------------',
     .      ' ----------------------     GRAVITY  -----------'/
     .1X,'NO.      KPA         PSIA         PA S          CP     ',
     .      '    SM3/SM3   BBL/MMSCF    RATIO,GAS  RES/STD VOL'/
     .1X,'---  ----------  ----------  ----------  ----------',
     .      ' ----------  ----------  ----------  -----------')
 2100 FORMAT (1X,I3,F12.0,F12.1,6G12.5)
C
 2130 FORMAT ('1'/
     .1X,'JOB IDENTIFICATION : ',A60//
     .1X,'RELATIVE PERMEABILITIES AS FUNCTIONS OF GAS SATURATION'/
     .1X,39('-')/
     .1X,'          GAS          OIL          GAS    '/
     .1X,'NO.  SATURATION    REL.PERM     REL.PERM '/
     .1X,'---  ----------  ----------  ----------')
 2140 FORMAT (1X,I3,3G12.5)
C
 2150 FORMAT ('1'/
     .1X,'JOB IDENTIFICATION : ',A60//
     .1X,'WELL CONTROL'/
     .1X,126('-')/
     .1X,'                                          NUM-',
     .   '       FIELD MINIMUM           FIELD TARGET      ',
     .   '     MINIMUM WELLHEAD    ',' SKIN FACTOR'/
     .1X,'                    TIME                  BER ',
     .   '    GAS PRODUCTION RATE     GAS PRODUCTION RATE ',
     .   '         PRESSURE        ','              '/
     .1X,'     ------------------------------   OF   ',
     .   ' ----------------------  ----------------------',
     .   ' ----------------------','  ----------'/
     .1X,'NO.          D              YEARS     WELLS ',
     .   '      SM3/D        SCF/D        SM3/D        SCF/D   ',
     .   '       KPA         PSIA    ',' DIM.LESS '/
     .1X,'---  --------------  -------------  -----',
     .   ' ----------  ----------  ----------  ----------',
```

```
     .    '  ----------  ----------','  ----------')
C
 2160 FORMAT ('1'/
     .1X,'JOB IDENTIFICATION : ',A60//
     .1X,'WELL CONTROL'/
     .1X,126('-')/
     .1X,'                                        NUM-',
     .    '       FIELD MINIMUM            FIELD TARGET     ',
     .    '     MINIMUM WELLHEAD    ',' SKIN FACTOR'/
     .1X,'                    TIME                BER ',
     .    '    OIL PRODUCTION RATE     OIL PRODUCTION RATE ',
     .    '         PRESSURE        ','             '/
     .1X,'     ------------------------------   OF  ',
     .    '  ---------------------  ----------------------',
     .    '  ----------------------','  ----------'/
     .1X,'NO.          D              YEARS     WELLS ',
     .    '     SM3/D        STB/D        SM3/D        STB/D  ',
     .    '      KPA         PSIA    ','   DIM.LESS '/
     .1X,'---  ---------------  -------------  -----',
     .    '  ----------  ----------  ----------  ----------',
     .    '  ----------  ----------','  ----------')
 2170 FORMAT (1X,I3,F8.1,' -',F7.1,F7.2,' -',F6.2,I6,1X,4G12.5,F12.0,
     .        F12.1,F12.2)
C
 3000 FORMAT (//
     .1X,'PRSI   : INITIAL PRESSURE IS ASSUMED TO BE EQUAL   '/
     .1X,'         TO MAX. INPUT PVT-DATA PRESSURE (KPA) ..: ',F11.0/
     .1X,'                                        (PSIA) .....: ',F12.1/
     .1X,'GASTI  : GAS VOLUME INITIALLY IN PLACE (SM3) ....: ',G12.5/
     .1X,'                                          (SCF) ....: ',G12.5)
 3010 FORMAT (//
     .1X,'PRSI   : INITIAL PRESSURE IS ASSUMED TO BE EQUAL   '/
     .1X,'         TO MAX. INPUT PVT-DATA PRESSURE (KPA) ..: ',F11.0/
     .1X,'                                        (PSIA) .....: ',F12.1/
     .1X,'OILTI  : OIL VOLUME INITIALLY IN PLACE (SM3) ....: ',G12.5/
     .1X,'                                          (STB) ....: ',G12.5)
C
 3020 FORMAT (//
     .1X,'SATOI  : INITIAL OIL SATURATION (FRACTION) ......: ',G12.5/
     .1X,'SATGI  : INITIAL GAS SATURATION (FRACTION) ......: ',G12.5/
     .1X,'VOLB   : BULK VOLUME OF RESERVOIR (M3) ..........: ',G12.5/
     .1X,'                                  (BBL) ..........: ',G12.5/
     .1X,'AREA   : TOTAL RESERVOIR AREA, FOR UNIFORM '/
     .1X,'               THICKNESS     (1E+3 M2) ..........: ',G12.5/
     .1X,'                                (ACRES) ..........: ',G12.5/
     .1X,'RADE   : RESERVOIR RADIUS, FOR CIRCULAR SHAPE (M): ',G12.5/
     .1X,'                                             (FT): ',G12.5)
C
```

```
 3200 FORMAT ('1'/
     .1X,'JOB IDENTIFICATION : ',A60//
     .1X,'SIMULATION RESULTS'/
     .1X,108('-')/
     .1X,'                                FIELD CUMULATIVE   ',
     .    '     FIELD CUMULATIVE         FIELD CUMULATIVE   ',
     .    ' RECOVERY OF'/
     .1X,'              TIME              GAS PRODUCTION     ',
     .    '      OIL PRODUCTION           GAS/OIL RATIO      ',
     .    ' PREF. PHASE'/
     .1X,'      -------------------  ----------------------',
     .    '  ----------------------  ----------------------',
     .    '  ----------'/
     .1X,'NO.        D        YEARS     1E+6 SM3       MMSCF  ',
     .    '  1E+3 SM3        MSTB    1E+3 SM3/SM3  MMSCF/MSTB',
     .    '   FRACTION '/
     .1X,'---  ----------  -------  ----------  ----------',
     .    '  ----------  ----------  ----------  ----------',
     .    '  ----------')
 3210 FORMAT (1X,I3,F12.1,F9.2,6G12.5,F12.5)
C
 3300 FORMAT ('1'/
     .1X,'JOB IDENTIFICATION : ',A60//
     .1X,'SIMULATION RESULTS'/
     .1X,120('-')/
     .1X,'                                AVERAGE RESERVOIR  ',
     .    '        BOTTOMHOLE                WELLHEAD       ',
     .    '         PRODUCING       '/
     .1X,'             TIME                 PRESSURE       ',
     .    '         PRESSURE                 PRESSURE       ',
     .    '       GAS/OIL RATIO     '/
     .1X,'      -------------------  ----------------------',
     .    '  ----------------------  ----------------------',
     .    '  ----------------------'/
     .1X,'NO.        D        YEARS       KPA         PSIA   ',
     .    '      KPA         PSIA          KPA         PSIA   ',
     .   '1E+3 SM3/SM3  MMSCF/MSTB'/
     .1X,'---  ----------  -------  ----------  ----------',
     .    '  ----------  ----------  ----------  ----------',
     .    '  ----------  ----------')
 3310 FORMAT (1X,I3,F12.1,F9.2,3(F12.0,F12.1),2G12.5)
C
 3400 FORMAT ('1'/
     .1X,'JOB IDENTIFICATION : ',A60//
     .1X,'SIMULATION RESULTS'/
     .1X,132('-')/
     .1X,'                                                ',
     .    '             GAS PRODUCTION RATE              ',
```

```
     .    '                OIL PRODUCTION RATE            '/
     .1X,'                                          NUM-',
     .    ' ---------------------------------------------',
     .    '  ---------------------------------------------'/
     .1X,'                    TIME                  BER ',
     .    '          WELL                     FIELD      ',
     .    '           WELL                     FIELD      '/
     .1X,'      ------------------------------  OF   ',
     .    ' --------------------  --------------------',
     .    '  --------------------  --------------------')
 3405 FORMAT (
     .1X,'NO.          D              YEARS      WELLS',
     .   '1E+3 SM3/D   MMSCF/D   1E+3 SM3/D   MMSCF/D  ',
     .    '    SM3/D      STB/D       SM3/D      STB/D   '/
     .1X,'---  ---------------  -------------  ----',
     .    ' ---------- ----------  ---------- ----------',
     .    '  ---------- ----------  ---------- ----------')
 3410 FORMAT (1X,I3,F8.1,' -',F7.1,F7.2,' -',F6.2,I5,1X,
     .        2G11.5,3(G12.5,G11.5))
C
 3500 FORMAT ('1',//
     .1X,'                  ITERATION REPORT'/
     .1X,'                  ----------------'//
     .1X,'      NAME       IN-CALLS       SOLVE      IT/SOLVE '/
     .1X,'  ----------  ----------  ----------  ----------')
 3510 FORMAT (1X,A11,I10,4X,I8,2X,F10.1)
 3520 FORMAT (//
     .1X,'NAME      = NAME OF SUBROUTINE'/
     .1X,'IN-CALLS  = NUMBER OF CALL TO THIS SUBROUTINE'/
     .1X,'SOLVE     = HOW MANY TIMES DID THE SUBROUTINE HAVE TO START'/
     .1X,'            A SOLUTION PROCEDURE WITH ITERATIONS'/
     .1X,'IT/SOLVE = (1) AVERAGE NUMBER OF ITERATIONS EACH TIME A'/
     .1X,'            SOLUTION PROCEDURE WAS NECESSARY, OR (2) AVERAGE'/
     .1X,'            NUMBER OF INTEGRATION STEPS PER INTEGRATION (IPR)')
C
      END
```

```
C * * * * * A GENERAL MATERIAL BALANCE AND INFLOW PERFORMANCE * * * * *
C * * * * SIMULATION MODEL FOR OIL AND GAS CONDENSATE RESERVOIRS  * * *
C * * * * * * * * * * * * * * * * GMS * * * * * * * * * * * * * * * * *
C * * * * * * * * * * * * * * * * SUBROUTINES * * * * * * * * * * * * * * *
C
C TITLE .......:  ITEST
C AUTHOR ......:  GUNNAR BORTHNE
C DATE ........:  APRIL 1986
C IN-CALLS ....:  GMS
C OUT-CALLS ...:  NONE
C
C FUNCTION ....: DETECT ERROR IN INTEGER INPUT DATA, AND WRITE ERROR
C     MESSAGE
C
      SUBROUTINE ITEST (IX,I1,I2,ZTXT,IERR)
C
C---- INPUT VARIABLES
C
      INTEGER IX,I1,I2
      CHARACTER ZTXT*(*)
C
C---- INPUT AND OUTPUT
C
      INTEGER IERR
C
      IF (IX.LT.I1 .OR. IX.GT.I2) THEN
          IERR=IERR+1
          WRITE (3,*)
          WRITE (3,*) '            *** ERROR ***'
          WRITE (3,*) 'MESSAGE ..............: ',ZTXT
          WRITE (3,*) 'VALUE ................: ',IX
          WRITE (3,*) 'PERMITTED INTERVAL ....: ',I1,I2
      ENDIF
      END
```

```
C * * * * * A GENERAL MATERIAL BALANCE AND INFLOW PERFORMANCE * * * * *
C * * * * SIMULATION MODEL FOR OIL AND GAS CONDENSATE RESERVOIRS  * * *
C * * * * * * * * * * * * * * * * GMS * * * * * * * * * * * * * * * * *
C * * * * * * * * * * * * * * * * SUBROUTINES * * * * * * * * * * * * * * *
C
C TITLE .......:  TEST
C AUTHOR ......:  GUNNAR BORTHNE
C DATE ........:  APRIL 1986
C IN-CALLS ....:  GMS
C OUT-CALLS ...:  NONE
C
C FUNCTION ....: DETECT ERROR IN NUMERICAL INPUT DATA, AND WRITE ERROR
C     MESSAGE
C
      SUBROUTINE TEST (X,X1,X2,ZTXT,IERR)
C
C---- INPUT VARIABLES
C
      DOUBLEPRECISION X,X1,X2
      CHARACTER ZTXT*(*)
C
C---- INPUT AND OUTPUT
C
      INTEGER IERR

      IF (X.LT.X1 .OR. X.GT.X2) THEN
          IERR=IERR+1
          WRITE (3,*)
          WRITE (3,*) '            *** ERROR ***'
          WRITE (3,*) 'MESSAGE ..............: ',ZTXT
          WRITE (3,*) 'VALUE ................: ',X
          WRITE (3,*) 'PERMITTED INTERVAL ....: ',X1,X2
      ENDIF
      END
```

```
C * * * * * A GENERAL MATERIAL BALANCE AND INFLOW PERFORMANCE * * * * *
C * * * * SIMULATION MODEL FOR OIL AND GAS CONDENSATE RESERVOIRS  * * *
C * * * * * * * * * * * * * * * * GMS * * * * * * * * * * * * * * * * *
C * * * * * * * * * * * * * * * * SUBROUTINES * * * * * * * * * * * * * * *
C
C TITLE .......:  TESTGE
C AUTHOR ......:  GUNNAR BORTHNE
C DATE ........:  APRIL 1986
C IN-CALLS ....:  GMS
C OUT-CALLS ...:  NONE
C
C FUNCTION ....: DETECT ERROR IN NUMERICAL INPUT DATA, AND WRITE ERROR
C     MESSAGE
C
      SUBROUTINE TESTGE (X1,X2,ZTXT,IERR)
C
C---- INPUT VARIABLES
C
      DOUBLEPRECISION X1, X2
      CHARACTER ZTXT*(*)
C
C---- INPUT AND OUTPUT
C
      INTEGER IERR

      IF (X1.GE.X2) THEN
          IERR=IERR+1
          WRITE (3,*)
          WRITE (3,*) '            *** ERROR ***'
          WRITE (3,*) 'VARIABLE ..............: ',ZTXT
          WRITE (3,*) 'VALUE .................: ',X1,X2
          WRITE (3,*) 'NOT INCREASING'
      ENDIF
      END
```

```
C tab f; () 7,72;
C * * * * * A GENERAL MATERIAL BALANCE AND INFLOW PERFORMANCE * * * * *
C * * * * SIMULATION MODEL FOR OIL AND GAS CONDENSATE RESERVOIRS  * * *
C * * * * * * * * * * * * * * * * GMS * * * * * * * * * * * * * * * * *
C * * * * * * * * * * * * * * * * SUBROUTINES * * * * * * * * * * * * * * *
C
C TITLE .......:  RATE
C AUTHOR ......:  GUNNAR BORTHNE
C DATE ........:  APRIL 1986
C IN-CALLS ....:  GMS
C OUT-CALLS ...:  WHPRS, ISGN
C
C FUNCTION ....: Determine a well production rate (RTE) which matches
C     the rate and  wellhead pressure requirements.
C 1.  The highest allowed rate (RTEHI) is tried first. If the calculated
C     wellhead pressure (PWHMIN) is greater than or equal to  the  spec-
C     ified  minimum wellhead pressure (PWHMIN), the task is finished. A
C     special situation may occur. If QPVT is true, the  rate  has  been
C     reduced  by  subroutine  RESPRS or IPR. It means that lack of PVT-
C     data is limiting the rate.  These  results  should  not  be  used.
C     Control is passed to the main program and execution is terminated.
C 2.  If  PRSWH  < PWHMIN the rate is lowered until PRSWH = PWHMIN. This
C     is done first by a stepwise search to establish an interval with a
C     solution.  If  an  interval  is found, the rate is calculated by a
C     modified chord method. If an interval is  not  found,  control  is
C     passed to the main program and execution is terminated.
C
C Summary:
C 1.  PRSWH >= PWHMIN at the first calculation (PW1>=0)
C       a) QPVT is false.  No need for further calculations.
C          The pressures and rates are OK. Return and continue.
C       b) QPVT is true.   Lack of PVT-data. Rate can not be
C          increased. Return and terminate execution.
C 2.  PRSWH < PWHMIN at the first calc. (PW1<0)
C     Search for a subinterval (R1,R2) on (RTELO,RTEHI)
C     with a solution to  PRSWH(RTE)=PWHMIN
C       a) An interval is found (PW1<0,PW2>=0)
C          Solve by modified chord method.  Return and continue.
C       b) An interval is not found  (R1=R2=RTELO)
C          Rate can not be reduced below RTELO. Return and terminate.
C
C
      SUBROUTINE  RATE  (PRSHI,  PRSLO,  PWHMIN,  RTEHI, RTELO, EPSPRS,
     .    EPSRTE, K, IPRT, IEXE, IHC, PRS, PRSWF, PRSWH, RTE, DGASP,
     .    DOILP, DGORP, QSTOP)
C
C---- INPUT VARIABLES
C
```

```
      DOUBLEPRECISION  PRSHI, PRSLO, PWHMIN, RTEHI, RTELO, EPSPRS,
     .    EPSRTE
      INTEGER K, IPRT, IEXE, IHC
C
C---- OUTPUT VARIABLES
C
      DOUBLEPRECISION  PRS, PRSWF, PRSWH, RTE, DGASP, DOILP, DGORP
      LOGICAL QSTOP
C
C---- LOCAL VARIABLES
C
      DOUBLEPRECISION DRTE, DR, R1, R2, R, PW1, PW2, PWD, PW
      INTEGER I, J, LOOP, MAXITR, ISGN
      LOGICAL QPVT
C
C---- COMMON BLOCK
C
      COMMON /ICOUNT/ IC, IT
      INTEGER         IC(8), IT(8)
C
C--- START EXECUTION
C
      IC(1)=IC(1)+1
      IF (IPRT.GE.4) WRITE (3,*) 'START RATE'
      QSTOP=.FALSE.
      LOOP=1
      MAXITR=30
      DRTE=(RTEHI-RTELO)/LOOP
      DRTE=1.001*DRTE
      R1=RTEHI
C
C---- INITIAL CALCULATION OF WELLHEAD PRESSURE, BOTTOMHOLE PRESSURE
C     RESERVOIR PRESSURE AND RATE
C
      CALL WHPRS (PRSHI, PRSLO, R1, EPSPRS, EPSRTE, K, IPRT, IEXE, IHC,
     .    PRS, PRSWF, PRSWH, RTE, DGASP, DOILP, DGORP, QPVT, QSTOP)
      IF (QSTOP) RETURN
      R1=RTE
      PW1=PRSWH-PWHMIN
      IF (PW1.GE.0. .AND. .NOT.QPVT) RETURN
      IF (PW1.GE.0. .AND.      QPVT) GOTO 991
      IF (RTE.LT.RTELO) GOTO 992
C
C---- START LOOP, SEQUENTIAL SEARCH
C
      J=0
      IT(1)=IT(1)+1
  100 CONTINUE
```

```
          J=J+1
          IF (J.GT.LOOP) GOTO 993
          R=MAX (R1-DRTE,RTELO)
C
C---- CALCULATE WELLHEAD PRESSURE, BOTTOMHOLE PRESSURE RESERVOIR
C     PRESSURE AND RATE
C
          CALL WHPRS (PRSHI, PRSLO, R, EPSPRS, EPSRTE, K, IPRT, IEXE,
     .         IHC, PRS, PRSWF, PRSWH, RTE, DGASP, DOILP, DGORP, QPVT,
     .         QSTOP)
          IF (QSTOP) RETURN
          IF (RTE.LT.RTELO) GOTO 992
          R=RTE
          PW=PRSWH-PWHMIN
C
C---- TEST IF A SUBINTERVAL WITH A SOLUTION IS FOUND
C
          IF (ISGN(PW1)*ISGN(PW).LE.0) GOTO 199
          R1=R
          PW1=PW
          IF (R1.LE.RTELO) GOTO 994
      GOTO 100
C
  199 CONTINUE
C
C---- START LOOP, MODIFIED CHORD METHOD (PRSWH CONTROLS THE RATE)
C
      R2=R
      PW2=PW
      I=0
  200 CONTINUE
          I=I+1
          IF (I.GE.MAXITR) GOTO 995
          IF (ABS(PW).LT.EPSPRS .AND. ABS(R1-R2).LT.EPSRTE) GOTO 299
          PWD=(PW2-PW1)/(R2-R1)
          DR=PW2/PWD
          R=R2-DR
C
C---- EMERGENCY EXIT
C
          IF ((R1-R)*(R-R2).LE.0) THEN
              WRITE (3,*) 'RATE.    TIME STEP:',K
              WRITE (3,3000) ABS(R1-R2),ABS(DR),PW2
              R=R2
              GOTO 299
          ENDIF
C
C---- CALCULATE WELLHEAD PRESSURE, BOTTOMHOLE PRESSURE RESERVOIR
```

```
C     PRESSURE AND RATE
C
          CALL WHPRS (PRSHI, PRSLO, R, EPSPRS, EPSRTE, K, IPRT, IEXE,
     .         IHC, PRS, PRSWF, PRSWH, RTE, DGASP, DOILP, DGORP, QPVT,
     .         QSTOP)
          IF (QSTOP) RETURN
          IF (R.NE.RTE) GOTO 996
          PW=PRSWH-PWHMIN
          IF (ISGN(PW)*ISGN(PW2).GE.0) THEN
              PW1=PW1/2.
          ELSE
              R1=R2
              PW1=PW2
          ENDIF
          R2=R
          PW2=PW
      GOTO 200
C
  299 CONTINUE
      RTE=R
      PRSWH=PW+PWHMIN
      RETURN
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                                           C
C             CHECK STOP CONDITIONS,  WRITE COMMENTS                        C
C                                                                           C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
  991 CONTINUE
      IF (PW1.GE.0. .AND. QPVT) THEN
          WRITE (3,*) 'RATE.  TIME STEP:',K
          WRITE (3,*) 'The rate has been reduced due to'
          WRITE (3,*) 'lack of PVT-data below PVTMIN'
          WRITE (3,*) 'The calculated wellhead pressure is higher'
          WRITE (3,*) 'than the specified minimum.'
          WRITE (3,*) 'This means that the rate (RTE) is controlled'
          WRITE (3,*) 'by the minimum PVT-data pressure and not by'
          WRITE (3,*) 'the minimum wellhead pressure (PWHMIN).'
          WRITE (3,*) 'Do not use the results from this time step.'
          WRITE (3,*) 'Return to the main program and terminate.'
          WRITE (3,*)
          QSTOP=.TRUE.
      ENDIF
  992 CONTINUE
      IF (RTE.LT.RTELO) THEN
          WRITE (3,*) 'RATE.  TIME STEP:',K
          WRITE (3,*) 'The rate (RTE) is now smaller than'
```

```
            WRITE (3,*) 'the minimum allowed rate (RTELO)'
            WRITE (3,*)
            QSTOP=.TRUE.
        ENDIF
        IF (QSTOP) RETURN
  993 CONTINUE
        IF (J.GT.LOOP) THEN
            WRITE (3,*) 'RATE.  TIME STEP:',K
            WRITE (3,*) 'Sequential search. J=',J
            WRITE (3,*) 'Too many iterations'
            WRITE (3,*)
            QSTOP=.TRUE.
            RETURN
        ENDIF
  994 CONTINUE
        IF (R1.EQ.RTELO) THEN
            WRITE (3,*) 'RATE.  TIME STEP:',K
            WRITE (3,*) 'The target rate results in a too low wellhead'
            WRITE (3,*) 'pressure.  The rate has been reduced stepwise'
            WRITE (3,*) 'down to the specified minimum rate, but the'
            WRITE (3,*) 'wellhead pressure is still too low.'
            WRITE (3,*) 'Return to the main program and terminate.'
            WRITE (3,*)
            QSTOP=.TRUE.
            RETURN
        ENDIF
  995 CONTINUE
        IF (I.GE.MAXITR) THEN
            WRITE (3,*) 'RATE.  TIME STEP:',K
            WRITE (3,2010)'Convergence not reached after',I,' iterations'
            WRITE (3,*)
            QSTOP=.TRUE.
            RETURN
        ENDIF
  996 CONTINUE
        IF (R.NE.RTE) THEN
            WRITE (3,*) 'RATE. ERROR, R .NE. RTE'
            WRITE (3,*)
            QSTOP=.TRUE.
            RETURN
        ENDIF
C
C---- FORMAT STATEMENTS
C
 2000 FORMAT (1X,/15('-')/1X,A,I4,A,I4)
 2010 FORMAT (1X,A,I4,A,I4)
 3000 FORMAT (
     .1X,'"EMERGENCY EXIT"',/
```

```
.1X,'LENGTH OF CURRENT RATE INTERVAL (SM3/D) ..........:',G15.8, /
.1X,'ESTIMATED ERROR (LENGTH OF NEXT RATE INTERVAL',             /
.1X,'WHICH IS TOO SMALL FOR CONTINUED ITERATION) (SM3/D)',G15.8,//
.1X,'WELLHEAD PRESSURE FUNCTION (SHOULD BE ZERO) (KPA) :',G15.8,/
./)
 END
```

```
C TAB F; () 7,72;
C * * * * * A GENERAL MATERIAL BALANCE AND INFLOW PERFORMANCE * * * * *
C * * * * SIMULATION MODEL FOR OIL AND GAS CONDENSATE RESERVOIRS  * * *
C * * * * * * * * * * * * * * * * GMS * * * * * * * * * * * * * * * * *
C * * * * * * * * * * * * * * * SUBROUTINES * * * * * * * * * * * * * * *
C
C TITLE .......:  WHPRS
C AUTHOR ......:  GUNNAR BORTHNE
C DATE ........:  APRIL 1986
C IN-CALLS ....:  RATE
C OUT-CALLS ...:  RESPRS, IPR, TUBING, ISGN
C

C FUNCTION ....: Calculate the wellhead pressure as a function of rate
C     and other variables. To do so, the average reservoir pressure,
C     bottomhole flowing pressure and pressure loss in tubing must be
C     calculated. While calulating the average reservoir pressure and
C     the well flowing pressure, the rate might get reduced due to lack
C     of PVT data below PVTMIN. QPVT is then set true. This should not
C     stop the execution since the rate might get further reduced
C     because of the specified minimum wellhead pressure. RTEHI1 is the
C     rate input variable and is generally different from RTEHI
C
      SUBROUTINE WHPRS (PRSHI, PRSLO, RTEHI1, EPSPRS, EPSRTE, K, IPRT,
     .    IEXE, IHC, PRS, PRSWF, PRSWH, RTE, DGASP, DOILP, DGORP, QPVT,
     .    QSTOP)

C---- INPUT VARIABLES

      DOUBLEPRECISION  PRSHI, PRSLO, RTEHI1, EPSPRS, EPSRTE
      INTEGER  K, IPRT, IEXE, IHC

C---- OUTPUT VARIABLES

      DOUBLEPRECISION  PRS, PRSWF, PRSWH, RTE, DGASP, DOILP, DGORP
      LOGICAL QPVT, QSTOP
C
C---- LOCAL VARIABLES
C
      DOUBLEPRECISION R1, R2, R, RTEA, RTEB, RTIN, FN1, FN2, FN,
     .    FND, DRTE, DR
      INTEGER LOOP, I, J, ISGN, MAXITR
C
C---- COMMON BLOCK
C
      COMMON /ICOUNT/ IC, IT
      INTEGER         IC(8), IT(8)
C
```

```
C---- START EXECUTION
C
      IC(2)=IC(2)+1
      LOOP=5
      MAXITR=40
      IF (IPRT.GE.4) WRITE (3,*) '     START WHPRS'
      QPVT=.FALSE.
      QSTOP=.FALSE.
      R=RTEHI1
C
C---- CALCULATE RESERVOIR PRESSURE AND RATE
C
      CALL RESPRS (PRSHI, PRSLO, R, EPSPRS, EPSRTE, K, IPRT, IHC, PRS,
     .    RTEA, DGASP, DOILP, QSTOP)
      DGORP=1E+20
      IF (DOILP.NE.0.) DGORP=DGASP/DOILP
      IF (QSTOP) RETURN
      IF (RTEA.LT.0.001) THEN
          PRSWF=PRS
          PRSWH=PRS
          GOTO 999
      ENDIF
C
C---- CALCULATE BOTTOMHOLE PRESSURE AND RATE
C
      RTIN=RTEA

      IF (IEXE.GE.1) THEN
          CALL IPR(PRS, PRSLO, RTIN, DGORP, EPSPRS, K, IPRT, IHC, PRSWF,
     .        RTEB)
      ELSE
          PRSWF=PRS
          RTEB=RTEA
      ENDIF
      IF (QSTOP) RETURN
      FN=RTEA-RTEB
C
      IF (FN.EQ.0.) THEN
          GOTO 299
      ELSEIF (FN.GT.0.) THEN
          QPVT=.TRUE.
      ELSE
          PRINT *,'ERROR'
          STOP
      ENDIF
C
C---- START LOOP, SEQUENTIAL SEARCH
C
```

```
      IT(2)=IT(2)+1
      R1=R
      FN1=FN
      DRTE=R/LOOP*1.001
      J=0
  100 CONTINUE
          J=J+1
          IF (J.GT.LOOP) GOTO 999
          R=MAX (R1-DRTE,0.)
C
C---- CALCULATE RESERVOIR PRESSURE AND RATE
C
          CALL RESPRS (PRSHI, PRSLO, R, EPSPRS, EPSRTE, K, IPRT, IHC,
     .         PRS, RTEA, DGASP, DOILP, QSTOP)
          DGORP=1E+20
          IF (DOILP.NE.0.) DGORP=DGASP/DOILP
          IF (QSTOP) RETURN
C
C---- CALCULATE BOTTOMHOLE PRESSURE AND RATE
C
          RTIN=RTEHI1
          CALL IPR (PRS, PRSLO, RTIN, DGORP, EPSPRS, K, IPRT, IHC,
     .         PRSWF, RTEB)
          IF (QSTOP) RETURN
          FN=RTEA-RTEB
C
C---- TEST IF A SUBINTERVAL WITH SOLUTION IS FOUND
C
          IF (ISGN(FN1)*ISGN(FN).LE.0) GOTO 199
          R1=R
          FN1=FN
          IF (R1.LE.0.) GOTO 994
      GOTO 100
C
  199 CONTINUE
C
C---- START LOOP, MODIFIED CHORD METHOD
C
      FN2=FN
      R2=R
      I=0
  200 CONTINUE
          I=I+1
          IF (I.GE.MAXITR) GOTO 995
          IF (ABS(R1-R2).LT.EPSRTE) GOTO 299
          FND=(FN2-FN1)/(R2-R1)
          DR=FN2/FND
          R=R2-DR
```

```
C
C---- EMERGENCY EXIT
C
          IF ((R1-R)*(R-R2).LE.0) THEN
              WRITE (3,*) 'WHPRS.   TIME STEP:',K
              WRITE (3,3000) ABS(R1-R2),ABS(DR)
              R=R2
              GOTO 299
          ENDIF
C
C---- CALCULATE RESERVOIR PRESSURE AND RATE
C
          CALL RESPRS (PRSHI, PRSLO, R, EPSPRS, EPSRTE, K, IPRT, IHC,
     .         PRS, RTEA, DGASP, DOILP, QSTOP)
          DGORP=1E+20
          IF (DOILP.NE.0.) DGORP=DGASP/DOILP
          IF (QSTOP) RETURN
C
C---- CALCULATE BOTTOMHOLE PRESSURE AND RATE
C
          RTIN=RTEHI1
          CALL IPR (PRS, PRSLO, RTIN, DGORP, EPSPRS, K, IPRT, IHC,
     .         PRSWF, RTEB)
          IF (QSTOP) RETURN
          FN=RTEA-RTEB
          IF (ISGN(FN)*ISGN(FN2).GE.0) THEN
              FN1=FN1/2.
          ELSE
              R1=R2
              FN1=FN2
          ENDIF
          R2=R
          FN2=FN
      GOTO 200
C
  299 CONTINUE
      RTE=R

C
C---- CALCULATE WELLHEAD PRESSURE
C
      IF (IEXE.GE.2 .AND. RTE.NE.0.) THEN
          CALL TUBING (PRSWF, R, K, IPRT, IHC, PRSWH)
      ELSE
          PRSWH=PRSWF
      ENDIF
      IF (QSTOP) RETURN
C
```

```
C---- RETURN TO THE CALLING SUBROUTINE
C
      RETURN
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                                              C
C                      CHECK ERROR CONDITIONS                                  C
C                                                                              C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
  994 CONTINUE
      IF (R1.LE.0.) THEN
          WRITE (3,*) 'WHPRS. TIME STEP:',K
          WRITE (3,*) 'Interval with solution not found'
          WRITE (3,*)
          QSTOP=.TRUE.
          RETURN
      ENDIF
  995 CONTINUE
      IF (I.GE.MAXITR) THEN
          WRITE (3,*) 'WHPRS. TIME STEP:',K
          WRITE (3,2010)'Convergence not reached after',I,' iterations'
          WRITE (3,*)
          QSTOP=.TRUE.
          RETURN
      ENDIF
  999 CONTINUE
      IF (J.GT.LOOP) THEN
          WRITE (3,*) 'WHPRS. TIME STEP:',K
          WRITE (3,*) 'Sequential search. J=',J
          WRITE (3,*) 'Too many iterations'
          WRITE (3,*)
          QSTOP=.TRUE.
          RETURN
      ENDIF
      IF (ABS(RTEA).LE.0.001 .OR. ABS(RTEB).LE.0.001) THEN
          WRITE (3,*) 'WHPRS. TIME STEP:',K
          WRITE (3,*) 'The rate is zero (or nearly zero)'
          WRITE (3,*) 'Terminate execution'
          WRITE (3,*)
          QSTOP=.TRUE.
          RETURN
      ENDIF
C
C---- FORMAT STATEMENTS
C
 2000 FORMAT (1X,/1X,A,I4,A,I4)
 2010 FORMAT (1X,A,I4,A,I4)
```

```
3000 FORMAT (
     .1X,'"EMERGENCY EXIT"',/
     .1X,'LENGTH OF CURRENT RATE INTERVAL (SM3/D) ..........:',G15.8, /
     .1X,'ESTIMATED ERROR (LENGTH OF NEXT RATE INTERVAL',            /
     .1X,'WHICH IS TOO SMALL FOR CONTINUED ITERATION) (SM3/D)',G15.8,/
     ./)
      END
```

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C tab f; () 7,72;
C * * * * * A GENERAL MATERIAL BALANCE AND INFLOW PERFORMANCE * * * * *
C * * * * SIMULATION MODEL FOR OIL AND GAS CONDENSATE RESERVOIRS  * * *
C * * * * * * * * * * * * * * * * GMS * * * * * * * * * * * * * * * * *
C * * * * * * * * * * * * * * * SUBROUTINES * * * * * * * * * * * * * * *
C
C TITLE .......:  RESPRS
C AUTHOR ......:  GUNNAR BORTHNE
C DATE ........:  APRIL 1986
C IN-CALLS ....:  WHPRS
C OUT-CALLS ...:  MATBAL, ISGN
C
C FUNCTION ....:  Calculate the average reservoir pressure at the end of
C     the current timestep.  This is done by making the material-balance
C     error, which is calculated by the subroutine MATBAL, approach
C     zero.  Normally, pressure is the free variable.  If the maximum
C     pressure is equal to the minimum PVT data pressure, the rate has
C     to be reduced and is used the free variable for calls to MATBAL.
C
C NOTE: The last call of subroutine MATBAL before the next timestep has
C     to be done with arguments equal to X and C  to obtain correct
C     calculation of AO1,AG1,RO1,RG1
C
      SUBROUTINE RESPRS (PRSHI, PRSLO, RTEX, EPSPRS, EPSRTE, K, IPRT,
     .    IHC, PRS, RTEY, DGASP, DOILP, QSTOP)
C
C---- INPUT VARIABLES
C
      DOUBLEPRECISION  PRSHI, PRSLO, RTEX, EPSPRS, EPSRTE
      INTEGER  K, IPRT, IHC
C
C---- OUTPUT VARIABLES
C
      DOUBLEPRECISION  PRS, RTEY, DGASP, DOILP
      LOGICAL  QSTOP
C
C---- LOCAL VARIABLES
C
      DOUBLEPRECISION DPRS, Y1, Y2, Y, YD, C, X1, X2, X, DX
      CHARACTER ZMODE*10
      INTEGER J, LOOP, I, MAXITR, ISGN
      PARAMETER (MAXITR=30)
C
C---- COMMON BLOCK
C
      COMMON /ICOUNT/ IC, IT
      INTEGER         IC(8), IT(8)
C
```

```
C---- START EXECUTION
C
      IC(3)=IC(3)+1
      IF (PRSHI.EQ.PRSLO) THEN
          ZMODE='rate'
          GOTO 199
      ENDIF
      IF (IPRT.GE.4) WRITE (3,*) '         START RESPRS'
      QSTOP=.FALSE.
      LOOP=4
      X1=PRSHI
      DPRS=(PRSHI-PRSLO)/LOOP*1.001
      CALL MATBAL(X1, RTEX, IPRT, IHC, DGASP, DOILP, Y1)
C
C---- START LOOP, SEQUENTIAL SEARCH
C
      IT(3)=IT(3)+1
      J=0
  100 CONTINUE
          J=J+1
          IF (J.GT.LOOP) GOTO 991
          X2=MAX(X1-DPRS, PRSLO)
          CALL MATBAL(X2, RTEX, IPRT, IHC, DGASP, DOILP, Y2)
C
C---- TEST IF A SUBINTERVAL WITH A SOLUTION IS FOUND
C
          IF (ISGN(Y1)*ISGN(Y2).LE.0) THEN
              ZMODE='pressure'
              GOTO 199
          ENDIF
          X1=X2
          Y1=Y2
          IF (X1.LT.PRSLO) GOTO 992
C
C---- TEST IF THE RATE HAS TO BE USED AS THE FREE VARIABLE
C
          IF (X1.EQ.PRSLO) THEN
              ZMODE='rate'
              GOTO 199
          ENDIF
      GOTO 100
C
C---- APPLY THE MODIFIED CHORD METHOD TO FIND THE SOLUTION
C
  199 CONTINUE
      IF (ZMODE.EQ.'pressure') THEN
          C=RTEX
          X=X2
```

```
          IF (Y1.EQ.0.) THEN
              X=X1
              GOTO 299
          ENDIF
          IF (Y2.EQ.0.) THEN
              X=X2
              GOTO 299
          ENDIF
      ELSEIF (ZMODE.EQ.'rate') THEN
          C=PRSLO
          X1=RTEX
          X2=0.
          X=0.
          CALL MATBAL(C, X1, IPRT, IHC, DGASP, DOILP, Y1)
          CALL MATBAL(C, X2, IPRT, IHC, DGASP, DOILP, Y2)
          IF (Y1.EQ.0.) THEN
              X=X1
              GOTO 299
          ENDIF
          IF (Y2.EQ.0.) THEN
              X=X2
              GOTO 299
          ENDIF
      ELSE
          WRITE (3,*) 'RESPRS. ERROR'
          WRITE (3,*)
          QSTOP=.TRUE.
          RETURN
      ENDIF
C
C---- START LOOP, CHORD METHOD
C
      I=0
  200 CONTINUE
          I=I+1
          IF (I.GE.MAXITR) GOTO 994
          IF (X2-X1.EQ.0. .OR. Y2-Y1.EQ.0.) GOTO 993
          IF (ABS(X1-X2).LT.EPSPRS.AND.ZMODE.EQ.'pressure') GOTO 299
          IF (ABS(X1-X2).LT.EPSRTE.AND.ZMODE.EQ.'rate')     GOTO 299
          YD=(Y2-Y1)/(X2-X1)
          DX=Y2/YD
          X=X2-DX
C
C---- EMERGENCY EXIT
C
          IF ((X1-X)*(X-X2).LE.0) THEN
              WRITE (3,*) 'RESPRS.  TIME STEP:',K
              IF (ZMODE.EQ.'pressure') THEN
```

```
                WRITE (3,3000) ABS(X1-X2),ABS(DX),Y2
            ELSEIF (ZMODE.EQ.'rate') THEN
                WRITE (3,3010) ABS(X1-X2),ABS(DX),Y2
            ENDIF
            X=X2
            GOTO 299
        ENDIF
C
C---- CALCULATE MATERIAL-BALANCE ERROR
C
        IF (ZMODE.EQ.'pressure') THEN
            CALL MATBAL(X, C, IPRT, IHC, DGASP, DOILP, Y)
        ELSEIF (ZMODE.EQ.'rate') THEN
            CALL MATBAL(C, X, IPRT, IHC, DGASP, DOILP, Y)
        ENDIF
        IF (ISGN(Y)*ISGN(Y2).GE.0) THEN
            Y1=Y1/2.
        ELSE
            X1=X2
            Y1=Y2
        ENDIF
        X2=X
        Y2=Y
    GOTO 200
C
C---- PREPARE TO EXIT
C
  299 CONTINUE
      PRS=X
      RTEY=C
      IF (ZMODE.EQ.'rate') THEN
          PRS=C
          RTEY=X
      ENDIF
      IF (RTEY.LT.RTEX) THEN
          WRITE (3,*) 'RESPRS.  TIME STEP:',K
          WRITE (3,*) 'THE RATE IS REDUCED DUE TO LACK OF PVT DATA'
          WRITE (3,*) 'INPUT  RATE: ',RTEX
          WRITE (3,*) 'OUTPUT RATE: ',RTEY
          WRITE (3,*)
      ENDIF
      RETURN
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                                             C
C                     CHECK ERROR CONDITIONS                                  C
C                                                                             C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
```

```
C
  991 CONTINUE
      IF (J.GT.LOOP) THEN
          WRITE (3,*) 'RESPRS.  TIME STEP:',K
          WRITE (3,*) 'SEARCH ROUTINE, J=',J
          WRITE (3,*)
          QSTOP=.TRUE.
          RETURN
      ENDIF
  992 CONTINUE
      IF (X1.LT.PRSLO) THEN
          WRITE (3,*) 'RESPRS.  TIME STEP:',K
          WRITE (3,*) 'ERROR,  X1 < PRSLO'
          WRITE (3,*)
          QSTOP=.TRUE.
          RETURN
      ENDIF
  993 CONTINUE
      IF (X2-X1.EQ.0.) THEN
          WRITE (3,*) 'RESPRS.  TIME STEP:',K
          WRITE (3,*) 'X2-X1 .EQ. 0.'
          WRITE (3,*)
          QSTOP=.TRUE.
          RETURN
      ENDIF
      IF (Y2-Y1.EQ.0.) THEN
          WRITE (3,*) 'RESPRS.  TIME STEP:',K
          WRITE (3,*) 'Y2-Y1 .EQ. 0.'
          WRITE (3,*)
          QSTOP=.TRUE.
          RETURN
      ENDIF
  994 CONTINUE
      IF (I .GE. MAXITR) THEN
          WRITE (3,*) 'RESPRS.  TIME STEP:',K
          WRITE (3,2000) 'CONVERGENCE NOT REACHED AFTER',I,' ITERATIONS'
          WRITE (3,*)
          QSTOP=.TRUE.
          RETURN
      ENDIF
C
C---- FORMAT STATEMENTS
C
 2000 FORMAT (1X,A,I4,A,I4)
 3000 FORMAT (
     .1X,'"EMERGENCY EXIT"',/
     .1X,'LENGTH OF CURRENT PRESSURE INTERVAL (KPA) ........:',G15.8, /
     .1X,'ESTIMATED ERROR (LENGTH OF NEXT PRESSURE INTERVAL',/
```

```
     .1X,'WHICH IS TOO SMALL FOR CONTINUED ITERATION) (KPA) :',G15.8,//
     .1X,'MATERIAL BALANCE ERROR (DIMENSIONLESS) ..........:',G15.8,//
     ./)
3010 FORMAT (
     .1X,'"EMERGENCY EXIT"',/
     .1X,'LENGTH OF CURRENT RATE INTERVAL (SM3/D) ..........:',G15.8, /
     .1X,'ESTIMATED ERROR (LENGTH OF NEXT RATE INTERVAL',/
     .1X,'WHICH IS TOO SMALL FOR CONTINUED ITERATION) (SM3/D)',G15.8,//
     .1X,'MATERIAL BALANCE ERROR (DIMENSIONLESS) ..........:',G15.8,//
     ./)
      END
```

```
C tab f; () 7,72;
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C * * * * SIMULATION MODEL FOR OIL AND GAS CONDENSATE RESERVOIRS  * * *
C * * * * * * * * * * * * * * * * GMS * * * * * * * * * * * * * * * * *
C * * * * * * * * * * * * * * * * SUBROUTINES * * * * * * * * * * * * * *
C
C TITLE .......:  TUBING
C AUTHOR ......:  GUNNAR BORTHNE
C DATE ........:  APRIL 1986
C IN-CALLS ....:  WHPRS
C OUT-CALLS ...:  NONE
C
C FUNCTION ....: Calculate wellhead pressure.  Artificial function
C     implemented as a preparation for future developments.
C
      SUBROUTINE TUBING (PRSWF, RTE, K, IPRT, IHC, PRSWH)
C
C---- INPUT VARIABLES
C
      DOUBLEPRECISION    PRSWF, RTE
      INTEGER  K, IPRT, IHC
C
C---- OUTPUT VARIABLES
C
      DOUBLEPRECISION    PRSWH
C
C---- COMMON BLOCK
C
      COMMON /TUB/    TF
      DOUBLEPRECISION TF
C
C---- START EXECUTION
C
      IF (IPRT.GE.4) PRINT *,'         START TUBING'
      IF (IHC.EQ.0) THEN
C         (Gas:)
          PRSWH=PRSWF-TF*RTE
      ELSEIF (IHC.EQ.1) THEN
C         (Oil:)
          PRSWH=PRSWF-TF*RTE
      ELSE
          PRINT *,'TUBING, TIMESTEP',K
          PRINT *,'ERROR, IHC'
          STOP
      ENDIF
      END
```

```
C TAB F; () 7,72;
C * * * * * A GENERAL MATERIAL BALANCE AND INFLOW PERFORMANCE * * * * *
C * * * * SIMULATION MODEL FOR OIL AND GAS CONDENSATE RESERVOIRS  * * *
C * * * * * * * * * * * * * * * * GMS * * * * * * * * * * * * * * * * *
C * * * * * * * * * * * * * * * * SUBROUTINES * * * * * * * * * * * * * *
C
C TITLE .......:  MATBAL
C AUTHOR ......:  GUNNAR BORTHNE
C DATE ........:  APRIL 1986
C IN-CALLS ....:  RESPRS
C OUT-CALLS ...:  INTPL
C
C FUNCTION ....: Calculate material-balance error and related quantities
C     as functions of average reservoir pressure, production rate,
C     timestep length and other variables.
C
      SUBROUTINE MATBAL(PRS, RTE, IPRT, IHC, DGASP, DOILP, XMBAL)
C
C---- INPUT VARIABLES
C
      DOUBLEPRECISION  PRS, RTE
      INTEGER IPRT, IHC
C
C---- OUTPUT VARIABLES
C
      DOUBLEPRECISION  DGASP, DOILP, XMBAL
C
C---- LOCAL VARIABLES
C
      INTEGER J
      DOUBLEPRECISION SATO, SATG, S, XMOBR, X1, X2, X3, ROAV, DOILPQ,
     .    DGASPQ, FRAC, Y
C
C---- COMMON BLOCKS  (MATBAL MODIFIES MBAL2, MBAL3)
C
      COMMON /PROP/ TDENRG, TDENRO, TFVFG, TFVFGX, TFVFO, TGORS,
     .    TOGRS, TPRMRG, TPRMRO, PRMLGO, TPRS, TSATG, TVISG, TVISO,
     .    NPVT, NRP
      DOUBLEPRECISION TDENRG(100), TDENRO(100), TFVFG(100), TFVFGX(100),
     .    TFVFO(100), TGORS(100), TOGRS(100), TPRMRG(100), TPRMRO(100),
     .    PRMLGO(100), TPRS(100), TSATG(100), TVISG(100), TVISO(100)
      INTEGER NPVT, NRP
      COMMON /MBAL1/  AG1, AO1, CMPF, DTIM, PORI, PRSI, RG1, RO1, SATWI,
     .    VOLBW
      DOUBLEPRECISION AG1, AO1, CMPF, DTIM, PORI, PRSI, RG1, RO1, SATWI,
     .    VOLBW
      COMMON /MBAL2/  AO2, AG2, RO2, RG2, RGAV
      DOUBLEPRECISION AO2, AG2, RO2, RG2, RGAV
```

```
      COMMON /MBAL3/  DENRG, DENRO, FVFG, FVFO, GORS, OGRS, POR, PRMGO,
     .    SATG1, SATO1, VISG, VISO, XMBAL1
      DOUBLEPRECISION DENRG, DENRO, FVFG, FVFO, GORS, OGRS, POR, PRMGO,
     .    SATG1, SATO1, VISG, VISO, XMBAL1
      COMMON /ICOUNT/ IC, IT
      INTEGER         IC(8), IT(8)
C
C---- START EXECUTION
C
      IC(4)=IC(4)+1
      IF (IPRT.GE.4) PRINT *,'            START MBAL'
C
C---- CALCULATE PRESSURE-DEPENDENT PROPERTIES
C
      CALL INTPL(TPRS,TGORS,PRS,1,NPVT,GORS,FRAC,J)
      FVFO=TFVFO(J)+FRAC*(TFVFO(J+1)-TFVFO(J))
      VISO=TVISO(J)+FRAC*(TVISO(J+1)-TVISO(J))
      OGRS=TOGRS(J)+FRAC*(TOGRS(J+1)-TOGRS(J))
      VISG=TVISG(J)+FRAC*(TVISG(J+1)-TVISG(J))
      DENRO=TDENRO(J)+FRAC*(TDENRO(J+1)-TDENRO(J))
      DENRG=TDENRG(J)+FRAC*(TDENRG(J+1)-TDENRG(J))
      FVFG=1/(TFVFGX(J)+FRAC*(TFVFGX(J+1)-TFVFGX(J)))
      POR=PORI*EXP(CMPF*(PRS-PRSI))
C
C---- CALCULATE SATURATIONS
C
      IF (IHC.EQ.0) THEN
C         (Calculate the oil saturation from)
C         (the gas material balance equation)
          DGASPQ=RTE*DTIM/VOL8W
          X1=GORS*DENRG/FVFO
          X2=POR*(1-SATWI)/FVFG
          X3=POR*(X1-1/FVFG)
          SATO=(AG1-DGASPQ-X2)/X3
      ELSEIF (IHC.EQ.1) THEN
C         (Calculate the oil saturation from)
C         (the oil material balance equation)
          DOILPQ=RTE*DTIM/VOL8W
          X1=OGRS*DENRO/FVFG
          X2=POR*(1-SATWI)*X1
          X3=POR*(1/FVFO-X1)
          SATO=(AO1-DOILPQ-X2)/X3
      ENDIF
      SATG=1-SATWI-SATO
C
C---- CALCULATE RELATIVE PERMEABILITY RATIO AS A FUNCTION OF GAS
C     SATURATION.  USE S FOR INTERPOLATION
C
```

```
      IF (SATG.LT.TSATG(1)) THEN
          S=TSATG(1)
      ELSEIF (SATG.GT.TSATG(NRP)) THEN
          S=TSATG(NRP)
      ELSE
          S=SATG
      ENDIF
      CALL INTPL(TSATG,PRMLGO,S,1,NRP,Y,FRAC,J)
      PRMGO=EXP(Y)
C
C---- CALCULATE MOBILITY RATIO AND AO2,AG2,RO2,RG2 WHICH CONTAIN PARTS
C     OF THE OIL MATERIAL BALANCE EQUATIONS
C
      XMOBR=PRMGO*VISO/VISG
      AO2=POR*(SATO/FVFO + SATG*OGRS*DENRO/FVFG)
      AG2=POR*(SATG/FVFG + SATO*GORS*DENRG/FVFO)
      RO2=(1. + OGRS*DENRO*XMOBR*FVFO/FVFG)
      RG2=GORS*DENRG + XMOBR*FVFO/FVFG
      ROAV=(RO1+RO2)/2.
      RGAV=(RG1+RG2)/2.
C
C---- CALCULATE INCREMENTAL OIL AND GAS PRODUCTION
C
      IF (IHC.EQ.0) THEN
          DOILPQ=DGASPQ/RGAV*ROAV
      ELSEIF (IHC.EQ.1) THEN
          DGASPQ=DOILPQ/ROAV*RGAV
      ENDIF
      DOILP=DOILPQ*VOLBW
      DGASP=DGASPQ*VOLBW
C
C---- CALCULATE MATERIAL BALANCE ERROR
C
      XMBAL1=AO2-AO1+DOILPQ+AG2-AG1+DGASPQ
      IF (RTE.EQ.0.) XMBAL1=0.
      XMBAL=XMBAL1
C
      SATO1=SATO
      SATG1=SATG
C
C---- FORMAT SPECIFICATIONS
C
   10 FORMAT (1X,4A16)
   12 FORMAT (1X,6I16)
   15 FORMAT (1X,4E16.8)
      END
```

```
C tab f; () 7,72;
C * * * * * A GENERAL MATERIAL BALANCE AND INFLOW PERFORMANCE * * * * *
C * * * * SIMULATION MODEL FOR OIL AND GAS CONDENSATE RESERVOIRS  * * *
C * * * * * * * * * * * * * * * * GMS * * * * * * * * * * * * * * * * *
C * * * * * * * * * * * * * * * * SUBROUTINES * * * * * * * * * * * * * * *
C
C TITLE .......:  IPR
C AUTHOR ......:  GUNNAR BORTHNE
C DATE ........:  APRIL 1986
C IN-CALLS ....:  WHPRS
C OUT-CALLS ...:  FNPRS
C
C FUNCTION ....: The function F is integrated numerically from PRS to
C     PRSWF.  PRSWF is the unknown and is found by iterations.  If the
C     pressure is trying to move below PRSMIN during integration, then
C     PRSWF is set equal to PRSMIN and a smaller rate is calculated. The
C     input and output units are: pressure, kPa; gas-oil ratio,
C     std.vol/std.vol; rate, m3/D
C
      SUBROUTINE IPR  (PRS, PRSMIN, RTEX, DGORP, EPSPRS, K, IPRT, IHC,
     .    PRSWF, RTEY)
C
C---- INPUT VARIABLES
C
      DOUBLEPRECISION  PRS, PRSMIN, RTEX, DGORP, EPSPRS
      INTEGER  K, IPRT, IHC
C
C---- OUTPUT VARIABLES
C
      DOUBLEPRECISION  PRSWF, RTEY
C
C---- COMMON BLOCK
C
      COMMON /IPR1/   DPINT, DSKN, PRM, RADEQ, SKN, THK
      DOUBLEPRECISION DPINT, DSKN, PRM, RADEQ, SKN, THK
      COMMON /ICOUNT/ IC, IT
      INTEGER         IC(8), IT(8)
C
C---- LOCAL VARIABLES AND CONVERSION FACTORS
C
      DOUBLEPRECISION AREA, C1, C2, C3, CN0, CN1, DP, DP2,
     .    DRVSUM, F1, F2, F4, P, P1, P2, PI, SUM1, SUM2
      INTEGER I
      CHARACTER*10 Z1, Z2, Z3
      DATA C1,Z1 / 1E-12, 'm2/um2' /,
     .     C2,Z2 / 1000., 'Pa/kPa' /,
     .     C3,Z3 / 86400, 's/D    ' /
C
```

```
C---- START EXECUTION
C
      IC(5)=IC(5)+1
      IF (IPRT.GE.4) WRITE (3,*) '         START IPR'
      DP=DPINT
      DP2=DP*2.
      PI=3.141592654
      CN0=LOG(RADEQ) -0.75 + SKN + DSKN*RTEX
      CN1=CN0/(2*PI*PRM*C1*THK)/C2
      AREA=RTEX*CN1/C3
C     (AREA has units kPa/Pa s)
      P1=PRS
      P2=P1
      F1=0.
C     (Initialize F2:)
      CALL FNPRS(DGORP,P2,IHC,F2)
      SUM1=0.
      SUM2=0.
C
C---- START INTEGRATION LOOP
C
      I=0
  100 CONTINUE
          I=I+1
          F1=F2
          P1=P2
          P2=P2-DP2
          IF (P2.LT.PRSMIN) THEN
              P2=PRSMIN
              DP2=P1-P2
              DP=DP2/2.
          ENDIF
          CALL FNPRS(DGORP,(P1-DP),IHC,F4)
          CALL FNPRS(DGORP,P2,IHC,F2)
C         (SUM has units kPa/Pa s)
          SUM1=SUM2
          SUM2=SUM2 + (F1+4*F4+F2) * DP/3.
          IF (SUM2.GE.AREA) GOTO 199
          IF (P2.EQ.PRSMIN) GOTO 399
      GOTO 100
  199 CONTINUE
C
C---- START LOOP, FIND INTEGRATION LIMIT WITH A MODIFIED NEWTON-RAPHSON
C     ITERATION METHOD
C
      I=0
  200 CONTINUE
          I=I+1
```

```
          IF (ABS(P2-P1) .LE. EPSPRS) GOTO 299
C
C---- EMERGENCY EXIT
C
          IF (P1-P2.EQ.0. .OR. SUM1-SUM2.EQ.0.) THEN
              WRITE (3,*) 'IPR.     TIME STEP:',K
              WRITE (3,3000) ABS(P1-P2),ABS(SUM1-SUM2)
              P=P2
              GOTO 299
          ENDIF
C
          DRVSUM=(SUM2-SUM1) / (P2-P1)
          DP=(SUM2-AREA)/DRVSUM
          P=P2-DP
          P=MIN(P,PRS)
          P=MAX(P,PRSMIN)
          P1=P2
          F1=F2
          P2=P
          CALL FNPRS(DGORP,P2,IHC,F2)
          SUM1=SUM2
          SUM2=SUM2 + (F1+F2)*(P1-P2)/2.
      GOTO 200
C
C---- PREPARE EXIT, NORMAL PROCEDURE
C
  299 CONTINUE
      PRSWF=P
      RTEY=RTEX
      RETURN
C
C---- PREPARE EXIT, LACK OF PVT DATA
C
  399 CONTINUE
      PRSWF=PRSMIN
      RTEY=SUM2/CN1*C3
      IF (IPRT.GE.4) THEN
          WRITE (3,*) 'IPR.  TIMESTEP:',K
          WRITE (3,*) 'The rate is reduced due to lack of PVT data'
          WRITE (3,*) 'Input  rate: ',RTEX
          WRITE (3,*) 'Output rate: ',RTEY
          WRITE (3,*)
      ENDIF
      RETURN
C
C---- FORMAT STATEMENTS
C
 2000 FORMAT (1X,A,I4,A,I4)
```

```
3000 FORMAT (
     .1X,'"EMERGENCY EXIT"',/
     .1X,'LENGTH OF CURRENT PRESSURE INTERVAL (KPA) .......:',G15.8, /
     .1X,'DIFFERENCE IN SUM (KPA/PA S) ....................:',G15.8, /
     ./)
      END
```

```
C tab f; () 7,72;
C * * * * * A GENERAL MATERIAL BALANCE AND INFLOW PERFORMANCE * * * * *
C * * * * SIMULATION MODEL FOR OIL AND GAS CONDENSATE RESERVOIRS  * * *
C * * * * * * * * * * * * * * * * GMS * * * * * * * * * * * * * * * * *
C * * * * * * * * * * * * * * * * SUBROUTINES * * * * * * * * * * * * * *
C
C TITLE .......:  FNPRS
C AUTHOR ......:  GUNNAR BORTHNE
C DATE ........:  APRIL 1986
C IN-CALLS ....:  IPR
C OUT-CALLS ...:  INTPL
C
C FUNCTION ....:  Calculate the pseudopressure integrand
C
      SUBROUTINE FNPRS(DGORP,P2,IHC,F)
C
C---- INPUT VARIABLES
C
      DOUBLEPRECISION  DGORP,P2
      INTEGER IHC
C
C---- OUTPUT VARIABLES
C
      DOUBLEPRECISION F
C
C---- COMMON BLOCKS
C
      COMMON /PROP/ TDENRG, TDENRO, TFVFG, TFVFGX, TFVFO, TGORS,
     .    TOGRS, TPRMRG, TPRMRO, PRMLGO, TPRS, TSATG, TVISG, TVISO,
     .    NPVT, NRP
      DOUBLEPRECISION TDENRG(100), TDENRO(100), TFVFG(100), TFVFGX(100),
     .    TFVFO(100), TGORS(100), TOGRS(100), TPRMRG(100), TPRMRO(100),
     .    PRMLGO(100), TPRS(100), TSATG(100), TVISG(100), TVISO(100)
      INTEGER NPVT, NRP
      COMMON /ICOUNT/ IC, IT
      INTEGER         IC(8), IT(8)
C
C---- LOCAL VARIABLES
C
      DOUBLEPRECISION XSATG,XPRMGO,XGORPF,GORS,FVFO,VISO,OGRS,FVFG,VISG,
     .    DENRO,DENRG,PRMRO,PRMRG,XPRML,FRAC
      INTEGER J
C
C---- START EXECUTION
C
      IC(6)=IC(6)+1
C
C---- CALCULATE PRESSURE-DEPENDENT PROPERTIES
```

```
C
      CALL INTPL(TPRS,TGORS,P2,1,NPVT,GORS,FRAC,J)
      FVFO=TFVFO(J)+FRAC*(TFVFO(J+1)-TFVFO(J))
      VISO=TVISO(J)+FRAC*(TVISO(J+1)-TVISO(J))
      OGRS=TOGRS(J)+FRAC*(TOGRS(J+1)-TOGRS(J))
      VISG=TVISG(J)+FRAC*(TVISG(J+1)-TVISG(J))
      DENRO=TDENRO(J)+FRAC*(TDENRO(J+1)-TDENRO(J))
      DENRG=TDENRG(J)+FRAC*(TDENRG(J+1)-TDENRG(J))
      FVFG=1/(TFVFGX(J)+FRAC*(TFVFGX(J+1)-TFVFGX(J)))
C
C---- CALCULATE RELATIVE PERMEABILITY RATIO
C
      XGORPF = (DGORP-GORS*DENRG) / (1-DGORP*OGRS*DENRO)
      XPRMGO = XGORPF * VISG*FVFG/VISO/FVFO
      IF (XPRMGO .LT. 0.)THEN
          PRINT *,'FNPRS. CALCULATED RELATIVE PERMEABILITY RATIO OF GAS'
          PRINT *,'TO OIL IS NEGATIVE'
          PRINT *,'XPRMGO = ',XPRMGO
          PRINT *,'AND IS SET EQUAL TO ZERO.'
          XPRML = -115
      ELSE
          XPRML=LOG(XPRMGO)
      ENDIF
C
C---- CALCULATE GAS SATURATION
C
      CALL INTPL(PRMLGO,TSATG,XPRML,1,NRP,XSATG,FRAC,J)
C
C---- CALCULATE RELATIVE PERMEABILITIES
C
      CALL INTPL(TSATG,TPRMRO,XSATG,1,NRP,PRMRO,FRAC,J)
      PRMRG=TPRMRG(J)+FRAC*(TPRMRG(J+1)-TPRMRG(J))
C
C---- CALCULATE THE PRESSURE FUNCTION
C
      IF (IHC.EQ.0) THEN
          F=PRMRG/VISG/FVFG + PRMRO*GORS/VISO/FVFO
      ELSEIF (IHC.EQ.1) THEN
          F=PRMRO/VISO/FVFO + PRMRG*OGRS/VISG/FVFG
      ENDIF
      END
```

```
C tab f; () 7,72;
C * * * * * A GENERAL MATERIAL BALANCE AND INFLOW PERFORMANCE * * * * *
C * * * * SIMULATION MODEL FOR OIL AND GAS CONDENSATE RESERVOIRS  * * *
C * * * * * * * * * * * * * * * * GMS * * * * * * * * * * * * * * * * *
C * * * * * * * * * * * * * * SUBROUTINES * * * * * * * * * * * * * * *
C
C TITLE .......:  INTPL
C AUTHOR ......:  GUNNAR BORTHNE
C DATE ........:  APRIL 1986
C IN-CALLS ....:  GMS, MATBAL, FNPRS
C OUT-CALLS ...:  NONE
C
C FUNCTION ....: Linear X - Linear Y interpolation.
C
      SUBROUTINE INTPL(TABX,TABY,X,I,MAX,Y,FRAC,J)
C
C---- INPUT VARIABLES
C
      DOUBLEPRECISION  TABX(500), TABY(500), X
      INTEGER  I, MAX
C
C---- OUTPUT VARIABLES
C
      DOUBLEPRECISION  Y, FRAC
      INTEGER  J
C
C---- COMMON BLOCK
C
      COMMON /ICOUNT/ IC, IT
      INTEGER         IC(8), IT(8)
C
C---- START EXECUTION
C
      IC(8)=IC(8)+1
      J=I
  100 CONTINUE
          IF (X.GE.TABX(J) .AND. X.LE.TABX(J+1)) THEN
C             (The appropriate interval is found)
              FRAC=(X-TABX(J))/(TABX(J+1)-TABX(J))
              Y=TABY(J) + FRAC * (TABY(J+1)-TABY(J))
              R E T U R N
          ENDIF
          J=J+1
      IF (J.LT.MAX) GOTO 100
      PRINT *,'ERROR. INTPL'
      PRINT *,'TABX(1),TABX(MAX),X',TABX(1),TABX(MAX),X
      STOP
      END
```

```
C tab f; () 7,72;
C * * * * * A GENERAL MATERIAL BALANCE AND INFLOW PERFORMANCE * * * * *
C * * * * SIMULATION MODEL FOR OIL AND GAS CONDENSATE RESERVOIRS  * * *
C * * * * * * * * * * * * * * * * GMS * * * * * * * * * * * * * * * * *
C * * * * * * * * * * * * * * * SUBROUTINES * * * * * * * * * * * * * * *
C
C TITLE .......:  ISGN
C AUTHOR ......:  GUNNAR BORTHNE
C DATE ........:  APRIL 1986
C IN-CALLS ....:  RATE, WHPRS, RESPRS
C OUT-CALLS ...:  NONE
C
C FUNCTION ....: Return sign of argument (-1, 0, +1)
C
      INTEGER FUNCTION ISGN (X)
      DOUBLEPRECISION X
C
C---- COMMON BLOCK
C
      COMMON /ICOUNT/ IC, IT
      INTEGER         IC(8), IT(8)
C
C
      IC(7)=IC(7)+1
      IF (X.GT.0.) THEN
          ISGN=1
      ELSEIF (X.EQ.0.) THEN
          ISGN=0
      ELSEIF (X.LT.0.) THEN
          ISGN=-1
      ENDIF
      END
```

```
C tab f; () 7,72;
C * * * * * A GENERAL MATERIAL BALANCE AND INFLOW PERFORMANCE * * * * *
C * * * * SIMULATION MODEL FOR OIL AND GAS CONDENSATE RESERVOIRS  * * *
C * * * * * * * * * * * * * * * * GMS * * * * * * * * * * * * * * * * *
C * * * * * * * * * * * * * * * SUBROUTINES * * * * * * * * * * * * * * *
C
C TITLE .......:  SKIP
C AUTHOR ......:  GUNNAR BORTHNE
C DATE ........:  APRIL 1986
C IN-CALLS ....:  GMS
C OUT-CALLS ...:  NONE
C
C FUNCTION ....: Skip text lines in data files
C
      SUBROUTINE SKIP (IUNT)
C
C---- INPUT VARIABLES
C
      INTEGER IUNT
C
C---- LOCAL VARIABLES
C
      INTEGER I, N
      CHARACTER ZA*80, ZSPACE*80, ZB*160, Z*1
      SAVE ZSPACE
      DATA ZSPACE /'
     .                                '/
 10   FORMAT (2A)
C
C---- START EXECUTION
C
 100  CONTINUE
          READ (IUNT,10,END=999) ZA
          I=0
          ZB=ZA//ZSPACE
          N=INDEX(ZB,ZSPACE)
 200      CONTINUE
              I=I+1
              Z=ZB(I:I)
          IF (Z.EQ.' '.AND.I.LT.N) GOTO 200
          IF (Z.GE.'0'.AND.Z.LE.'9'.OR.Z.EQ.'.'
     .        .OR.Z.EQ.'-'.OR.Z.EQ.'+') THEN
              BACKSPACE IUNT
              GOTO 999
          ENDIF
      GOTO 100
 999  CONTINUE
      END
```

A.2 GMS Flowcharts

Figs. A.1 - A.6 present GMS flowcharts of the main routine and the subroutines RATE, WHPRS, RESPRS, IPR, MATBAL, and FNPRS. Only the main structure and flow of control is illustrated in the figures. For more details, see Section 6.2 and Appendix A.1.

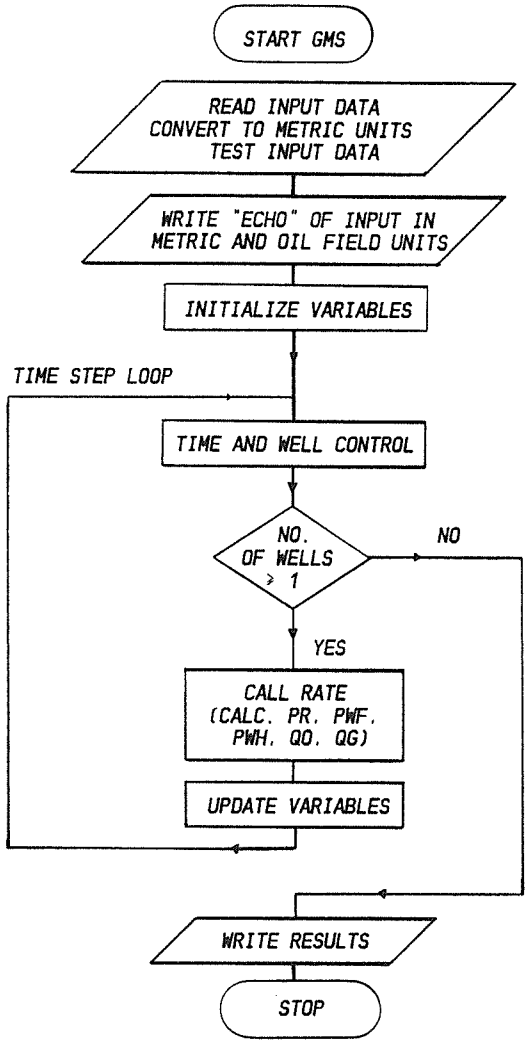


Fig. A.1 - GMS flowchart, main structure of the MAIN program.

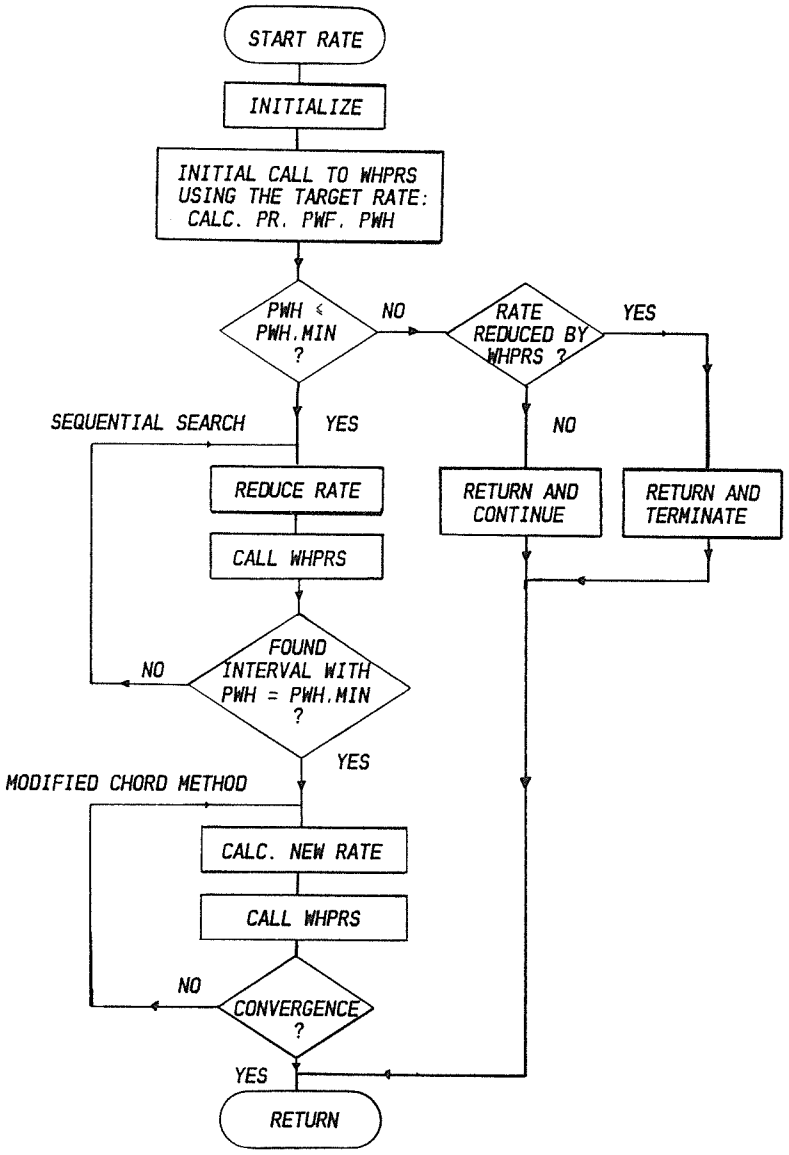


Fig. A.2 - GMS flowchart, main structure of the RATE subroutine.

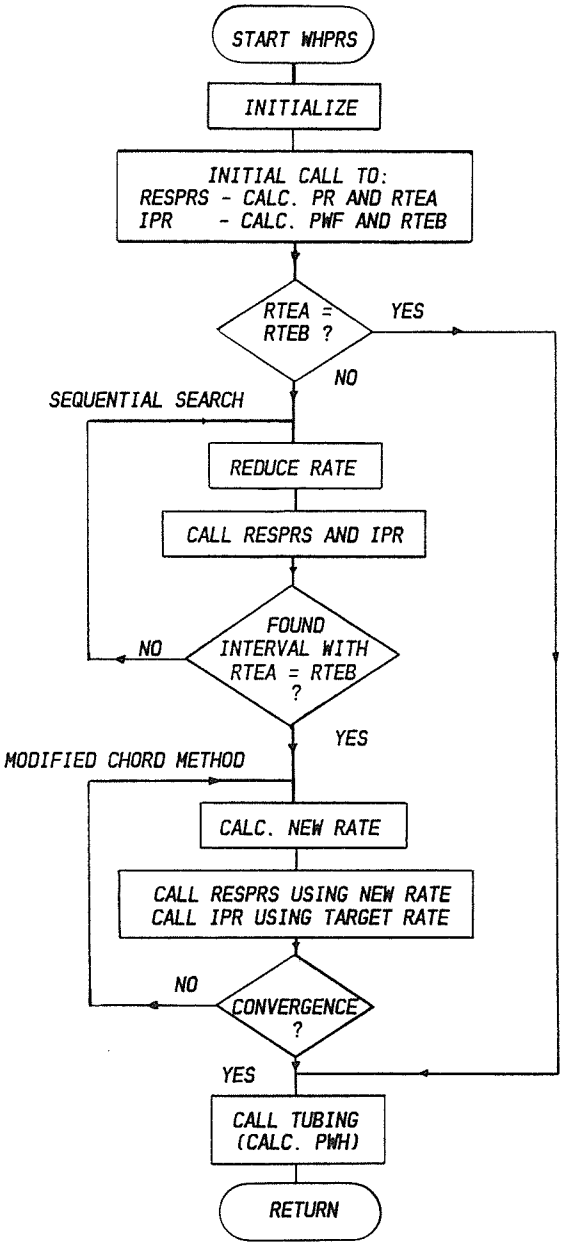


Fig. A.3 - GMS flowchart, main structure of the WHPRS subroutine.

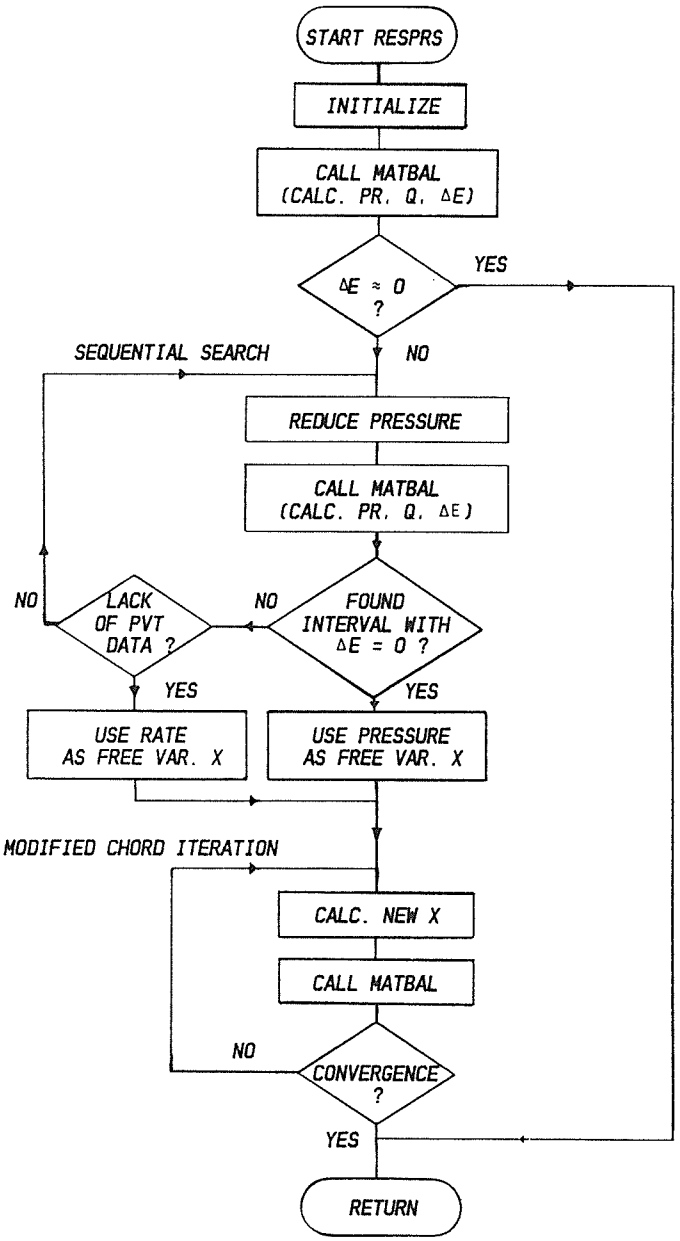


Fig. A.4 - GMS flowchart, main structure of the RESPRS subroutine.

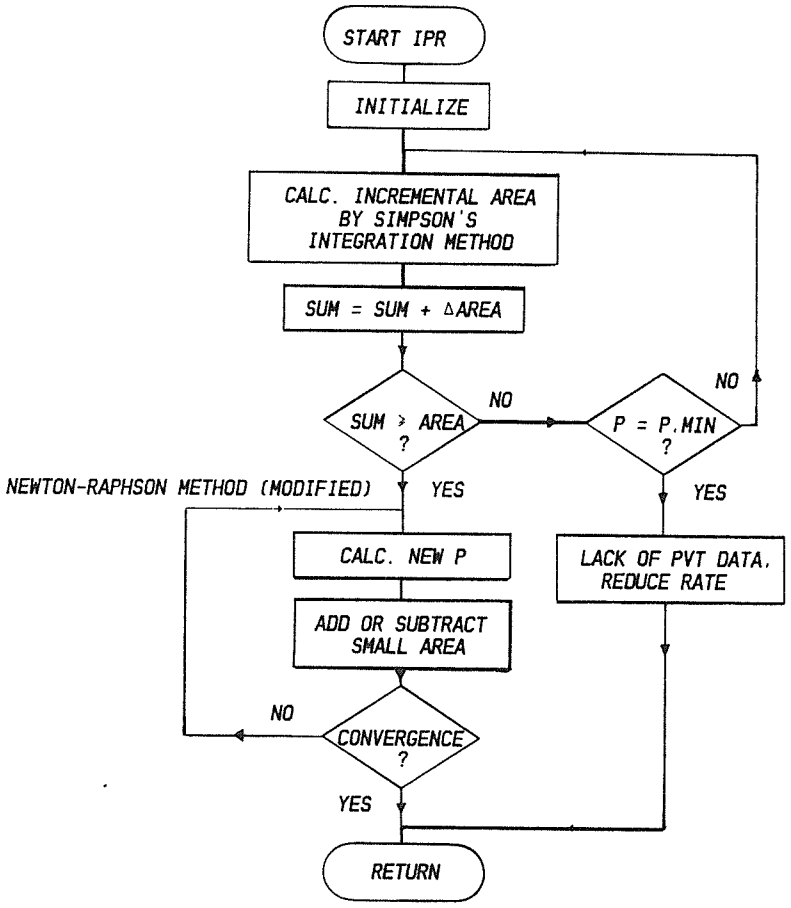
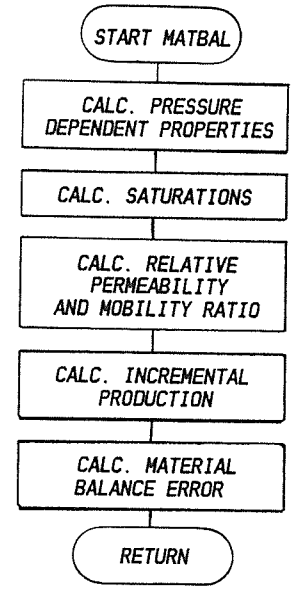


Fig. A.5 - GMS flowchart, main structure of the IPR subroutine.



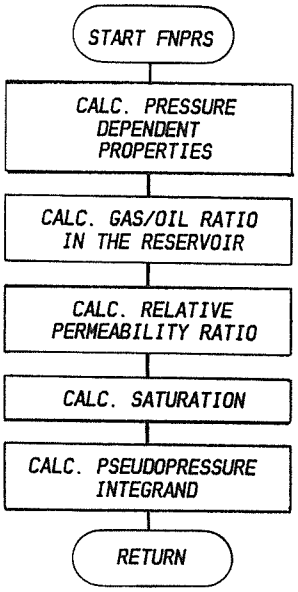


Fig. A.6 - GMS flowchart, main structure of the MATBAL and FNPRS subroutines.

A.3 Variable Lists for GMS

The variables used by GMS are listed in Table A.1. Some variables, which are defined by their use in the program, are not included in the list. Note that arrays with first letter T are read from the input file, and arrays with first letter V are updated each timestep. Initial quantities end with an "I". When possible, the variable names comply with the SPE standard.[25-27]

TABLE A.1 - VARIABLES USED BY GMS

1-Dimensional Integer Arrays

Name	*Description*
IC	Counts the number of calls to each routine.
IT	Counts how often iterations are started in each routine.
IVNWEL	Number of producing wells each timestep.
NWELLS	Number of wells assigned by well control in input file.

1-Dimensional Character Arrays

Name	*Description*
ZC	Array which contains the GMS function and subroutine names.

1-Dimensional Double Precision Arrays

Name	*Description*
PRMLGO	Logarithm to the relative permeability ratio, gas / oil.
TABX	Interpolation table.
TABY	Interpolation table.
TDENRG	Density ratio, gas from free reservoir gas / gas from free reservoir oil flashed to standard conditions, function of reservoir pressure.
TDENRO	Density ratio, oil (analogous to TDENRG). Oil from oil / gas from gas.
TFVFG	Gas formation volume factor.
TFVFGX	1/TFVFG
TFVFO	Oil formation volume factor.

TGORS	Solution gas/oil ratio in oil.
TOGRS	Solution oil/gas ratio in gas.
TPRMRG	Relative permeability, gas.
TPRMRO	Relative permeability, oil.
TPRS	Pressure.
TPWMIN	Minimum wellhead pressure.
TRTEFM	Minimum field production rate of preferred phase (See IHC).
TRTEFT	Target field production rate of preferred phase.
TSATG	Gas saturation.
TSKN	Skin factor.
TTIM	Time for well control data.
TVISG	Gas viscosity.
TVISO	Oil viscosity.
VGASP	Field cumulative gas production.
VGOR	Producing gas/oil ratio.
VOILP	Field cumulative oil production.
VPRSR	Average reservoir pressure.
VPRSWF	Bottomhole pressure.
VPRSWH	Wellhead pressure.
VRTEG	Gas production rate per well.
VRTEO	Oil production rate per well.
VTIME	Report time.

Integer Variables

Name	*Description*
I	Counter.
I1, I2	Interval limit.
IERR	Error flag.
IEXE	Execution flag.
IHC	Preferred phase.
IPRT	Print option.
IUNIN	Flag for selection of unit system in input.
IUNT	Logical I/O unit.
IWCTR	Well specification counter.
IX	Variable to be tested.
J	Iteration counter.
K	Timestep counter.
LOOP	Max number of loops.
MAXITR	Max number of iterations.
N1	Dimension of T arrays.
N2	Dimension of V arrays.
NPVT	Number of PVT data lines on input.
NRP	Number of relative permeability data lines on input.
NSTEP	Number of timesteps performed.
NWELL	Number of wells.

NWT Number of well control specification lines on input.

Logical Variables

Name	*Description*
QPVT	"Lack of PVT data" - flag.
QSTOP	Stop flag.
QWCTR	Well counter flag.

Character Variables

Name	*Description*
ZINPFL	Input file name.
ZJOBID	Job identification.
ZSPACE	Space string.
ZTXT	Error message.

Double Precision Variables

Name	*Description*
AG1, AG2, AO1, AO2	Represents part of the oil MB equation.
AREA	Reservoir area.
C	Pressure or rate in RESPRS depending on iteration mode.
C1-C8	Conversion factors.
CMPF	Formation compressibility.
CN0, CN1	Constants used by IPR integration.
DELTIM	Timestep length before adjustment by well and time control.
DENRG	Density ratio (gravity ratio), gas.
DENRO	Density ratio (gravity ratio), oil.
DGASP	Incremental gas production during timestep per well.
DGASPQ	same as DGASP but per unit bulk volume of well drainage area.
DGASPS	Field incremental gas production during current timestep.
DGORP	Producing gas/oil ratio.
DOILP	Incremental oil production during timestep per well.
DOILPQ	same as DOILP but per unit bulk volume of well drainage area.
DOILPS	Field incremental oil production during current timestep.
DP, DP2, DPRS	Incremental pressure.
DPINT	Pressure interval in IPR integration.
DRTE	Incremental rate.
DRVSUM	Numerical derivative of the integration sum.
DSKN	Non-Darcy flow coefficient (rate dependent skin term).
DTIM	Timestep length for simulation.

DX Small number.
EPSPRS Iteration tolerance for pressure.
EPSRTE Iteration tolerance for rate.
F, F1, F2, F4, FN, FN1, FN2 Function values.
FND Numerical derivative of the function.
FRAC Interpolation fraction.
FVFG Gas formation volume factor.
FVFO Oil formation volume factor.
GASTI Initial gas in place.
GORS Solution gas/oil ratio in oil.
HCPV Initial hydrocarbon pore volume.
OGRS Solution oil/gas ratio in gas.
OILTI Initial oil in place.
P Pressure.
P1,P2 Pressure interval.
PI 3.14159...
POR Porosity.
PORI Initial porosity.
PRM Permeability.
PRMGO Relative permeability ratio, gas / oil.
PRMRG Relative permeability to gas.
PRMRO Relative permeability to oil.
PRS Average reservoir pressure.
PRSHI Maximum pressure each timestep.
PRSI Initial reservoir pressure.
PRSLO Minimum pressure each timestep.
PRSMIN Minimum pressure each timestep (IPR routine).
PRSWF Bottomhole pressure.
PRSWH Wellhead pressure.
PVTMAX Maximum PVT data pressure on input.
PVTMIN Minimum PVT data pressure on input.
PW, PW1, PW2 Wellhead pressure function.
PWD Wellhead pressure function slope.
PWHMIN Minimum wellhead pressure.
R Rate
R1,R2 Rate interval.
RADE External radius.
RADEQ Dimensionless radius.
RADW Wellbore radius.
RG1, RG2, RGAV, RO1, RO2, ROAV Represents parts of the oil MB equation.
RTE Production rate.
RTEA Production rate returned from MATBAL.
RTEB Production rate returned from IPR.
RTEHI Maximum production rate of preferred phase each timestep.
RTEHI1 Target rate for the WHPRS routine.
RTELO Minimum production rate of preferred phase.
RTEMAX Maximum production rate of preferred phase.
RTEW Well rate of preferred phase.

RTEX Input rate.
RTEY Output rate.
RTIN Input rate to IPR routine.
S Pseudo saturation.
SATG, SATG1 Gas saturation.
SATO, SATO1 Oil saturation.
SATWI Initial water saturation.
SKN Skin factor.
SUM1, SUM2 Sum during integration.
THK Reservoir thickness.
VISG Gas viscosity.
VISO Oil viscosity.
VOLB Bulk volume of reservoir.
VOLBW Bulk volume of reservoir divided by number of wells.
XGORPF Producing GOR of free phases in the reservoir.
XMBAL, XMBAL1 Material balance error.
XMOBR Mobility ratio.
XMXTIM Maximum simulation time.
XPRMGO Relative permeability ratio, gas / oil.
XPRML Logarithm to the relative permeability ratio.
XSATG Gas saturation.
Y, Y1, Y2 Function values.
YD Numerical derivative.

A.4 Program Efficiency

Three methods have been employed to make the GMS program more efficient. These are briefly described below together with examples from the development of GMS.

1. *Change to more efficient algorithms.* An example from GMS is the WHPRS routine which originally applied a "fix point" iteration algorithm. This algorithm was found to be rather inefficient for certain data sets. WHPRS was rewritten into a modified chord solution method which is considerably faster and also reliable. The trapezoid integration method in the IPR routine was replaced by Simpson's method to allow larger pressure steps and a faster execution without any loss of accuracy.

2. *Reduce the number of iterations.* This is usually done by adjusting iteration tolerances and increasing step lengths.

When the convergence of the modified chord method is fast (solving F(X)=0), the solution will not be located in the middle of the X interval, but rather close to one of the endpoints, after a limited number of steps. (Actually, the "newest" X is identical to this endpoint.) This implies that, if the process is interrupted, the accuracy will be a lot better than the length of the whole X interval (see Fig. A.7). This is applicable for production rate in subroutines RATE, WHPRS, and RESPRS (in RESPRS for "rate" iteration mode), and for pressure in subroutine RESPRS ("pressure" iteration mode). The IPR subroutine utilizes Newton-Raphson iteration, so an upper error limit here is estimated to be equal to the length of the last pressure interval.

3. *Reduce the work per iteration.* This can be done by removal of unnecessary operations, and rewriting to avoid time consuming constructions, especially in critical parts of the program. A rule of thumb says that 10% of the program code is responsible for 90 % of the time consumption in many programs. In such cases it would pay off to start the rationalization on the time consuming part. To get some guide-lines on where to start, one should know how many times each routine (and each loop) is performed, and the time consumption of each

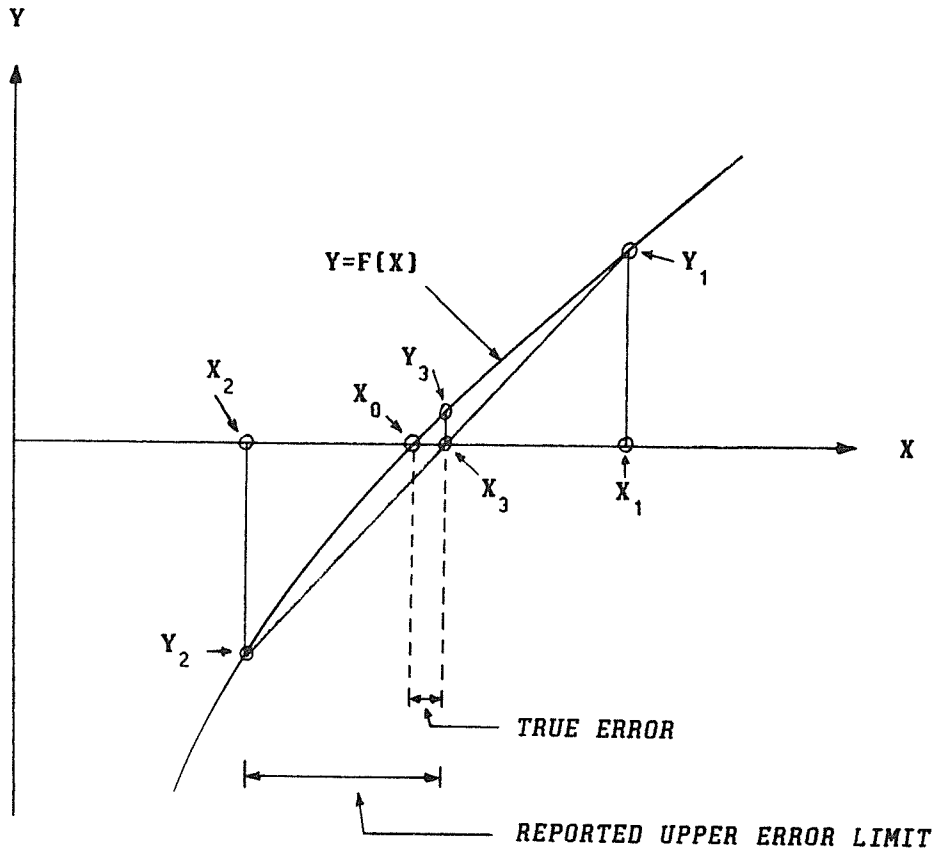


Fig. A.7 - The modified chord method solves F(X)=0. The true error in X ($|X_3-X_0|$) is in this case considerably less than the length of the new iteration interval ($|X_3-X_2|$) which is reported as the upper error limit.

operation. During this study, test programs were made to investigate the CPU time used by various program statements. A general table of time consumption not given here; however, one example is mentioned. Experience from test programs showed that CALL SUB(A,B,C) needed the same CPU time as 18 of the arithmetic operators (+,-,*,/, or =), [e.g., A=A*B*C*D... (18 operators)], and also that time increased with increasing number of variables in the parameter list. The tests were performed on ND-500 Fortran with double precision variables.

The interpolation subroutine (INTPL) of GMS was for the old version called 1,068,210 times and the execution CPU time was 120 seconds for the BASE case. Also, the interpolation routine was quite sophisticated, with many options and a long parameter list. This routine was completely rewritten and simplified. The options were removed, the parameter list was minimized, and most of the interpolation calculations were moved to the calling routines. [When a series of interpolations is needed (e.g., for calculation of pressure-dependent properties) INTPL performs the first interpolation including the search in tables and then returns information which enables the calling routine to continue.] These measures together with a general "clean-up" reduced the CPU time from 120 to 33 seconds.

A.5 Convergence Criteria

The subroutines RATE, WHPRS, and RESPRS perform iterations by applying a modified chord method, and IPR iterates applying a modified Newton-Raphson algorithm. Iteration tolerances for these procedures were set equal to: pressure, 0.5 kPa [0.073 psi]; and production rate, 0.0005 multiplied by the target rate (see Section A.4, point 2). If these tolerances are changed (by manipulations of the well and time control specification procedure of the main program) and set too small (e.g., they are changed by the user, or a difficult simulation problem is introduced), or if "double precision" is replaced by "real" in the program (to gain some processing speed), the tolerances may be stricter than what is possible to obtain owing to the limited accuracy (rounding error) of the variables. In such cases an *"emergency exit"* will cause exit from the iteration loop, a message will be written (giving information about subroutine, timestep, and accuracy), and

processing will continue with reduced accuracy (see Appendix A.1 Program Listing). The emergency exit works as follows:

1. For the modified chord method, where the problem to be solved can be formulated as F(X)=0, the program leaves the iteration loop if the new X is not in the open interval <X1,X2> containing the solution.

2. For the Newton-Raphson routine, the program stops iterations when the interval <X1,X2> is empty or the F equals zero. *This will ensure continued operation.*

A.6 Calculation with "Unphysical" Saturations

The relative permeability ratio (RPR), k_{rg}/k_{ro}, is calculated as a function of gas saturation by interpolation in tables. If the rate and pressure, during material-balance iterations, are too far from the values giving a material-balance error equal to zero, the gas saturation as calculated by the MB routine (see the procedures outlined above) might be outside the interval of the gas-saturation table. This gas saturation can *not* be used for interpolation. In such cases, the interpolation variable is set equal to the endpoint of the gas-saturation table being closest to the calculated saturation, and RPR is found from this endpoint saturation. This approach does not create any problems for the subsequent calculations because as the RPR → 0, the gas saturation → 0 and as RPR → ∞, the gas saturation → maximum possible gas saturation, asymptotically (see Appendix B.1 for plot of RPR).

Though saturation values might be *"unphysical"* (i.e., negative or greater than unity) during the iteration process, the material-balance error is a monotonous, smooth function of pressure for the whole pressure range. Because of this, the unphysical gas saturations can be used *unaltered* in all the equations following the RPR interpolation Figs. A.8 and A.9 show an example of a smooth material-balance error function for unphysical saturations. This example is taken from a run of GMS for the gas-condensate data. The normal calculation procedure was stopped at a given timestep and the material-balance error and gas saturation were calculated as functions of pressure. This shows that unphysical saturation during iterations is no problem. If, however, a saturation is unphysical for a material-balance error of *zero* after

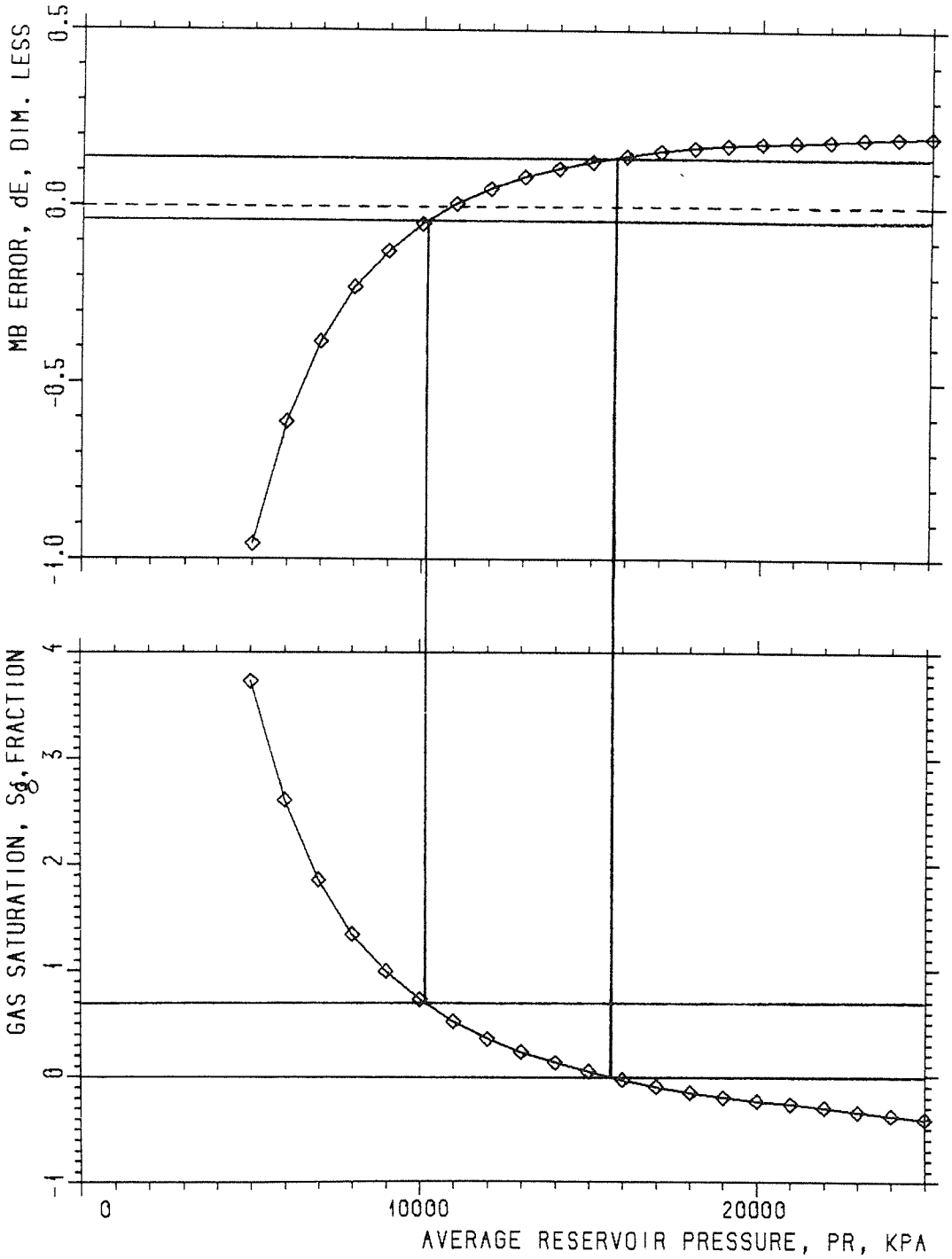


Fig. A.8 - The material-balance error (dE) is a smooth, monotonous function of pressure for unphysical gas and oil saturations. (Normal gas saturation interval is from 0.0 to 0.7 for this run (connate water saturation is 0.3).) This shows that the MB procedure searching for a solution to dE=0 can continue even though unphysical gas saturations are encountered during iterations. (For dE=0, saturations <u>are</u> physical.)

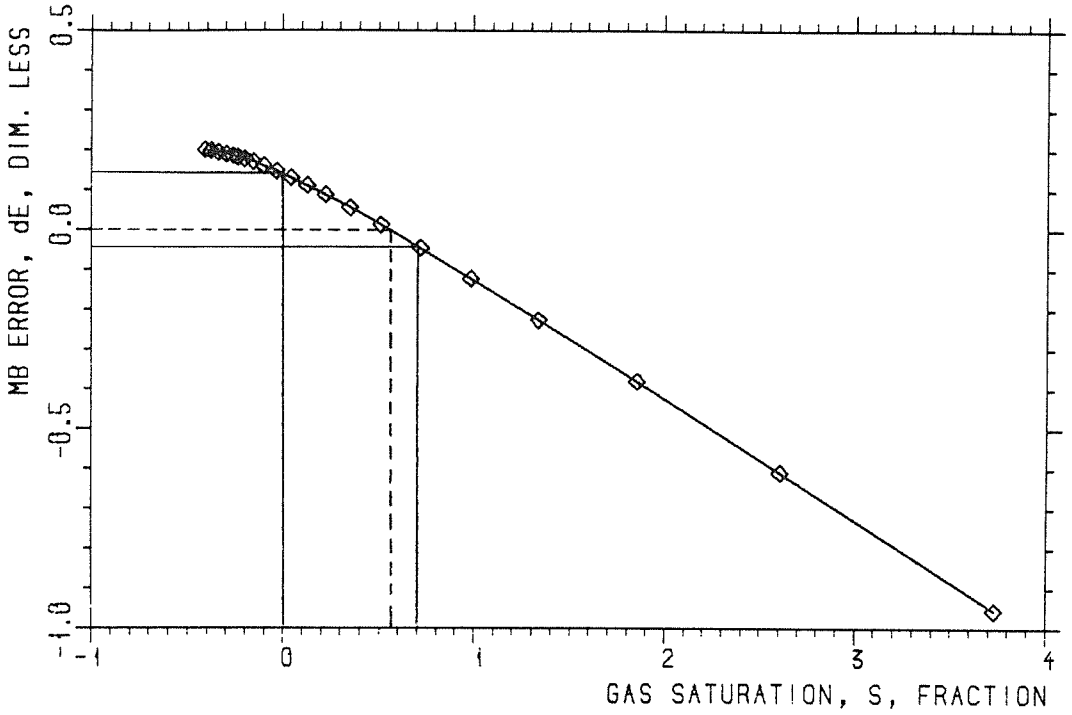


Fig. A.9 - A cross plot of material-balance error vs. gas saturation from Fig. A.8 showing that the gas saturation is physical for a material- balance error equal to zero.

finishing the iteration process, something is fundamentally wrong and the simulation is stopped, but this has nothing to do with the phenomenon described above.

A.7 Listing of the PLOT-GMS program

PLOT-GMS reads output files from GMS and produces files for the plotting program PLOT which is installed on an ND-500 computer at The Division of Petroleum Engineering and Applied Geophysics, The Norwegian Institute of Technology, U. of Trondheim. This listing is the only documentation given for PLOT-GMS in this report.

```
C TAB F; () 7,72;
C * * * * * A GENERAL MATERIAL BALANCE AND INFLOW PERFORMANCE * * * * *
C * * * * SIMULATION MODEL FOR OIL AND GAS CONDENSATE RESERVOIRS  * * *
C * * * * * * * * * * * * * * * * GMS * * * * * * * * * * * * * * * * *
C * * * * * * * * * * * * * * PLOTTING PROGRAM  * * * * * * * * * * * * *
C
C TITLE .......: PGMS (PLOT-GMS)
C AUTHOR ......: GUNNAR BORTHNE
C DATE ........: APRIL 1986
C IN-CALLS ....: NONE
C OUT-CALLS ...: SUBROUTINES ON THIS FILE
C
C---- FUNCTION: The program reads output files from gms and prepares
C     input files for the plotting program "PLOT".  The user selects
C     options from menus during the program run.  Lines from different
C     GMS runs can be combined in the same plot.
C
      PROGRAM PGMS
C
      REAL TAB(6,0:900,16),PNT(0:900,2)
      INTEGER NUMPNT(6),NUMCRV,NUMFIL,I,J,K,K2,
     .    I1,I2,I3,I4,I5,N1,N2,N3,N4,N5,NPNT,ITRAPP
      CHARACTER*21 FIL1(6),FIL2
      CHARACTER*75 TX1(30),TX2(30),TX3(30),TX4(30),TX5(30)
      LOGICAL L1
C
C---- READ INPUT DATA
C
      PRINT *,'SELECT CURVE SHAPE:'
      PRINT *,'1 = ONE POINT  PER TIMESTEP (STRAIGHT LINE)'
      PRINT *,'2 = TWO POINTS PER TIMESTEP (VERTICAL JUMPS, HISTOGRAM)'
      PRINT *
      READ  *,ITRAPP
C
C     PRINT *,'NUMBER OF LINES IN EACH PLOT :'
```

```
C     PRINT *
C     READ *,NUMCRV
C
      PRINT *,'NUMBER OF GMS OUTPUT FILES TO BE READ AND'
      PRINT *,'COMBINED (I.E., NUMBER OF LINES IN EACH PLOT)'
      PRINT *
      READ *,NUMFIL
      PRINT *
      PRINT *
      PRINT *,'WRITE NAMES OF GMS OUTPUT FILES TO BE READ:'
      PRINT *
      DO 100 I=1,NUMFIL
          PRINT 5040,'FILE NAME NO.',I
          PRINT *
          READ 5000,FIL1(I)
  100 CONTINUE
      NUMCRV=NUMFIL

      DO 110 I=1,NUMFIL
          OPEN (11,FILE=FIL1(I))
          CALL INN(11,I,TAB,NUMPNT(I))
          CLOSE (11)
  110 CONTINUE
C
C---- READ THE TEXT FILE
C
      OPEN (11,FILE='PLOT-GMS:TXT')
      I=0
  400 CONTINUE
          I=I+1
          READ (11,5000) TX1(I)
          IF (TX1(I)(1:1).EQ.'0') GOTO 499
      GOTO 400
C
  499 CONTINUE
      N1=I-1
      I=0
  500 CONTINUE
          I=I+1
          READ (11,5000) TX2(I)
          IF (TX2(I)(1:1).EQ.'0') GOTO 599
      GOTO 500
C
  599 CONTINUE
      N2=I-1
      I=0
  600 CONTINUE
          I=I+1
```

```
          READ (11,5000) TX3(I)
          IF (TX3(I)(1:1).EQ.'0') GOTO 699
      GOTO 600
C
  699 CONTINUE
      N3=I-1
      I=0
  700 CONTINUE
          I=I+1
          READ (11,5000) TX4(I)
          TX5(I)=TX4(I)
          IF (TX4(I)(1:1).EQ.'0') GOTO 799
      GOTO 700
C
  799 CONTINUE
      N4=I-1
      N5=N4
      CLOSE (11)
C
C---- CREATE INPUT FILES FOR "PLOT"
C
 1000 CONTINUE
          PRINT *,'WRITE NAME OF PLOT FILE'
          PRINT *,'TO BE MADE (TO END SESSION, WRITE: 0)'
          PRINT *
          READ 5000,FIL2
          IF (FIL2.EQ.'0') GOTO 999
          OPEN (20,FILE=FIL2)
          PRINT 5020,'1. HEADING (INDEPENDENT OF AXES)'
          CALL DSPLAY (TX1,N1,I1)
          PRINT 5020,'2. HEADING'
          CALL DSPLAY (TX2,N2,I2)
          PRINT 5020,'3. HEADING'
          CALL DSPLAY (TX3,N3,I3)
          PRINT 5020,'X AXIS (DETERMINES WHAT TO BE PLOTTED)'
          CALL DSPLAY (TX4,N4,I4)
          PRINT 5020,'Y AXIS (DETERMINES WHAT TO BE PLOTTED)'
          CALL DSPLAY (TX5,N5,I5)
C
C---- WRITE PARAMETERS TO PLOT FILE
C
          WRITE (20,4000) TX1(I1)(5:75),TX2(I2)(5:75),TX3(I3)(5:75),
     .        TX4(I4)(5:52),TX5(I5)(5:52),NUMCRV+1
          WRITE (20,4005)
C
C---- LOOP REPEATED FOR EACH LINE IN THE SAME PLOT
C
          DO 140 J=1,NUMFIL
```

```
              IF (I5.EQ.16) CALL PND(TAB,J,NUMPNT(J))
C
C---- ONE OR TWO POINTS PER TIMESTEP?
C
              L1=.FALSE.
              NPNT=NUMPNT(J)
              IF (ITRAPP.EQ.2) THEN
                  L1=.TRUE.
                  NPNT=NPNT*2
              ENDIF
C
C---- CREATE TABLE OF POINTS TO BE PLOTTED
C
              DO 120 K=1,NUMPNT(J)
                  K2=K
                  IF (L1) THEN
C----                 (TWO POINTS PER TIMESTEP)
                      K2=K*2
                      PNT(K2-1,1)=TAB(J,K-1,I4)
                      PNT(K2-1,2)=TAB(J,K,I5)
                  ENDIF
                  PNT(K2,1)=TAB(J,K,I4)
                  PNT(K2,2)=TAB(J,K,I5)
  120         CONTINUE
C
C---- WRITE THE DATA POINTS TO THE PLOT FILE
C
              WRITE (20,4010) NPNT
              DO 130 K=1,NPNT
                  WRITE (20,4100) PNT(K,1),PNT(K,2)
  130         CONTINUE
  140     CONTINUE
          CLOSE (20)
      PRINT *,'FILE ',FIL2
      PRINT *,'DONE'
      PRINT *
      GOTO 1000
  999 CONTINUE
C
C---- FORMAT STATEMENTS
C
 5000 FORMAT (A)
 5010 FORMAT (1X,12E10.3)
 5020 FORMAT (//1X,A,/79('-'))
 5040 FORMAT (1X,A,I4)
 4000 FORMAT (
     . A/A/A/A/A/
     .'55,0              IDEV,FRAME'/
```

```
     .'27,20,50,50       FRXCM,FRYCM,XCM,YCM'/
     . I2,',0,0,10,10      NUMCRV,AXTYP,GRIDTP,NTICX,NTICY')
 4005 FORMAT (
     .'1,0,0,0,0,0       NUMPNT,ILINTP,ISMOTH,IMAR,ILEGND,ICOLOR'/
     .'1,2               NXCOL,NYCOL'/
     .'0.   0.')
 4010 FORMAT (
     . I3,',1,1,0,0,0     NUMPNT,ILINTP,ISMOTH,IMAR,ILEGND,ICOLOR'/
     .'1,2               NXCOL,NYCOL')
 4100 FORMAT (15G11.5)
 4200 FORMAT (I5)

      END

C-----------------------------------------------------------------------

      SUBROUTINE INN (UN,IFL,T,NL)

C---- FUNCTION: LOCATE DATA TABLES IN GMS OUTPUT AND READ IN DATA POINTS
C
C---- INPUT VARIABLES
C
      INTEGER UN,IFL
C
C---- OUTPUT VARIABLES
C
      REAL T(6,0:900,16)
      INTEGER NL
C
C---- LOCAL VARIABLES
C
      REAL V1,V2,V3,V4,V5,V6,V7,V8,V9
      INTEGER I
      CHARACTER LINE*132
      LOGICAL JUMP
C
C---- LOCATE THE FIRST DATA TABLE
C
      I=1
  100 CONTINUE
          I=I+1
          CALL REPORT(I)
          READ (UN,1000) LINE
          IF (LINE(1:3).EQ.'SIM'.OR.LINE(1:4).EQ.' SIM') GOTO 199
      GOTO 100
  199 CONTINUE
      PRINT *
      DO 150 I=1,6
```

```
          READ (UN,1000) LINE
  150 CONTINUE
      PRINT *
      PRINT *,'READING TABLE...'
      PRINT *
C
C---- TABLE OF TIME AND CUMULATIVE PRODUCTION
C
      I=1
  200 CONTINUE
          READ (UN,*) V1,V2,T(IFL,I,1),T(IFL,I,2),V3,
     .        T(IFL,I,3),V4,T(IFL,I,4)
          CALL SKIP(UN,JUMP)
          IF (JUMP) GOTO 299
          I=I+1
      GOTO 200
  299 CONTINUE
      NL=I
C
C---- TABLE OF PRESSURES
C
      I=1
  300 CONTINUE
          READ (UN,*) V1,V2,V3,T(IFL,I,5),V4,T(IFL,I,6),V5,
     .        T(IFL,I,7),V6,T(IFL,I,8)
          CALL SKIP(UN,JUMP)
          IF (JUMP) GOTO 399
          I=I+1
      GOTO 300
C
C---- TABLE OF PRODUCTION RATES
C
  399 CONTINUE
      I=1
  400 CONTINUE
          READ (UN,*) V1,V2,V3,V4,V5,V6,T(IFL,I,14),T(IFL,I,9),
     .        T(IFL,I,10),V7,T(IFL,I,11),V8,T(IFL,I,12),V9,T(IFL,I,13)
          CALL SKIP(UN,JUMP)
          IF (JUMP) GOTO 499
          I=I+1
      GOTO 400
  499 CONTINUE
 1000 FORMAT (A)
      END

C-----------------------------------------------------------------------

      SUBROUTINE SKIP (UN,JUMP)
```

```
C
C---- FUNCTION: SKIPTEXT LINES IN DATA FILES.  SPECIAL VERSION: '-'
C     REGARDED AS TEXT. LOGICAL VAR. JUMP = TRUE IF LINES HAVE BEEN
C     SKIPPED.
C
C     NB! 1. COLUMN NOT CONSIDERED OWING TO THE GMS OUTPUT FORMAT
C
C
C---- INPUT VARIABLES
C
      INTEGER UN
C
C---- OUTPUT VARIABLES
C
      LOGICAL JUMP
C
C---- LOCAL VARIABLES
C
      INTEGER I, N
      CHARACTER A*80, SPACE*80, B*160, X*1
      SAVE SPACE
      DATA SPACE /'
     .                                '/
 10   FORMAT (2A)
C
C---- START EXECUTION
C
      JUMP=.FALSE.
 100  CONTINUE
          READ (UN,10,END=999) A
          I=0
          B=A(2:80)//SPACE
          N=INDEX(B,SPACE)
 200      CONTINUE
              I=I+1
              X=B(I:I)
          IF (X.EQ.' '.AND.I.LT.N) GOTO 200
          IF (X.GE.'0'.AND.X.LE.'9'.OR.X.EQ.'.'
     .        .OR.X.EQ.'+') THEN
              BACKSPACE UN
              GOTO 999
          ENDIF
          JUMP=.TRUE.
      GOTO 100
 999  CONTINUE
      END

C---------------------------------------------------------------------
```

```
      SUBROUTINE DSPLAY (TX,N,NR)
      CHARACTER*(*) TX(30)
      INTEGER N,NR,I
 5030 FORMAT (1X,79('-'),/1X,A)
C
      DO 100 I=1,N
          PRINT *,TX(I)
  100 CONTINUE
      PRINT 5030,'WRITE LINE NUMBER:'
      PRINT *
      READ *,NR
      END

C-------------------------------------------------------------------------

      SUBROUTINE REPORT(I)
      INTEGER I
      IF (MOD(I,10).EQ.0) THEN
          PRINT 3000,'PROCESSING LINE',I
      ENDIF
 3000 FORMAT ('+',A,I4)
      END

C-------------------------------------------------------------------------

      SUBROUTINE PND(TAB,J,NL)
      REAL TAB(6,0:900,16), QO, PR, PWF
      INTEGER I, J, NL
      DO 100 I=1,NL
          QO=TAB(J,I,12)
          PR=TAB(J,I,5)
          PWF=TAB(J,I,6)
          TAB(J,I,16)=QO/(PR*PR-PWF*PWF)*1E6
  100 CONTINUE
      END
```

Text file necessary to run PLOT-GMS.

```
1.  FIG ...:   TIME, YEARS                                    *.
2.  FIG ...:   FIELD CUMULATIVE GAS PRODUCTION VS. TIME       *.
3.  FIG ...:   FIELD CUMULATIVE OIL PRODUCTION VS. TIME       *.
4.  FIG ...:   FIELD CUMULATIVE GAS/OIL RATIO VS. TIME        *.
5.  FIG ...:   AVERAGE RESERVOIR PRESSURE VS. TIME            *.
6.  FIG ...:   BOTTOMHOLE PRESSURE VS. TIME                   *.
7.  FIG ...:   WELLHEAD PRESSURE VS. TIME                     *.
8.  FIG ...:   PRODUCING GAS/OIL RATIO VS. TIME               *.
```

```
9.  FIG ...:   NUMBER OF WELLS VS. TIME                          *.
10. FIG ...:   GAS PRODUCTION RATE PER WELL VS. TIME             *.
11. FIG ...:   GAS PRODUCTION RATE PER FIELD VS. TIME            *.
12. FIG ...:   OIL PRODUCTION RATE PER WELL VS. TIME             *.
13. FIG ...:   OIL PRODUCTION RATE PER FIELD VS. TIME            *.
14. FIG ...:   AV. RESERVOIR PRESSURE VS. CUM. OIL PRODUCTION    *.
15. FIG ...:   PRODUCING GAS/OIL RATIO VS. CUM. OIL PRODUCTION   *.
16. FIG ...:   QO/(PR2-PWF2) VS. TIME                            *.
17. FIG ...:   QO/(PR2-PWF2) VS. CUM. OIL PRODUCTION             *.
0
1.                      TEST CASE                                *.
0
1.                         GMS                                   *.
2.                                                               *.
0
1.  TIME, YEARS*.
2.  FIELD CUMULATIVE GAS PRODUCTION, 1E+6 SM3*.
3.  FIELD CUMULATIVE OIL PRODUCTION, 1E+3 SM3*.
4.  FIELD CUMULATIVE GAS/OIL RATIO, 1E+3 SM3/SM3*.
5.  AVERAGE RESERVOIR PRESSURE, KPA*.
6.  BOTTOMHOLE PRESSURE, KPA*.
7.  WELLHEAD PRESSURE, KPA*.
8.  PRODUCING GAS/OIL RATIO, 1E+3 SM3/SM3*.
9.  NUMBER OF WELLS*.
10. GAS PRODUCTION RATE PER WELL, 1E+3 SM3/D*.
11. GAS PRODUCTION RATE PER FIELD, 1E+3 SM3/D*.
12. OIL PRODUCTION RATE PER WELL, SM3/D*.
13. OIL PRODUCTION RATE PER FIELD, SM3/D*.
14.
15.
16. QO/(PR2-PWF2) 1E-6 SM3/D/KPA2*.
0
```

Appendix B

INPUT AND OUTPUT DATA

B.0 Introduction

The GMS program, which is described in the main part of the report, was run with various input data sets. The entire BASE data set (a volatile oil fluid system) and parts of a gas-condensate data set (PVT data) are presented in this appendix. (The data sets can be found on the diskette, see Section 5.3.) The BASE data set is also given in a form as required by ECLIPSE. (ECLIPSE is a commercial, three-dimensional, fully implicit reservoir simulator.) Finally, a sample output from GMS is shown.

B.1 GMS BASE Case Input Data

The PVT data for the BASE data set (a volatile oil) are plotted in Figs. B.1a - B.1k. Note that the solution gas/oil ratio and the formation volume factors for oil and gas from the conventional formulation (CONV) are included in Figs. B.1a - B.1c. The bubblepoint or dewpoint pressure is indicated with a dotted line in the figures. Relative permeability data are given by Figs. B.1l - B.1m. Table B.1 lists the BASE case data set for the GMS model.

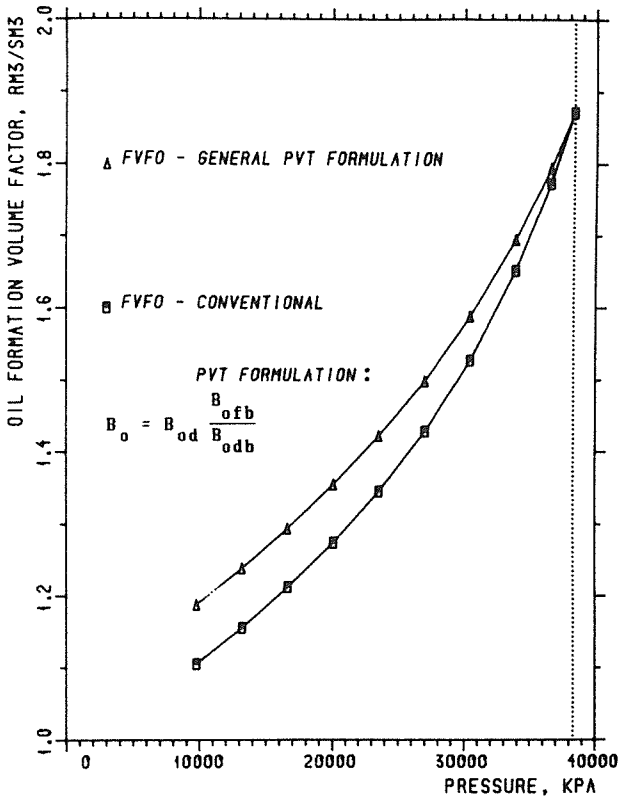


Fig. B.1a - Oil formation volume factor for the oil data set, for the general and the conventional PVT formulation.

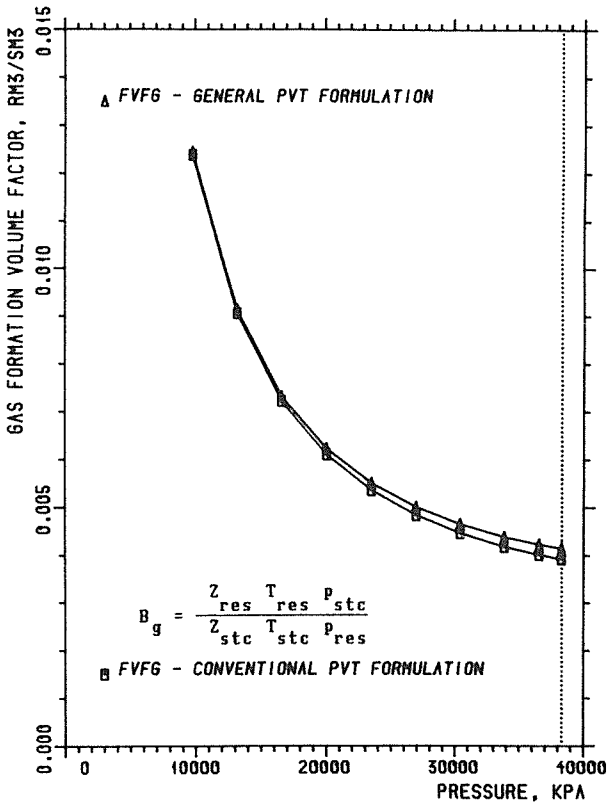


Fig. B.1b - Gas formation volume factor for the oil data set, for the general and the conventional PVT formulation.

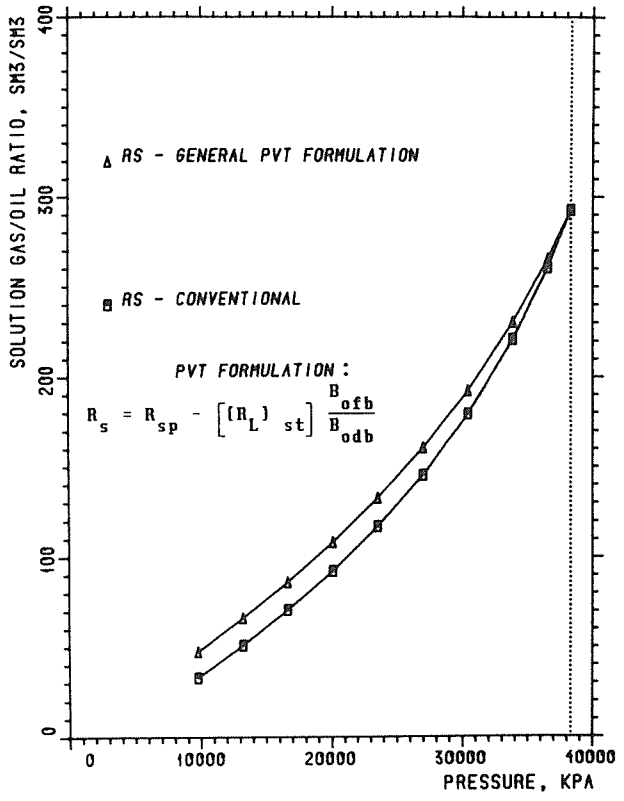


Fig. B.1c - Solution gas/oil ratio in oil for the oil data set, for the general and the conventional PVT formulation.

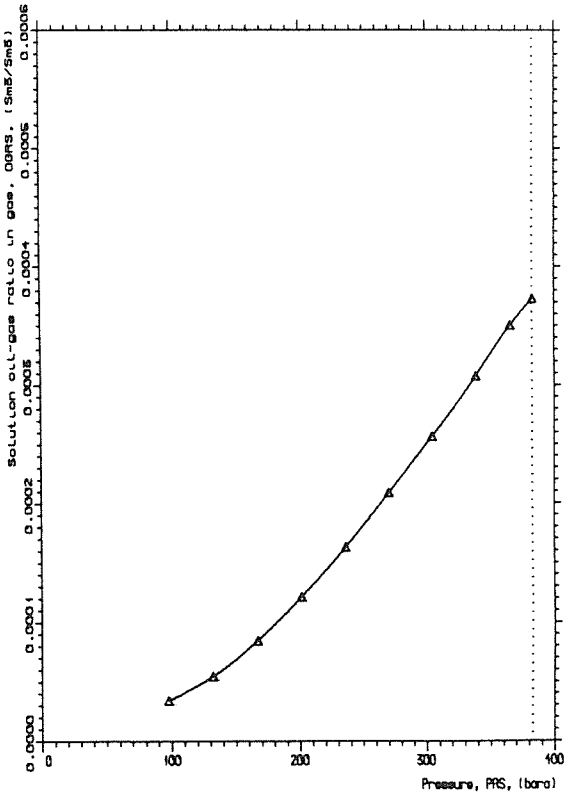


Fig. B.1d - Solution oil/gas ratio in gas for the oil data set (general PVT formulation).

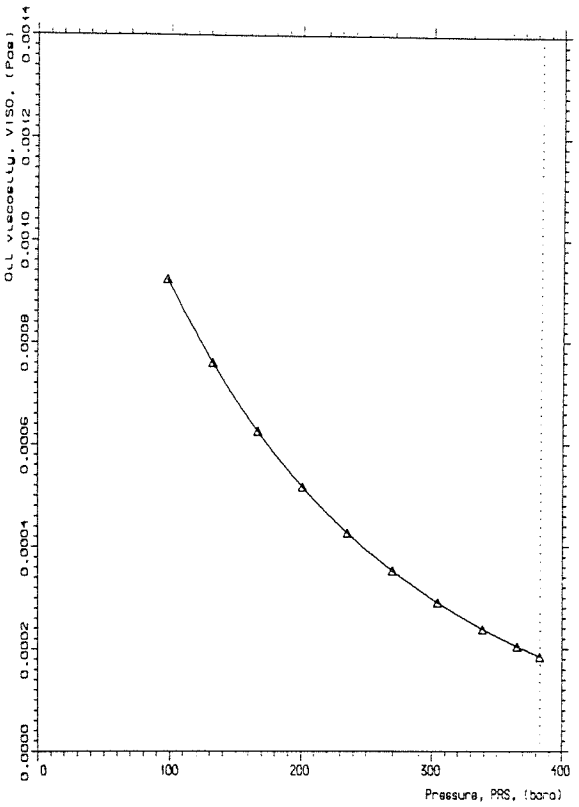


Fig. B.1e - Oil viscosity for the oil data set (general PVT formulation).

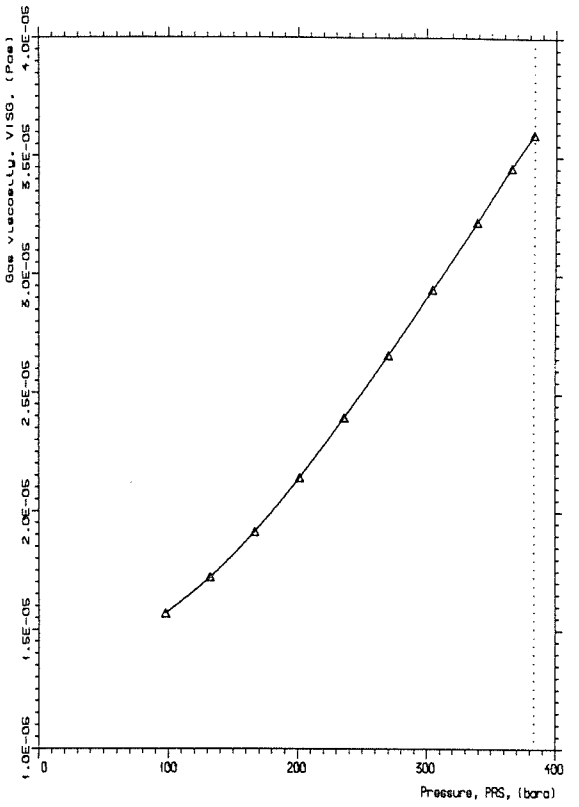


Fig. B.1f - Gas viscosity for the oil data set (general PVT formulation).

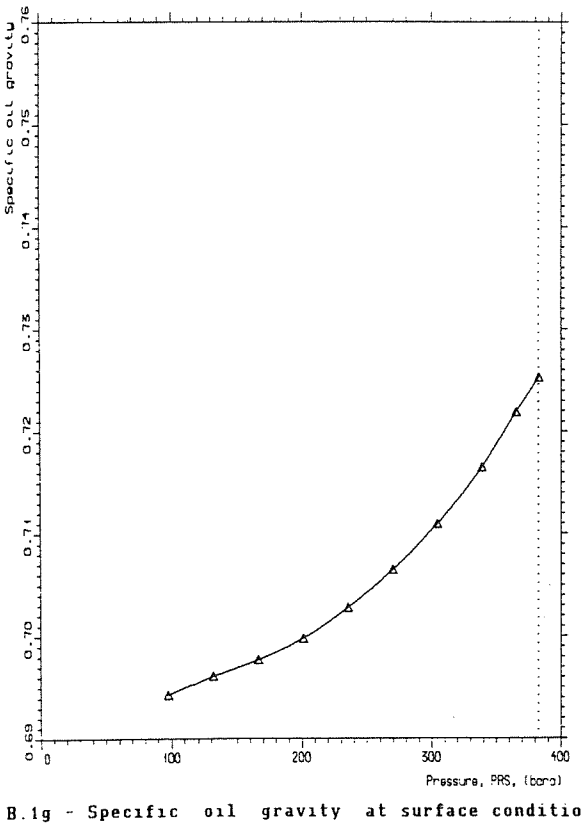


Fig. B.1g - Specific oil gravity at surface conditions for oil evolved from free reservoir gas, for the oil data set (general PVT formulation).

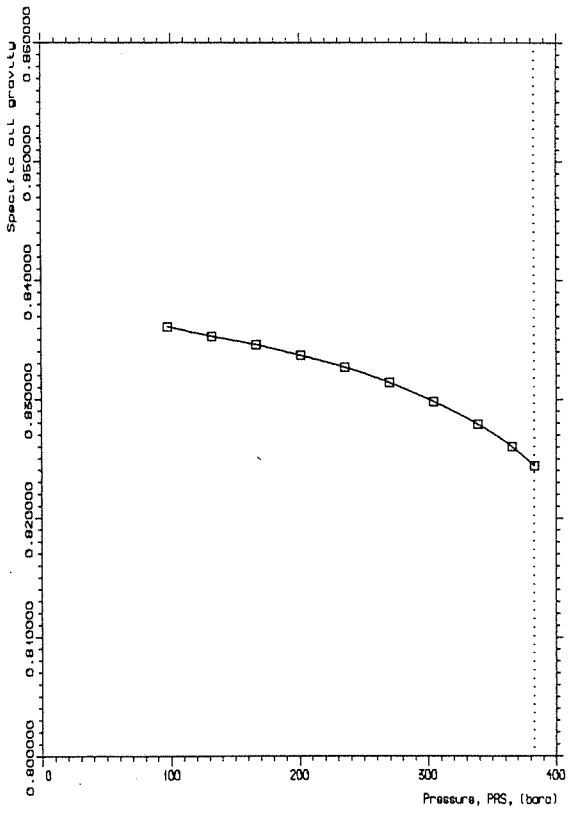


Fig. B.1h - Specific oil gravity at surface conditions for oil evolved from free reservoir oil, for the oil data set (general PVT formulation).

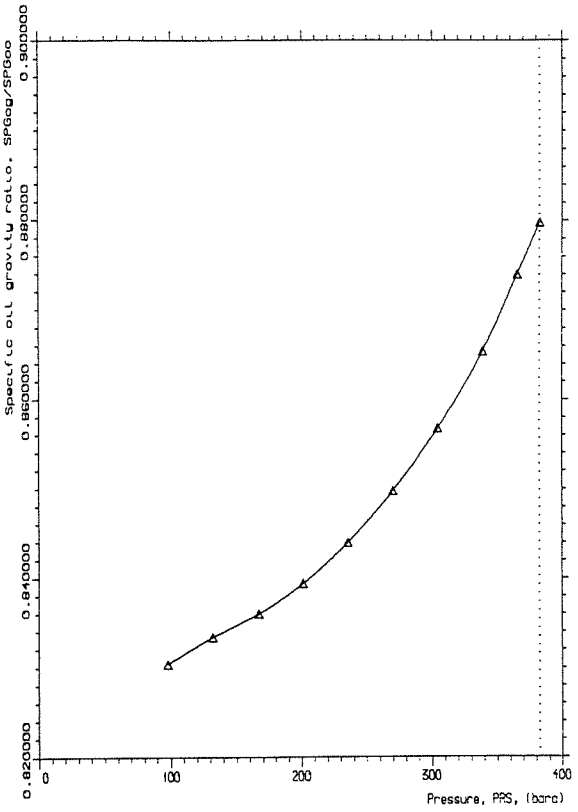


Fig. B.1i - Specific oil gravity ratio, "oil from gas" divided by "oil from oil" (see Fig. B.1g and Fig B.1h).

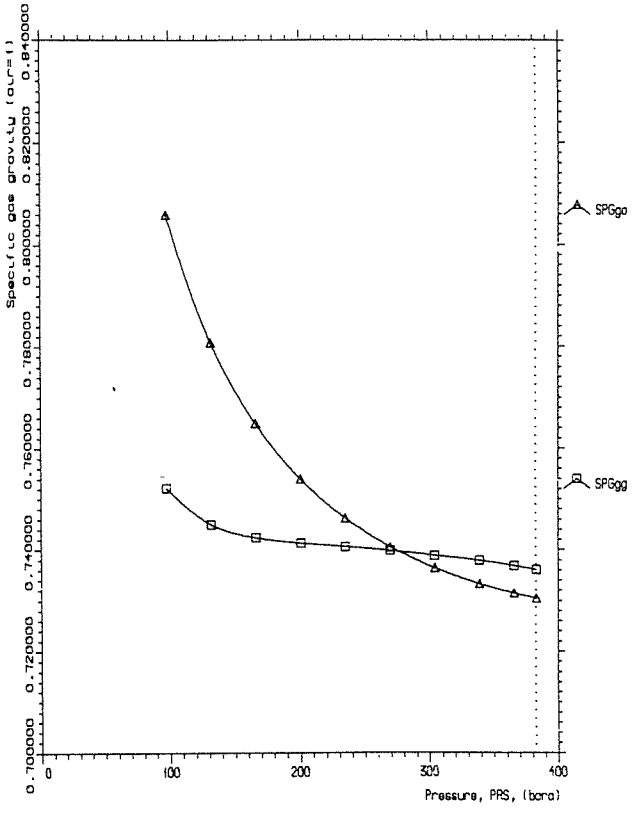


Fig. B.1j - Specific gas gravity at surface conditions for gas evolved from free reservoir oil, and gas evolved from free reservoir gas, for the oil data set (general PVT formulation).

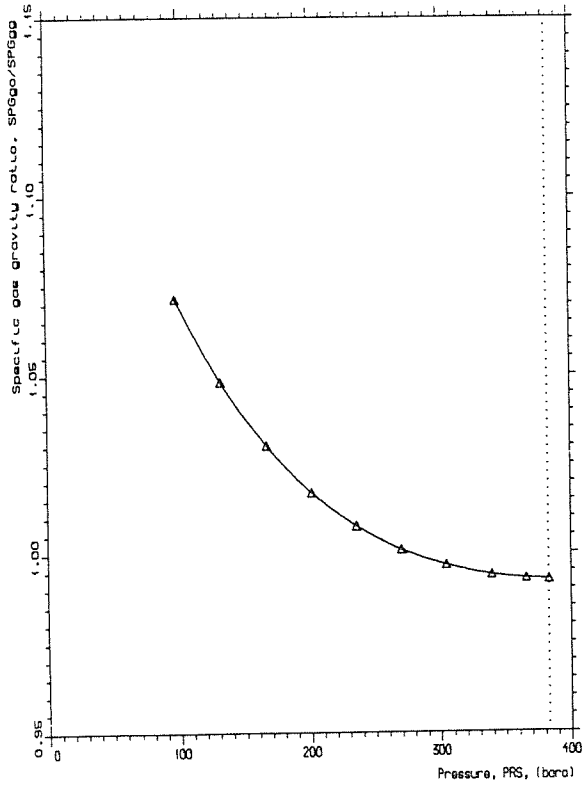


Fig. B.1k - Specific gas gravity ratio, "gas from oil" divided by "gas from gas" (see Fig. B.1j).

Note that the dotted lines indicate the bubblepoint pressure in Figs. B.1a - k and the dewpoint pressure in Figs. B.2a - l.

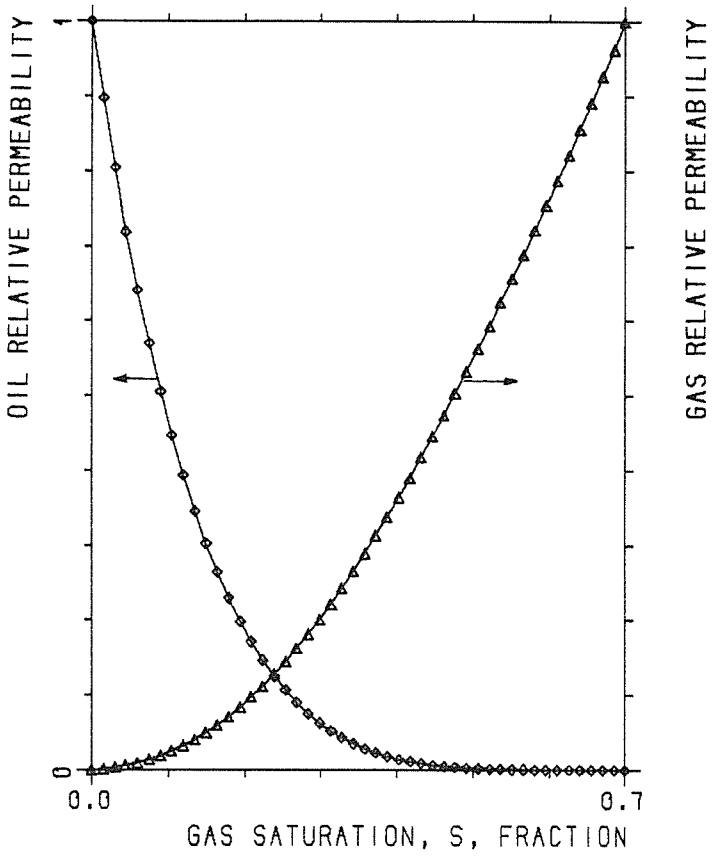


Fig. B.11 - Relative permeabilities to gas and oil vs. gas saturation - used for all the simulation runs.

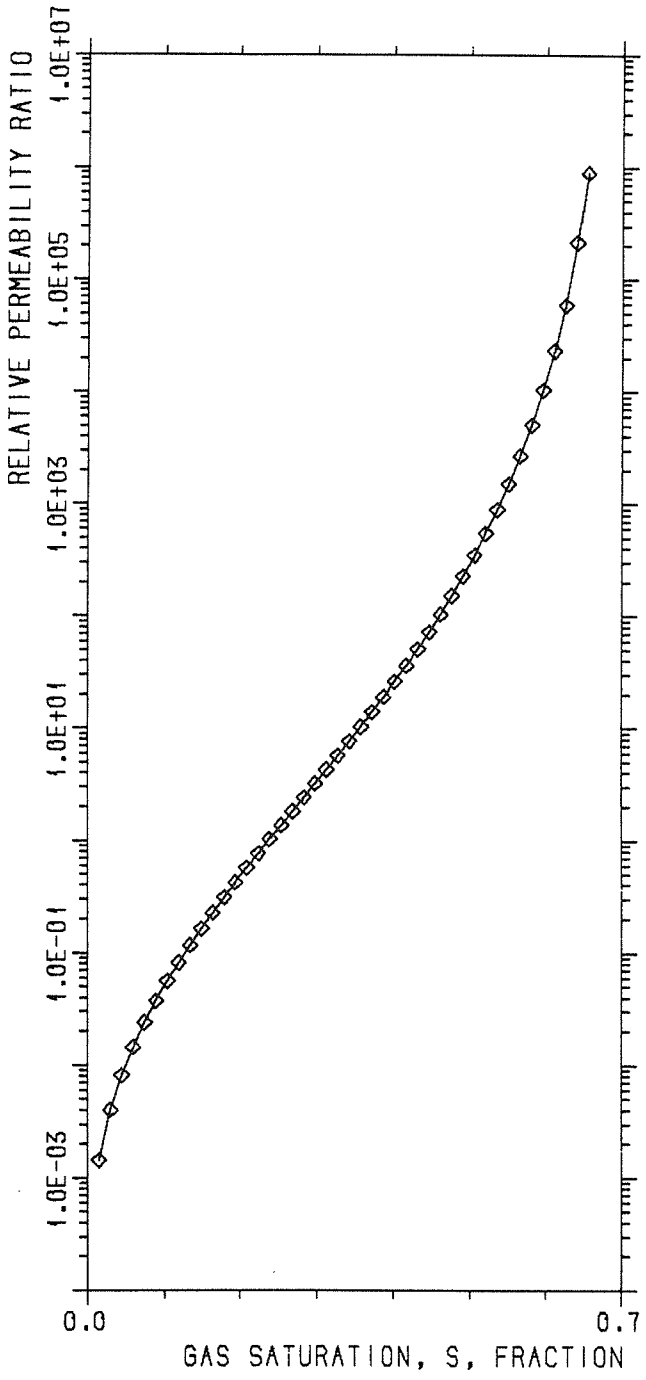


Fig. B.1m - Relative permeability ratio (gas / oil) vs. gas saturation (see Fig. B.1l) - used for all the simulation runs.

TABLE B.1 - BASE CASE DATA SET FOR GMS

BASE CASE - A volatile oil

IHC	IUNIN	IPRT	IEXE
1	0	1	2

DELTIM	XMXTIM	HCPV	PORI	SATWI	CMPF
0.04166667	25.	9.0E7	0.40	0.30	0.0

PRM	THK	RADW	DSKN	DPINT	TF
14E-3	50.0	0.20	0.0	1500.	0.0

TTIM	NWELLS	TRTEFM	TRTEFT	TPWMIN	TSKN
0.0	1	12.	1200.1	10000.	0.0

-1

TPRS	TVISO	TGORS	TDENRO	TFVFO
9754.	.0009244	47.5	1.0	1.188
13201.	.0007611	66.0	1.0	1.239
16649.	.0006274	85.9	1.0	1.294
20096.	.0005181	107.8	1.0	1.355
23544.	.0004280	132.2	1.0	1.422
26991.	.0003535	159.9	1.0	1.499
30438.	.0002914	192.0	1.0	1.589
33886.	.0002394	230.2	1.0	1.696
36540.	.0002051	265.5	1.0	1.795
38291.	.0001846	292.6	1.0	1.872

-1

TVISG	TOGRS	TDENRG	TFVFG
.00001569	.0000340	1.0	.012463
.00001721	.0000545	1.0	.009145
.00001914	.0000844	1.0	.007327
.00002142	.0001214	1.0	.006221
.00002395	.0001634	1.0	.005498
.00002662	.0002087	1.0	.005001
.00002939	.0002565	1.0	.004644
.00003225	.0003073	1.0	.004382
.00003456	.0003503	1.0	.004226
.00003596	.0003729	1.0	.004139

-1

TSATG	TPRMRO	TPRMRG
.00000	1.000000	.000000
.01489	.898049	.001289
.02979	.804587	.003219
.04468	.719074	.005872
.05957	.640992	.009319
.07447	.569845	.013622
.08936	.505160	.018835
.10426	.446488	.025004
.11915	.393399	.032167
.13404	.345484	.040353
.14894	.302356	.049587
.16383	.263646	.059886
.17872	.229007	.071258
.19362	.198109	.083710

.20851	.170639	.097241
.22340	.146305	.111844
.23830	.124829	.127510
.25319	.105953	.144225
.26809	.089433	.161968
.28298	.075041	.180720
.29787	.062565	.200455
.31277	.051806	.221146
.32766	.042580	.242763
.34255	.034719	.265274
.35745	.028064	.288648
.37234	.022471	.312850
.38723	.017808	.337846
.40213	.013953	.363601
.41702	.010796	.390080
.43191	.008239	.417250
.44681	.006191	.445079
.46170	.004572	.473534
.47660	.003311	.502586
.49149	.002345	.532208
.50638	.001619	.562374
.52128	.001085	.593063
.53617	.000702	.624256
.55106	.000436	.655940
.56596	.0002574	.688102
.58085	.0001429	.720738
.59574	.7326E-4	.753846
.61064	.3391E-4	.787432
.62553	.1363E-4	.821504
.64043	.4466E-5	.856081
.65532	.1060E-5	.891185
.67021	.1395E-6	.926847
.68511	.4360E-8	.963103
.70000	.1000E-9	1.000000

-1

B.2 ECLIPSE BASE Case Input Data

Table B.2 presents the BASE data set as required by ECLIPSE. The keywords appearing in this data file are explained in the ECLIPSE Reference Manual*

* The ECLIPSE Reference Manual is supplied by Exploration Consultants Limited, Highlands Farm, Greys Road, Henley-on-Thames, Oxon RG9 4PS England.

TABLE B.2 - ECLIPSE BASE CASE INPUT DATA

```
RUNSPEC
ECLIPSE BASE CASE
= NDIVIX NDIVIY NDIVIZ QRDIAL NUMRES QNNCON MXNAQN MXNAQC QDPORO QDPERM
    20      1       1       T       1       F       0       0       F       F /
= OIL WAT GAS DISGAS VAPOIL QAPITR QWATTR QGASTR NOTRAC NWTRAC NGTRAC
   T   T   T     T       T       F       F       F       0       0       0   /
= UNIT CONVENTION
     'METRIC'                                          /
=  NRPVT  NPPVT  NTPVT NTROCC QROCKC QRCREV
    20      20      1       1       F       T       /
= NSSFUN NTSFUN QDIRKR QREVKR QVEOP QHYST QSCAL QSDIR QSREV NSEND NTEND
    50      1       F       T       F       F       F       F       T       1       1 /
= NDRXVD NTEQUL NDPRVD QUIESC QTHPRS QREVTH QMOBIL NTTRVD NSTRVD
    20      1     100       F       F       T       F       1       1         /
=  NTFIP QGRAID  QPAIR QTDISP
     1      F       F       F                         /
= NWMAXZ NCWMAX NGMAXZ NWGMAX
    10      1       1      10                         /
= QIMCOL NWCOLC NUPCOL
     F      0       5                                 /
= MXMFLO MXMTHP MXMWFR MXMGFR MXMALQ NMMVFT
     0      0       0       0       0       0       /
= MXSFLO MXSTHP NMSVFT MXCFLO MXCWOC MXCGOC NCRTAB
     0      0       0       0       0       0       0       /
= NAQFET NCAMAX
     0      0                                         /
=   DAY   MONTH  YEAR
     1    'JAN'  1986                                /
= QSOLVE NSTACK QFMTOU QFMTIN QUNOUT QUNINP
     T     10      F       F       T       T       /

GRID
NOGGF
RPTGRID
   0   /

INRAD
```

```
 0.20   /
OUTRAD
 1430.5 /
DTHETAV
 360.   /
DZ
 20*50. /
TOPS
 20*0.  /
OLDTRAN
PERMR
 20*14.1855 /
PERMTHT
 20*0.      /
PERMZ
 20*0.      /
PORO
 20*0.40    /

PROPS
RPTPROPS
   0   /
DENSITY
 0.8  1.0  0.07 /
PVTG
--    Pg          Rv            Bg          ug
      97.54     .0000340     .012463       .01569  /
     132.01     .0000545     .009145       .01721  /
     166.49     .0000844     .007327       .01914  /
     200.96     .0001214     .006221       .02142  /
     235.44     .0001634     .005498       .02395  /
     269.91     .0002087     .005001       .02662  /
     304.38     .0002565     .004644       .02939  /
     338.86     .0003073     .004382       .03225  /
     365.40     .0003503     .004226       .03456  /
     382.91     .0003729     .004139       .03596
                .0000000     .004139       .03596  /
/
PVTO
--  Rs           Po        Bo         uo
     47.5       97.54     1.188      .9244  /
     66.0      132.01     1.239      .7611  /
     85.9      166.49     1.294      .6274  /
    107.8      200.96     1.355      .5181  /
    132.2      235.44     1.422      .4280  /
    159.9      269.91     1.499      .3535  /
    192.0      304.38     1.589      .2914  /
    230.2      338.86     1.696      .2394  /
    265.5      365.40     1.795      .2051  /
    292.6      382.91     1.872      .1846
               400.00     1.871      .1846  /
/
PVTW
 1  1  0  .5  0  /
ROCK
 1  0  /
SGFN
```

```
--      Sg       krg     Pc g-l
     .00000   .000000      0
     .01489   .001289      0
     .02979   .003219      0
     .04468   .005872      0
     .05957   .009319      0
     .07447   .013622      0
     .08936   .018835      0
     .10426   .025004      0
     .11915   .032167      0
     .13404   .040353      0
     .14894   .049587      0
     .16383   .059886      0
     .17872   .071258      0
     .19362   .083710      0
     .20851   .097241      0
     .22340   .111844      0
     .23830   .127510      0
     .25319   .144225      0
     .26809   .161968      0
     .28298   .180720      0
     .29787   .200455      0
     .31277   .221146      0
     .32766   .242763      0
     .34255   .265274      0
     .35745   .288648      0
     .37234   .312850      0
     .38723   .337846      0
     .40213   .363601      0
     .41702   .390080      0
     .43191   .417250      0
     .44681   .445079      0
     .46170   .473534      0
     .47660   .502586      0
     .49149   .532208      0
     .50638   .562374      0
     .52128   .593063      0
     .53617   .624256      0
     .55106   .655940      0
     .56596   .688102      0
     .58085   .720738      0
     .59574   .753846      0
     .61064   .787432      0
     .62553   .821504      0
     .64043   .856081      0
     .65532   .891185      0
     .67021   .926847      0
     .68511   .963103      0
     .70000  1.000000      0
/
SOF3
--       So          kro           kro
--                   o-w           o-g-cw
    0.00000        .1000E-9      .1000E-9
    0.01489        .4360E-8      .4360E-8
    0.02979        .1395E-6      .1395E-6
    0.04468        .1060E-5      .1060E-5
```

```
   0.05957        .4466E-5        .4466E-5
   0.07447        .1363E-4        .1363E-4
   0.08936        .3391E-4        .3391E-4
   0.10426        .7326E-4        .7326E-4
   0.11915        .0001429        .0001429
   0.13404        .0002574        .0002574
   0.14894         .000436         .000436
   0.16383         .000702         .000702
   0.17872         .001085         .001085
   0.19362         .001619         .001619
   0.20851         .002345         .002345
   0.22340         .003311         .003311
   0.23830         .004572         .004572
   0.25319         .006191         .006191
   0.26809         .008239         .008239
   0.28298         .010796         .010796
   0.29787         .013953         .013953
   0.31277         .017808         .017808
   0.32766         .022471         .022471
   0.34255         .028064         .028064
   0.35745         .034719         .034719
   0.37234         .042580         .042580
   0.38723         .051806         .051806
   0.40213         .062565         .062565
   0.41702         .075041         .075041
   0.43191         .089433         .089433
   0.44681         .105953         .105953
   0.46170         .124829         .124829
   0.47660         .146305         .146305
   0.49149         .170639         .170639
   0.50638         .198109         .198109
   0.52128         .229007         .229007
   0.53617         .263646         .263646
   0.55106         .302356         .302356
   0.56596         .345484         .345484
   0.58085         .393399         .393399
   0.59574         .446488         .446488
   0.61064         .505160         .505160
   0.62553         .569845         .569845
   0.64043         .640992         .640992
   0.65532         .719074         .719074
   0.67021         .804587         .804587
   0.68511         .898049         .898049
   0.70000        1.000000        1.000000
/
SWFN
--   Sw    krw    Pc w-o
 .3     0           0
 1      1           0
/

SOLUTION
RPTSOL
   0   /
SWAT
 20*0.30   /
SGAS
```

```
 20*0.      /
VAPPARS
 0.   0. /
PRESSURE
 20*382.91 /
RS
 20*292.6  /
RV
 20*.0003729  /

SUMMARY
RPTSMRY
 1 /
RUNSUM
FGPT
FOPT
FGOR
FPR
WBHP
 'GMS1'
/
WGPR
 'GMS1'
/
FGPR
WOPR
 'GMS1'
/
FOPR

SCHEDULE
TUNING
 1  15.2083333333 /
 /
 /
RPTSCHED
   0   /
WELSPECS
'GMS1     ','G1       ',  1,  1,  1*   ,'OIL'
   .0000,'NO ','SHUT','NO ',1* ,'AVG',   /
/
COMPDAT
'GMS*     '  2*  1   1 'OPEN'  2*    .2000  /
/
WCONPROD
'GMS*     ','OPEN','BHP '   5*   100.0000   /
/
GCONPROD
'G1       ','ORAT' 1200.1    3*   'RATE'  'YES'  /
/
GECON
'FIELD    ' 12.0    4*   'NONE','YES' /
/
TSTEP
  7201
/
END
```

B.3 Gas-Condensate PVT Data

A gas-condensate composition of unknown origin was differentially liberated and flashed by the CVD program (see Section 7.3). The resulting black-oil parameters are plotted in Figs. B.2a - B.2l and presented as tables in the gas-condensate data file on the diskette (see Section 5.3).

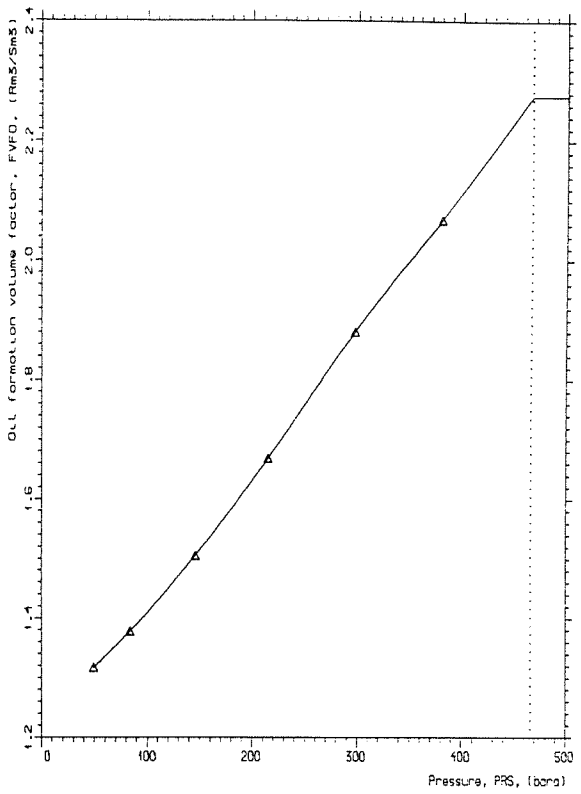


Fig. B.2a - Oil formation volume factor for the gas-condensate data set (general PVT formulation).

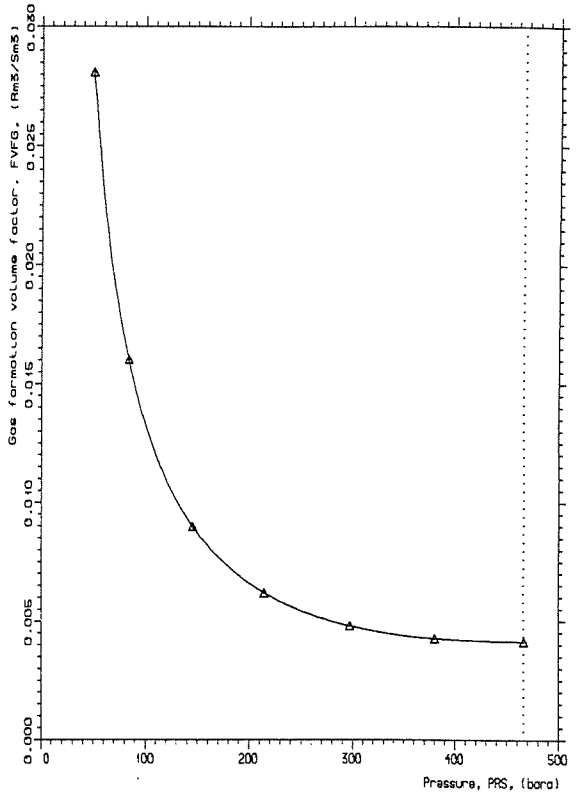


Fig. B.2b - Gas formation volume factor for the gas-condensate data set (general PVT formulation).

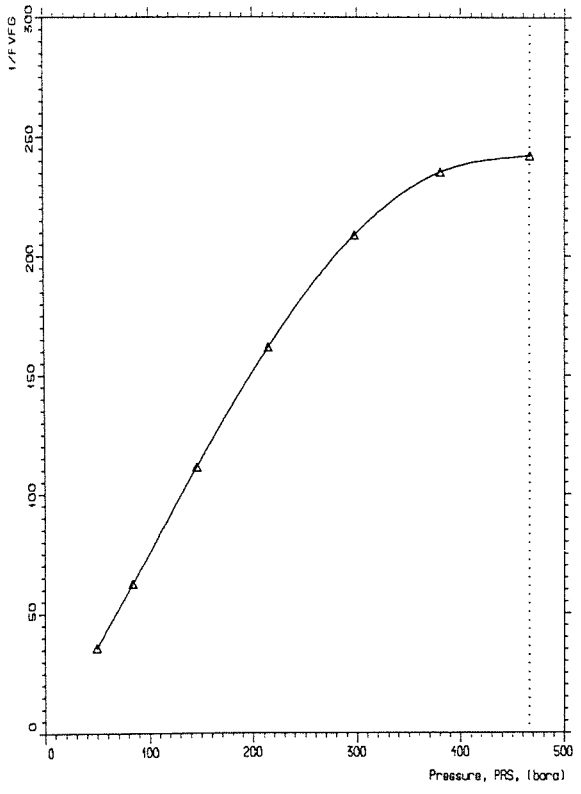


Fig. B.2c - Inverse of the gas formation volume factor for the gas-condensate data set (general PVT formulation).

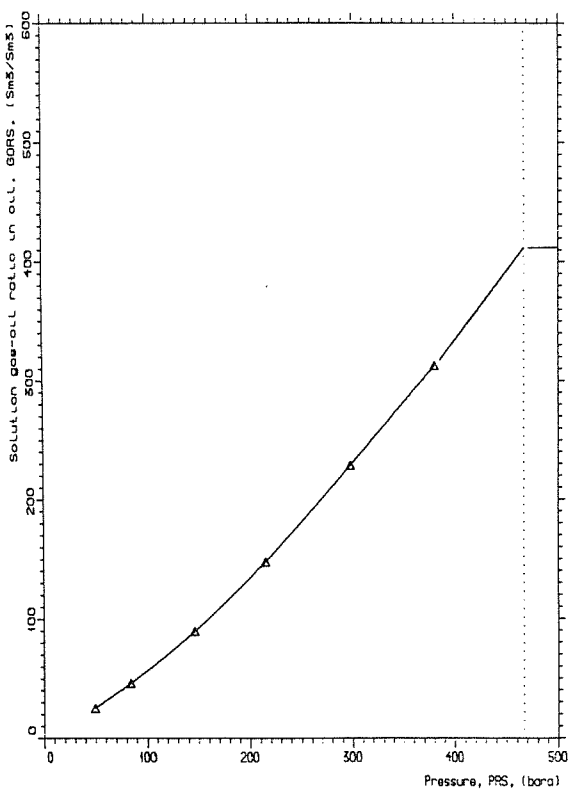


Fig. B.2d - Solution gas/oil ratio in oil for the gas-condensate data set (general PVT formulation).

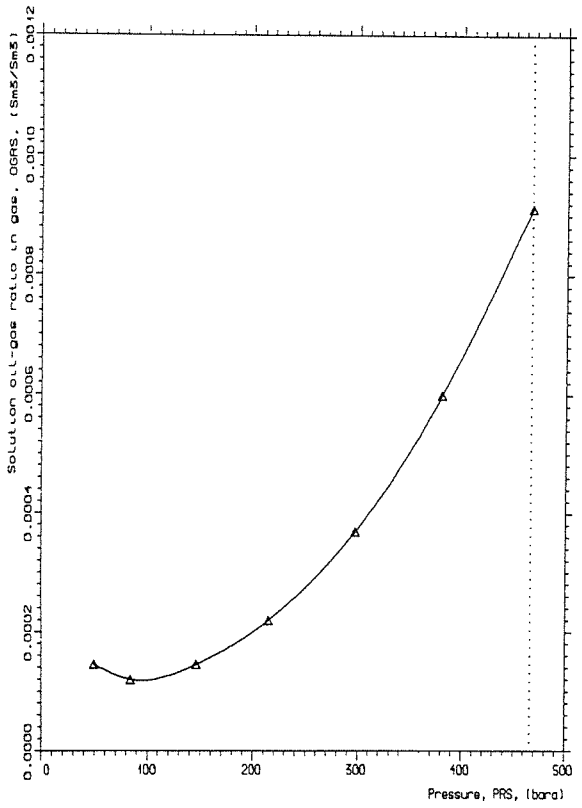


Fig. B.2e - Solution oil/gas ratio in gas for the gas-condensate data set (general PVT formulation).

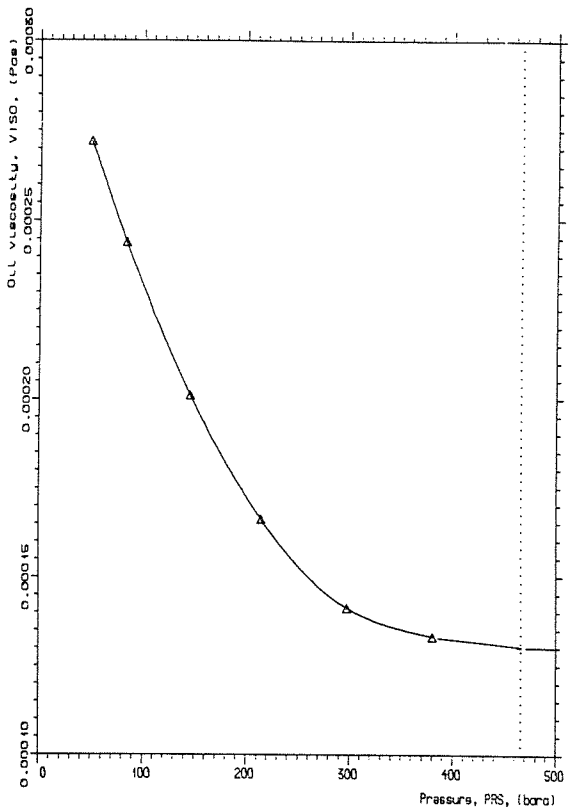


Fig. B.2f - Oil viscosity for the gas-condensate data set (general PVT formulation).

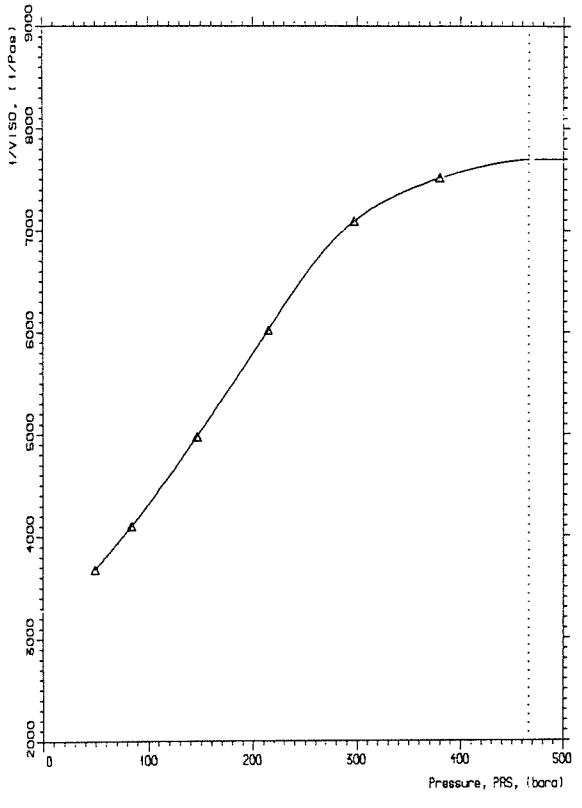


Fig. B.2g - Inverse of the oil viscosity for the gas-condensate data set (general PVT formulation).

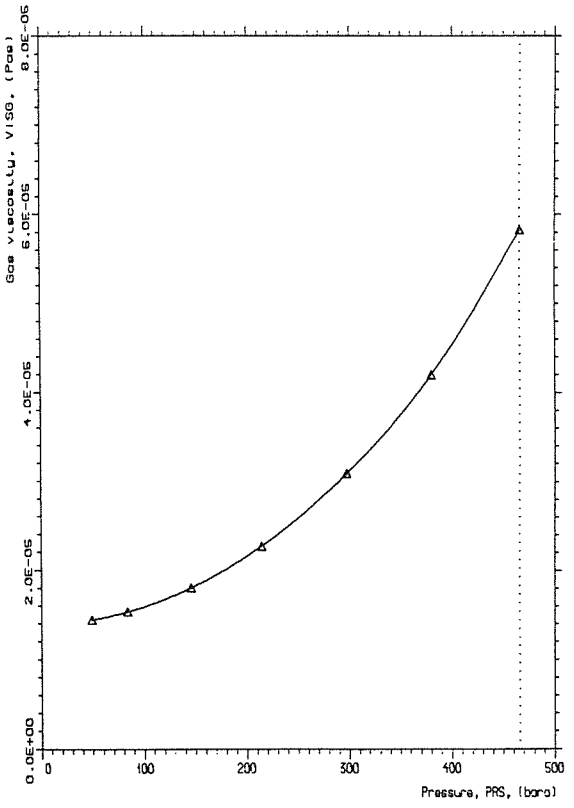


Fig. B.2h - Gas viscosity for the gas-condensate data set (general PVT formulation).

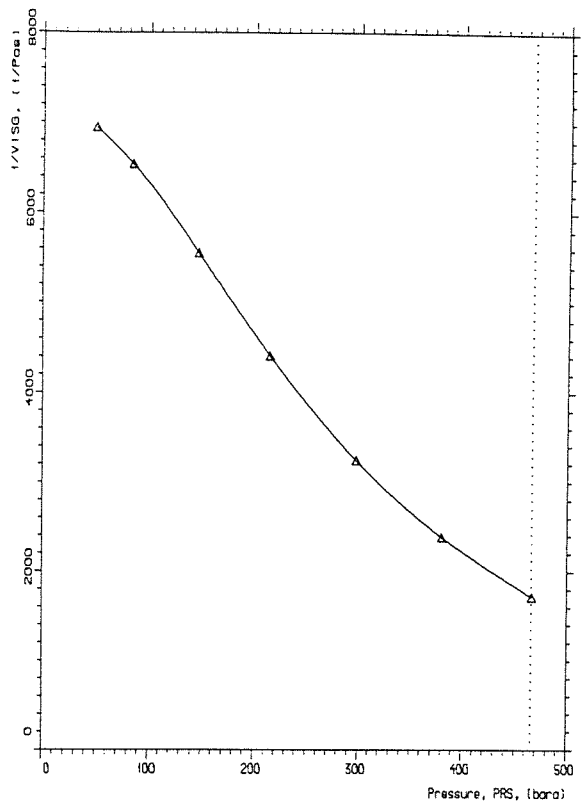


Fig. B.2i - Inverse of the gas viscosity for the gas-condensate data set (general PVT formulation).

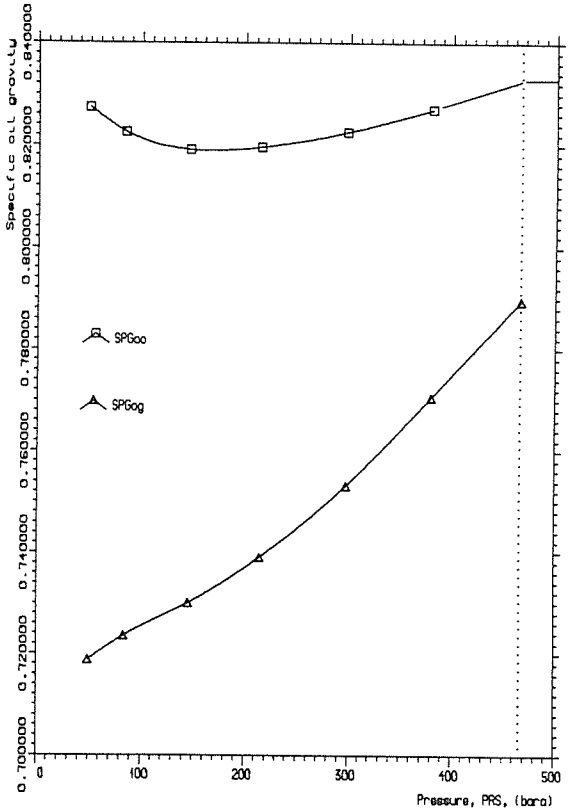


Fig. B.2j - Specific oil gravity at surface conditions for oil evolved from free reservoir gas (SPGog), and oil evolved from free reservoir oil (SGPoo), for the gas-condensate data set (general PVT formulation).

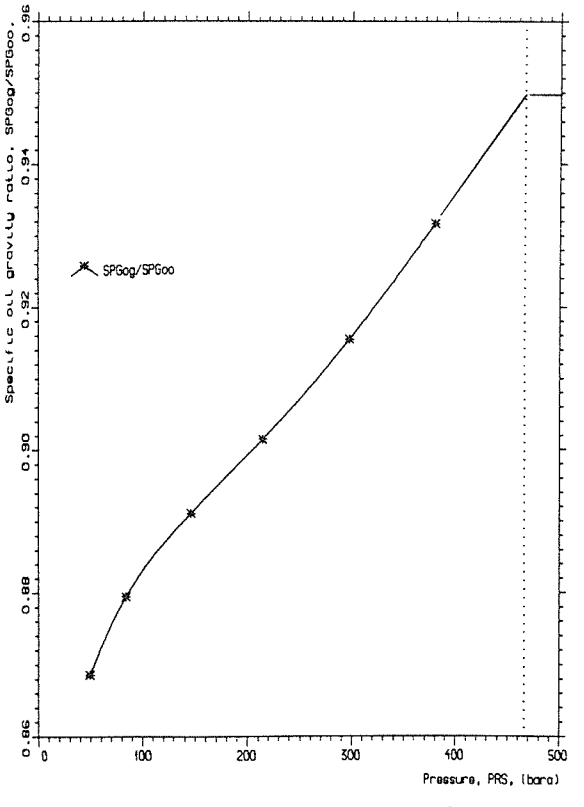


Fig. B.2k - Specific oil gravity ratio, 'oil from gas' divided by 'oil from oil' (see Fig. B.2j).

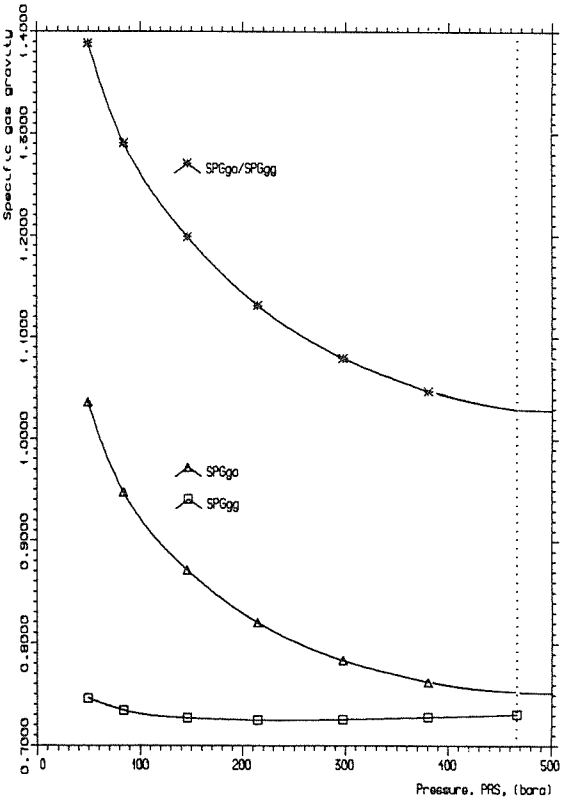


Fig. B.2l - Specific gas gravity at surface conditions for gas evolved from free reservoir oil (SPGgo), and gas evolved from free reservoir gas (SPGgg), and the ratio of these, for the gas-condensate data set (general PVT formulation).

B.4 DEMO Case Output from GMS

The DEMO case described in Section 7.4 is printed below. (Longer timesteps have been used here to reduce the printout.)

```
*****************************************************************
*****************************************************************
**                                                             **
**                                                             **
**          ********       **          *       ********        **
**         **       **      **         **      **       **      **
**         **               ***       * *      **               **
**         **               ** *    *   *       ********        **
**         **    *****      **   * *    *               **      **
**         **        *      **    *     *      **       **      **
**          *********       **          *       ********        **
**                                                             **
**                                                             **
**** A GENERAL MATERIAL-BALANCE AND INFLOW-PERFORMANCE *****
** SIMULATION MODEL FOR OIL AND GAS-CONDENSATE RESERVOIRS **
****************** AUTHOR: GUNNAR BORTHNE *********************
```

REVIEW OF INPUT DATA

JOB IDENTIFICATION : DEMO CASE - A volatile oil

```
IHC    : HYDROCARBON TYPE .....:     1
         = 0 : GAS CONDENSATE
         = 1 : OIL
IUNIN  : UNITS IDENTIFIER FOR INPUT DATA .....:     0
         = 0 : METRIC UNITS
         = 1 : OIL FIELD UNITS
IPRT   : PRINT OPTION .....:     2
         = 0 : TABLES OF RESULTS ONLY
         = 1 : + ECHO OF INPUT DATA
         = 2 : + ITERATION REPORT
         = 3 : + RESULTS PRINTED TO THE SCREEN EACH TIMESTEP
         = 4 : + A MESSAGE FROM EACH ROUTINE
IEXE   : EXECUTION MODE .....:     2
         = 0 : MATERIAL BALANCE ONLY
         = 1 : MATERIAL BALANCE AND IPR
         = 2 : MATERIAL BALANCE, IPR AND TUBING
NWT    : NUMBER OF WELL CONTROL SPECIFICATIONS ..:     5
NPVT   : NUMBER OF PVT DATA INPUT LINES .....:    10
NRP    : NUMBER OF REL. PERM. DATA INPUT LINES ..:    48
DELTIM : TIMESTEP LENGTH (YEARS) .....:   .50000
XMXTIM : LENGTH OF SIMULATION (YEARS) .....:  20.000
HCPV   : HYDROCARBON PORE VOLUME (M3) .....:   .30000E+08
                                 (BBL) .....:   .18869E+09
PORI   : INITIAL POROSITY (FRACTION) .....:   .25000
SATWI  : INITIAL WATER SATURATION (FRACTION) ....:   .30000
CMPF   : FORMATION COMPRESSIBILITY (1/KPA) .....:   .60000E-06
                                   (1/PSI) .....:   .41369E-05
PRM    : PERMEABILITY (uM2) .....:   .50000E-02
                      (MD) .... .....:   5.0663
THK    : RESERVOIR THICKNESS (M) .....:   50.000
                             (FT) .....:   164.04
RADW   : WELLBORE RADIUS  (M) .....:   .10000
                          (FT) .....:   .32808
DSKN   : NON-DARCY FLOW COEFFICIENT (D/M3) .....:   .00000E+00
                                    (D/FT3) .....:   .00000E+00
                                    (D/BBL) .....:   .00000E+00
DPINT  : PRESSURE INCREMENT IN SIMPSON-
         INTEGRATION (KPA) .....:      1500.
                     (PSI) .....:       217.6
TF     : "TUBING FACTOR" (NO PHYSICAL MEANING,
         USED ONLY IN TEMPORARY TUBING ROUTINE) .:   12.000
```

JOB IDENTIFICATION : DEMO CASE - A volatile oil

PRESSURE-DEPENDENT PROPERTIES, OIL

	PRESSURE		OIL VISCOSITY		SOLUTION GAS/OIL RATIO		SPECIFIC GRAVITY	OIL FVF
NO.	KPA	PSIA	PAS	CP	SM3/SM3	SCF/BBL	RATIO,OIL	RES/STD VOL
1	9754.	1414.7	.92440E-03	.92440	47.500	266.69	1.0000	1.1880
2	13201.	1914.6	.76110E-03	.76110	66.000	370.56	1.0000	1.2390
3	16649.	2414.7	.62740E-03	.62740	85.900	482.29	1.0000	1.2940
4	20096.	2914.7	.51810E-03	.51810	107.80	605.25	1.0000	1.3550
5	23544.	3414.8	.42800E-03	.42800	132.20	742.25	1.0000	1.4220
6	26991.	3914.7	.35350E-03	.35350	159.90	897.77	1.0000	1.4990
7	30438.	4414.7	.29140E-03	.29140	192.00	1078.0	1.0000	1.5890
8	33886.	4914.7	.23940E-03	.23940	230.20	1292.5	1.0000	1.6960
9	36540.	5299.7	.20510E-03	.20510	265.50	1490.7	1.0000	1.7950
10	38291.	5553.6	.18460E-03	.18460	292.60	1642.8	1.0000	1.8720

JOB IDENTIFICATION : DEMO CASE - A volatile oil

PRESSURE-DEPENDENT PROPERTIES, GAS

	PRESSURE		GAS VICOSITY		SOLUTION OIL/GAS RATIO		SPECIFIC GRAVITY	GAS FVF
NO.	KPA	PSIA	PAS	CP	SM3/SM3	BBL/MMSCF	RATIO,GAS	RES/STD VOL
1	9754.	1414.7	.15690E-04	.15690E-01	.34000E-04	6.0557	1.0000	.12463E-01
2	13201.	1914.6	.17210E-04	.17210E-01	.54500E-04	9.7069	1.0000	.91450E-02
3	16649.	2414.7	.19140E-04	.19140E-01	.84400E-04	15.032	1.0000	.73270E-02
4	20096.	2914.7	.21420E-04	.21420E-01	.12140E-03	21.622	1.0000	.62210E-02
5	23544.	3414.8	.23950E-04	.23950E-01	.16340E-03	29.103	1.0000	.54980E-02
6	26991.	3914.7	.26620E-04	.26620E-01	.20870E-03	37.171	1.0000	.50010E-02
7	30438.	4414.7	.29390E-04	.29390E-01	.25650E-03	45.685	1.0000	.46440E-02
8	33886.	4914.7	.32250E-04	.32250E-01	.30730E-03	54.733	1.0000	.43820E-02
9	36540.	5299.7	.34560E-04	.34560E-01	.35030E-03	62.391	1.0000	.42260E-02
10	38291.	5553.6	.35960E-04	.35960E-01	.37290E-03	66.416	1.0000	.41390E-02

JOB IDENTIFICATION : DEMO CASE - A volatile oil

RELATIVE PERMEABILITIES AS FUNCTIONS OF GAS SATURATION

NO.	GAS SATURATION	OIL REL.PERM	GAS REL.PERM
1	.00000E+00	1.0000	.00000E+00
2	.14890E-01	.89805	.12890E-02
3	.29790E-01	.80459	.32190E-02
4	.44680E-01	.71907	.58720E-02
5	.59570E-01	.64099	.93190E-02
6	.74470E-01	.56984	.13622E-01
7	.89360E-01	.50516	.18835E-01
8	.10426	.44649	.25004E-01
9	.11915	.39340	.32167E-01
10	.13404	.34548	.40353E-01
11	.14894	.30236	.49587E-01
12	.16383	.26365	.59886E-01
13	.17872	.22901	.71258E-01
14	.19362	.19811	.83710E-01
15	.20851	.17064	.97241E-01
16	.22340	.14630	.11184
17	.23830	.12483	.12751
18	.25319	.10595	.14422
19	.26809	.89433E-01	.16197
20	.28298	.75041E-01	.18072
21	.29787	.62565E-01	.20045
22	.31277	.51806E-01	.22115
23	.32766	.42580E-01	.24276
24	.34255	.34719E-01	.26527
25	.35745	.28064E-01	.28865
26	.37234	.22471E-01	.31285
27	.38723	.17808E-01	.33785
28	.40213	.13953E-01	.36360
29	.41702	.10796E-01	.39008
30	.43191	.82390E-02	.41725
31	.44681	.61910E-02	.44508
32	.46170	.45720E-02	.47353
33	.47660	.33110E-02	.50259
34	.49149	.23450E-02	.53221
35	.50638	.16190E-02	.56237
36	.52128	.10850E-02	.59306
37	.53617	.70200E-03	.62426
38	.55106	.43600E-03	.65594
39	.56596	.25740E-03	.68810
40	.58085	.14290E-03	.72074
41	.59574	.73260E-04	.75385
42	.61064	.33910E-04	.78743
43	.62553	.13630E-04	.82150
44	.64043	.44660E-05	.85608
45	.65532	.10600E-05	.89118
46	.67021	.13950E-06	.92685
47	.68511	.43600E-08	.96310
48	.70000	.10000E-09	1.0000

JOB IDENTIFICATION : DEMO CASE - A volatile oil

WELL CONTROL

NO.	TIME D	TIME YEARS	NUMBER OF WELLS	FIELD MINIMUM OIL PRODUCTION RATE SM3/D	FIELD MINIMUM OIL PRODUCTION RATE STB/D	FIELD TARGET OIL PRODUCTION RATE SM3/D	FIELD TARGET OIL PRODUCTION RATE STB/D	MINIMUM WELLHEAD PRESSURE KPA	MINIMUM WELLHEAD PRESSURE PSIA	SKIN FACTOR DIM.LESS
1	.0 - 547.5	.00 - 1.50	1	5.0000	31.449	225.00	1415.2	22000.	3190.8	.00
2	547.5 - 1689.9	1.50 - 4.63	2	5.0000	31.449	450.00	2830.4	22000.	3190.8	.00
3	1689.9 - 3285.0	4.63 - 9.00	5	5.0000	31.449	450.00	2830.4	22000.	3190.8	.00
4	3285.0 - 4197.5	9.00 - 11.50	5	5.0000	31.449	450.00	2830.4	10000.	1450.4	.00
5	4197.5 - 7300.0	11.50 - 20.00	5	5.0000	31.449	450.00	2830.4	10000.	1450.4	-6.00

CALCULATED RESULTS

PRSI : INITIAL PRESSURE IS ASSUMED TO BE EQUAL
TO MAX. INPUT PVT-DATA PRESSURE (KPA) ..: 38291.
(PSIA) .....: 5553.6

OILTI : OIL VOLUME INITIALLY IN PLACE (SM3) ....: .16026E+08
(STB) ....: .10080E+09

SATOI : INITIAL OIL SATURATION (FRACTION) .....: .70000

SATGI : INITIAL GAS SATURATION (FRACTION) .....: .00000E+00

VOLB : BULK VOLUME OF RESERVOIR (M3) .....: .17143E+09
(BBL) .....: .10783E+10

AREA : TOTAL RESERVOIR AREA, FOR UNIFORM
THICKNESS (1E+3 M2) .....: 3428.6
(ACRES) .....: 847.22

RADE : RESERVOIR RADIUS, FOR CIRCULAR SHAPE (M): 1044.7
(FT): 3427.4

RATE. TIME STEP: 38
The target rate results in a too low wellhead
pressure. The rate has been reduced stepwise
down to the specified minimum rate, but the
wellhead pressure is still too low.
Return to the main program and terminate.

JOB IDENTIFICATION : DEMO CASE - A volatile oil

SIMULATION RESULTS

	TIME		FIELD CUMULATIVE GAS PRODUCTION		FIELD CUMULATIVE OIL PRODUCTION		FIELD CUMULATIVE GAS/OIL RATIO		RECOVERY OF PREF. PHASE
NO.	D	YEARS	1E+6 SM3	MMSCF	1E+3 SM3	MSTB	1E+3 SM3/SM3	MMSCF/MSTB	FRACTION
1	182.5	.50	11.926	421.17	41.063	258.28	.29044	1.6307	.00256
2	365.0	1.00	23.697	836.85	82.125	516.55	.28855	1.6201	.00512
3	547.5	1.50	35.401	1250.2	123.19	774.83	.28737	1.6135	.00769
4	730.0	2.00	58.756	2074.9	205.31	1291.4	.28618	1.6068	.01281
5	912.5	2.50	82.146	2901.0	287.44	1807.9	.28579	1.6046	.01794
6	1095.0	3.00	105.88	3739.0	369.56	2324.5	.28650	1.6085	.02306
7	1277.5	3.50	128.83	4549.6	446.91	2811.0	.28827	1.6185	.02789
8	1460.0	4.00	151.02	5333.2	518.94	3264.1	.29102	1.6339	.03238
9	1642.5	4.50	172.68	6098.0	585.97	3685.7	.29468	1.6545	.03656
10	1689.9	4.63	178.33	6297.5	602.89	3792.1	.29578	1.6607	.03762
11	1825.0	5.00	199.38	7041.0	663.67	4174.3	.30042	1.6867	.04141
12	2007.5	5.50	230.11	8126.1	745.79	4690.9	.30854	1.7323	.04654
13	2190.0	6.00	264.15	9328.3	827.92	5207.4	.31905	1.7913	.05166
14	2372.5	6.50	302.44	10680.	910.04	5724.0	.33233	1.8659	.05679
15	2555.0	7.00	346.18	12225.	992.17	6240.6	.34891	1.9590	.06191
16	2737.5	7.50	396.99	14019.	1074.3	6757.1	.36953	2.0748	.06704
17	2920.0	8.00	451.09	15930.	1149.1	7227.6	.39256	2.2041	.07170
18	3102.5	8.50	504.77	17826.	1213.3	7631.2	.41604	2.3359	.07571
19	3285.0	9.00	557.58	19691.	1268.6	7979.4	.43951	2.4677	.07916
20	3467.5	9.50	650.23	22963.	1350.7	8496.0	.48138	2.7028	.08429
21	3650.0	10.00	764.33	26992.	1432.9	9012.5	.53343	2.9950	.08941
22	3832.5	10.50	897.23	31685.	1510.3	9499.5	.59408	3.3355	.09424
23	4015.0	11.00	1031.2	36417.	1574.3	9902.3	.65502	3.6776	.09824
24	4197.5	11.50	1164.0	41105.	1627.6	10238.	.71513	4.0151	.10156
25	4380.0	12.00	1421.8	50210.	1709.8	10754.	.83157	4.6689	.10669
26	4562.5	12.50	1773.0	62613.	1791.9	11271.	.98946	5.5554	.11181
27	4745.0	13.00	2092.7	73902.	1847.7	11622.	1.1326	6.3588	.11530
28	4927.5	13.50	2336.1	82497.	1881.7	11836.	1.2414	6.9701	.11742
29	5110.0	14.00	2515.4	88831.	1903.1	11970.	1.3217	7.4210	.11875
30	5292.5	14.50	2644.7	93395.	1917.0	12058.	1.3796	7.7458	.11962
31	5475.0	15.00	2736.5	96638.	1926.2	12115.	1.4207	7.9764	.12020
32	5657.5	15.50	2801.3	98926.	1932.4	12154.	1.4496	8.1391	.12058
33	5840.0	16.00	2846.8	.10053E+06	1936.6	12181.	1.4700	8.2535	.12084
34	6022.5	16.50	2878.8	.10166E+06	1939.5	12199.	1.4843	8.3337	.12102
35	6205.0	17.00	2901.2	.10245E+06	1941.5	12211.	1.4943	8.3899	.12115
36	6387.5	17.50	2916.8	.10301E+06	1942.8	12220.	1.5013	8.4292	.12123
37	6570.0	18.00	2927.8	.10339E+06	1943.8	12226.	1.5062	8.4567	.12129

JOB IDENTIFICATION : DEMO CASE - A volatile oil

SIMULATION RESULTS

	TIME		AVERAGE RESERVOIR PRESSURE		BOTTOMHOLE PRESSURE		WELLHEAD PRESSURE		PRODUCING GAS/OIL RATIO	
NO.	D	YEARS	KPA	PSIA	KPA	PSIA	KPA	PSIA	1E+3 SM3/SM3	MMSCF/MSTB
1	182.5	.50	38012.	5513.2	28533.	4138.4	25833.	3746.8	.29044	1.6307
2	365.0	1.00	37742.	5474.1	28191.	4088.8	25491.	3697.2	.28665	1.6094
3	547.5	1.50	37479.	5435.9	27689.	4015.9	24989.	3624.3	.28502	1.6003
4	730.0	2.00	36970.	5362.1	27156.	3938.7	24456.	3547.1	.28438	1.5967
5	912.5	2.50	36475.	5290.2	26118.	3788.2	23418.	3396.6	.28482	1.5991
6	1095.0	3.00	35956.	5215.0	24895.	3610.7	22195.	3219.1	.28897	1.6224
7	1277.5	3.50	35479.	5145.7	24543.	3559.7	22000.	3190.8	.29675	1.6661
8	1460.0	4.00	35038.	5081.9	24368.	3534.3	22000.	3190.8	.30804	1.7295
9	1642.5	4.50	34628.	5022.4	24204.	3510.5	22000.	3190.8	.32308	1.8139
10	1689.9	4.63	34524.	5007.3	24140.	3501.2	22000.	3190.8	.33390	1.8747
11	1825.0	5.00	34148.	4952.8	29555.	4286.6	28475.	4129.9	.34644	1.9451
12	2007.5	5.50	33601.	4873.4	28610.	4149.5	27530.	3992.9	.37414	2.1007
13	2190.0	6.00	33006.	4787.1	27533.	3993.4	26453.	3836.7	.41450	2.3273
14	2372.5	6.50	32383.	4696.8	26369.	3824.4	25289.	3667.8	.46622	2.6176
15	2555.0	7.00	31720.	4600.6	25105.	3641.2	24025.	3484.6	.53260	2.9903
16	2737.5	7.50	31002.	4496.4	23678.	3434.2	22598.	3277.6	.61871	3.4738
17	2920.0	8.00	30279.	4391.5	22984.	3333.5	22000.	3190.8	.72329	4.0610
18	3102.5	8.50	29575.	4289.5	22844.	3313.2	22000.	3190.8	.83652	4.6967
19	3285.0	9.00	28917.	4194.1	22728.	3296.4	22000.	3190.8	.95392	5.3559
20	3467.5	9.50	27830.	4036.4	16893.	2450.2	15813.	2293.5	1.1282	6.3342
21	3650.0	10.00	26578.	3854.8	13783.	1999.1	12703.	1842.5	1.3894	7.8010
22	3832.5	10.50	25208.	3656.2	11018.	1598.1	10000.	1450.4	1.7164	9.6370
23	4015.0	11.00	23906.	3467.2	10842.	1572.5	10000.	1450.4	2.0925	11.748
24	4197.5	11.50	22695.	3291.6	10701.	1552.1	10000.	1450.4	2.4902	13.981
25	4380.0	12.00	20491.	2971.9	16401.	2378.8	15321.	2222.1	3.1393	17.626
26	4562.5	12.50	17761.	2576.0	12265.	1779.0	11185.	1622.3	4.2766	24.011
27	4745.0	13.00	15480.	2245.1	10735.	1556.9	10000.	1450.4	5.7230	32.132
28	4927.5	13.50	13845.	2008.1	10447.	1515.2	10000.	1450.4	7.1606	40.204
29	5110.0	14.00	12687.	1840.1	10281.	1491.2	10000.	1450.4	8.3886	47.099
30	5292.5	14.50	11878.	1722.8	10182.	1476.8	10000.	1450.4	9.3127	52.287
31	5475.0	15.00	11312.	1640.6	10121.	1467.9	10000.	1450.4	9.9728	55.993
32	5657.5	15.50	10915.	1583.2	10081.	1462.2	10000.	1450.4	10.467	58.769
33	5840.0	16.00	10639.	1543.1	10055.	1458.4	10000.	1450.4	10.830	60.805
34	6022.5	16.50	10446.	1515.1	10038.	1455.9	10000.	1450.4	11.092	62.277
35	6205.0	17.00	10311.	1495.5	10026.	1454.2	10000.	1450.4	11.280	63.330
36	6387.5	17.50	10217.	1481.8	10018.	1453.0	10000.	1450.4	11.413	64.077
37	6570.0	18.00	10151.	1472.3	10012.	1452.2	10000.	1450.4	11.507	64.604

JOB IDENTIFICATION : DEMO CASE - A volatile oil

SIMULATION RESULTS

	TIME		NUMBER OF	GAS PRODUCTION RATE				OIL PRODUCTION RATE			
				WELL		FIELD		WELL		FIELD	
NO.	D	YEARS	WELLS	1E+3 SM3/D	MMSCF/D	1E+3 SM3/D	MMSCF/D	SM3/D	STB/D	SM3/D	STB/D
1	.0 - 182.5	.00 - .50	1	65.350	2.3078	65.350	2.3078	225.00	1415.2	225.00	1415.2
2	182.5 - 365.0	.50 - 1.00	1	64.497	2.2777	64.497	2.2777	225.00	1415.2	225.00	1415.2
3	365.0 - 547.5	1.00 - 1.50	1	64.131	2.2647	64.131	2.2647	225.00	1415.2	225.00	1415.2
4	547.5 - 730.0	1.50 - 2.00	2	63.986	2.2596	127.97	4.5193	225.00	1415.2	450.00	2830.4
5	730.0 - 912.5	2.00 - 2.50	2	64.083	2.2631	128.17	4.5262	225.00	1415.2	450.00	2830.4
6	912.5 - 1095.0	2.50 - 3.00	2	65.018	2.2961	130.04	4.5922	225.00	1415.2	450.00	2830.4
7	1095.0 - 1277.5	3.00 - 3.50	2	62.887	2.2208	125.77	4.4417	211.92	1332.9	423.84	2665.9
8	1277.5 - 1460.0	3.50 - 4.00	2	60.789	2.1468	121.58	4.2935	197.34	1241.2	394.68	2482.5
9	1460.0 - 1642.5	4.00 - 4.50	2	59.333	2.0953	118.67	4.1906	183.65	1155.1	367.30	2310.2
10	1642.5 - 1689.9	4.50 - 4.63	2	59.534	2.1024	119.07	4.2049	178.30	1121.5	356.60	2243.0
11	1689.9 - 1825.0	4.63 - 5.00	5	31.179	1.1011	155.90	5.5054	90.000	566.08	450.00	2830.4
12	1825.0 - 2007.5	5.00 - 5.50	5	33.673	1.1891	168.36	5.9457	90.000	566.08	450.00	2830.4
13	2007.5 - 2190.0	5.50 - 6.00	5	37.305	1.3174	186.53	6.5871	90.000	566.08	450.00	2830.4
14	2190.0 - 2372.5	6.00 - 6.50	5	41.960	1.4818	209.80	7.4090	90.000	566.08	450.00	2830.4
15	2372.5 - 2555.0	6.50 - 7.00	5	47.934	1.6928	239.67	8.4639	90.000	566.08	450.00	2830.4
16	2555.0 - 2737.5	7.00 - 7.50	5	55.683	1.9664	278.42	9.8322	90.000	566.08	450.00	2830.4
17	2737.5 - 2920.0	7.50 - 8.00	5	59.291	2.0938	296.45	10.469	81.973	515.60	409.87	2578.0
18	2920.0 - 3102.5	8.00 - 8.50	5	58.826	2.0774	294.13	10.387	70.323	442.32	351.61	2211.6
19	3102.5 - 3285.0	8.50 - 9.00	5	57.873	2.0437	289.36	10.219	60.668	381.59	303.34	1908.0
20	3285.0 - 3467.5	9.00 - 9.50	5	101.54	3.5857	507.68	17.929	90.000	566.08	450.00	2830.4
21	3467.5 - 3650.0	9.50 - 10.00	5	125.05	4.4160	625.24	22.080	90.000	566.08	450.00	2830.4
22	3650.0 - 3832.5	10.00 - 10.50	5	145.64	5.1433	728.22	25.717	84.853	533.71	424.26	2668.5
23	3832.5 - 4015.0	10.50 - 11.00	5	146.83	5.1852	734.15	25.926	70.169	441.35	350.85	2206.8
24	4015.0 - 4197.5	11.00 - 11.50	5	145.49	5.1377	727.43	25.689	58.423	367.47	292.12	1837.4
25	4197.5 - 4380.0	11.50 - 12.00	5	282.53	9.9776	1412.7	49.888	90.000	566.08	450.00	2830.4
26	4380.0 - 4562.5	12.00 - 12.50	5	384.89	13.592	1924.5	67.962	90.000	566.08	450.00	2830.4
27	4562.5 - 4745.0	12.50 - 13.00	5	350.32	12.372	1751.6	61.858	61.213	385.02	306.07	1925.1
28	4745.0 - 4927.5	13.00 - 13.50	5	266.73	9.4195	1333.7	47.098	37.250	234.30	186.25	1171.5
29	4927.5 - 5110.0	13.50 - 14.00	5	196.56	6.9415	982.80	34.707	23.432	147.38	117.16	736.91
30	5110.0 - 5292.5	14.00 - 14.50	5	141.63	5.0015	708.13	25.007	15.208	95.654	76.039	478.27
31	5292.5 - 5475.0	14.50 - 15.00	5	100.63	3.5537	503.15	17.769	10.091	63.468	50.453	317.34
32	5475.0 - 5657.5	15.00 - 15.50	5	71.007	2.5076	355.04	12.538	6.7838	42.669	33.919	213.35
33	5657.5 - 5840.0	15.50 - 16.00	5	49.910	1.7625	249.55	8.8127	4.6085	28.987	23.043	144.93
34	5840.0 - 6022.5	16.00 - 16.50	5	35.016	1.2366	175.08	6.1830	3.1569	19.856	15.784	99.282
35	6022.5 - 6205.0	16.50 - 17.00	5	24.533	.86636	122.66	4.3318	2.1750	13.680	10.875	68.401
36	6205.0 - 6387.5	17.00 - 17.50	5	17.160	.60600	85.801	3.0300	1.5036	9.4574	7.5180	47.287
37	6387.5 - 6570.0	17.50 - 18.00	5	11.993	.42354	59.966	2.1177	1.0423	6.5559	5.2115	32.779

ITERATION REPORT

NAME	IN-CALLS	SOLVE	IT/SOLVE
RATE	38	22	6.4
WHPRS	156	11	5.1
RESPRS	201	201	6.4
MATBAL	1282	0	.0
IPR	201	0	8.4
FNPRS	1691	0	.0
ISGN	2488	0	.0
INTPL	7637	0	.0

NAME = NAME OF SUBROUTINE
IN-CALLS = NUMBER OF CALL TO THIS SUBROUTINE
SOLVE = HOW MANY TIMES DID THE SUBROUTINE HAVE TO START A SOLUTION PROCEDURE WITH ITERATIONS
IT/SOLVE = (1) AVERAGE NUMBER OF ITERATIONS EACH TIME A SOLUTION PROCEDURE WAS NECESSARY, OR (2) AVERAGE NUMBER OF INTEGRATION STEPS PER INTEGRATION (IPR)

Appendix C

USER'S INPUT MANUAL

C.0 Introduction

In the oil industry, both the traditional Oil Field units and the SI units are used. For "oil applications" SI units can be inconvenient and that is why "Metric units" or "preferred API standard SI units", which are based on the SI system, often are chosen. Consider "seconds" ("pure SI") as the time unit for oil field simulation. That is obviously not practical. In the GMS program, Metric and Oil Field units are available as given in the input description below. Conversion factors are listed in Section C.2.

C.1 Input Description

Table C.1 gives a quick overview of the input data file required by GMS. The lines and data items on each line have to appear in the order illustrated in this table. The first line on the input file is the "job identification". Below this line there are two kinds of lines (cards), (1) data lines and (2) comment lines. Any line, which starts with a number (0-9), a decimal point (.) or the signs (+ -) in the first nonblank position, is treated as a data line. All other lines are regarded as comment lines and are ignored by GMS. Thus, one may write comments between the data lines. Table C.2 gives a detailed description of the lines and data tables in the input file. The units to be used are given in this table: Metric units followed by Oil Field units in brackets.

TABLE C.1 - PRESENTATION OF THE VARIABLE NAMES
OF AN INPUT DATA FILE FOR GMS

```
JOBID
          IHC      IUNIN       IPRT       IEXE
       DELTIM     XMXTIM       HCPV       PORI      SATWI       CMPF
          PRM        THK       RADW       DSKN      DPINT         TF
         TTIM     NWELLS     TRTEFM     TRTEFT     TPWMIN       TSKN
   -1
         TPRS      TVISO      TGORS     TDENRO      TFVFO
   -1
                   TVISG      TOGRS     TDENRG      TFVFG
   -1
        TSATG     TPRMRO     TPRMRG
   -1
```

- JOBID is a character variable (see Table C.1 above). IHC, IUNIN, IPRT, IEXE are integer variables and NWELL is an integer array. All the other variables and arrays are double precision.

- Important: *The tables are terminated by -1.* This feature enables the user to change the number of entries in the tables without counting them up.

- Data items are separated by a comma and/or spaces (blank characters). Counting columns is not necessary.

- The unit system chosen by IUNIN has to be used for all data in the input file. Output is written in both Metric and Oil Field units.

TABLE C.2 - DESCRIPTION OF INPUT DATA

Data line 1

Format: A text string.

JOBID

The job identification is a text string placed on the first line of the data file. It is printed above each table on the output.

TABLE C.2 (continued)

Data line 2

Format: four integers.

IHC IUNIN IPRT IEXE

IHC .... hydrocarbon type, dimensionless
= 0 : gas condensate
= 1 : oil.

Indicates which hydrocarbon phase is present initially.

IUNIN ... units identifier for input data
= 0 : Metric units
= 1 : Oil Field units.

Unit system selected to be used for all input data.

IPRT .... print option
= 0 : tables of results are printed to the output file at the end of simulation
= 1 : + "echo" of input data printed after read
= 2 : + iteration report
= 3 : + results printed each timestep to the screen, mainly inteded for debug purposes
= 4 : + a message from each routine.

IEXE .... execution mode
= 0 : material balance only
= 1 : material balance and IPR
= 2 : material balance, IPR and tubing performance.

Determines which calculations are to be performed.

TABLE C.2 (continued)

Data line 3

Format: six doubleprecision variables.

DELTIM XMXTIM HCPV PORI SATWI CMPF

DELTIM ..	timestep length	years [years]
XMXTIM ..	length of simulation	years [years]
HCPV	hydrocarbon pore volume	m^3 [bbl]
PORI	initial porosity	fraction
SATWI ...	initial water saturation. The water present initially is assumed to be immobile.	fraction
CMPF	formation compressibility	kPa^{-1} [psi^{-1}]

TABLE C.2 (continued)

Data line 4

Format: six doubleprecision variables.

PRM THK RADW DSKN DPINT TF

PRM	permeability. Average, absolute reservoir permeability.	μm^2 [md]
THK	reservoir thickness. The reservoir is assumed to be of uniform thickness.	m [ft]
RADW	wellbore radius	m [ft]
DSKN	non-Darcy flow coefficient (rate dependent skin term)	
	** if IHC=0 (gas)	d/Sm^3 [D/scf]
	** if IHC=1 (oil)	d/Sm^3 [D/STB]
DPINT ...	pressure increment in Simpson-integration in the IPR subroutine	kPa [psi]
TF	"tubing factor" (no physical meaning, used only in temporary tubing routine)	dimensionless

TABLE C.2 (continued)

Data Table 1

Table of well control specifications
Format: 1 doubleprecision + 1 integer + 4 doubleprecision on each line
(repeat lines, end with -1)

TTIM NWELLS TRTEFM TRTEFT TPWMIN TSKN

TTIM	time for well control	years [years]
NWELLS ..	number of wells	
TRETFM ..	field minimum production rate	
	** if IHC=0 (gas)	Sm^3/d [scf/D]
	** if IHC=1 (oil)	Sm^3/d [STB/D]
TRTEFT ..	field target production rate	
	** if IHC=0 (gas)	Sm^3/d [scf/D]
	** if IHC=1 (oil)	Sm^3/d [STB/D]
TPWMIN ..	minimum wellhead pressure	kPa [psia]
TSKN	total skin (except rate dependent skin)	dimensionless

- TTIM must increase down the column.

- To end the table, put: -1 on the next line.

TABLE C.2 (continued)

Data Table 2

Table of PVT data for the oil phase
Format : 5 doubleprecision variables on each line
(repeat lines, end with -1)

TPRS TVISO TGORS TDENRO TFVFO

TPRS	pressure for PVT data	kPa [psia]
TVISO ...	oil viscosity	Pa s [cp]
TGORS ...	solution gas/oil ratio, in oil phase	Sm^3/Sm^3 [scf/STB]
TDENRO ..	density ratio (specific gravity ratio), oil-from-gas / oil-from-oil	dimensionless
TFVFO ...	oil formation volume factor	(res.vol/std.vol)

- TPRS must increase down the column.

- To end the table, put: -1 on the next line.

TABLE C.2 (continued)

Data Table 3

Table of PVT data for the gas phase
Format : 4 doubleprecision variables on each line
(repeat lines, end with -1)
** note : same pressures as above

TVISG TOGRS TDENRG TFVFG

TVISG ...	gas viscosity	Pa s [cp]
TOGRS ...	solution oil/gas ratio, in gas phase	Sm^3/Sm^3 [STB/10^6 scf]
TDENRG ..	density ratio (specific gravity ratio), gas-from-oil / gas-from-gas	dimensionless
TFVFG ...	gas formation volume factor	(res.vol/std.vol)

TABLE C.2 (continued)

Data Table 4

Table of relative permeability versus saturation
Format : 3 doubleprecision variables on each line
(repeat lines, end with -1)

TSATG TPRMRO TPRMRG

TSATG ...	gas saturation	(fraction)
TPRMRO ..	relative permeability to oil	(fraction)
TPRMRG ..	relative permeability to gas	(fraction)

- TSATG must increase down the column.

- To end the table, put: -1 on the next line.

C.2 SI Metric - Oil Field Units Conversion Factors

SI Metric				Oil Field
3.048000*	E-01	m	=	1 ft
4.046856	E+03	m^2	=	1 acre
2.831685	E-02	m^3	=	1 ft^3
2.831685	E-02	Sm^3/d	=	1 scf/D
1.589873	E-01	m^3	=	1 bbl
1.589873	E-01	Sm^3/d	=	1 STB/D
9.86923	E-04	μm^2	=	1 md
6.894757	E+00	kPa	=	1 psi
1.000000*	E-03	Pa s	=	1 cp

Note: $\mu m^2 \equiv 10^{-12}\ m^2$.

* Conversion factor is exact; all following digits are zero.