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**One-Dimensional Steam Flow  
in Porous Media**

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### **Abstract**

This report describes a computer program for simulation of 1-D steam flow in vapor dominated geothermal reservoirs taking into account the effects of adsorption and desorption. Energy transport is neglected. The pseudo-pressure substitution is applied to the the equation for material balance and the resulting equation is solved by a finite difference technique.

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# 1 Introduction

Petroleum reservoir engineering principles were first applied to geothermal reservoir problems with the Whiting-Ramey material-energy balance (Whiting and Ramey, 1969). The geothermal reservoir is taken to be a thermodynamic system, and then follows the vapor pressure curve found in thermodynamic charts for pure water with a flat liquid-vapor interface. The model was applied successfully to a compressed liquid reservoir assuming that the depletion path is first isothermal, and then follows the vapor pressure curve found in thermodynamic charts for pure water with a flat liquid-vapor interface.

Cady (1969), Bilhartz (1971), Strobel (1973) and Chicoine (1975) considered the effect of vapor pressure lowering in porous media on the Whiting-Ramey model. Capillarity and/or adsorption can cause a decrease in vapor pressure in a porous medium.

Hsieh (1980) studied vapor pressure lowering in vapor dominated reservoirs. He found that adsorption, not capillarity, was the most important factor causing vapor pressure lowering at low liquid content. Furthermore, the amount of water adsorbed was found to be much greater than the amount of compressed steam in pore space, suggesting that adsorbed water may be the source of steam in vapor-dominated reservoirs.

Economides (1983) presented modified material balance equations taking into account adsorbed liquid. Moench and Atkinson (1978) considered the effect of boiling on transient flow in porous media. Herkelrath and Moench (1982) and Herkelrath et al. (1983) investigated the effect of adsorption on pressure transient tests. They used superheated steam in experimental work and assumed adsorbed water to be saturated liquid in their mathematical model. The numerical results agreed with the experimental results, indicating that adsorbed water causes a large delay in pressure transient response. Ramey (1990) proposed adsorption as a storage mechanism for liquid storage in vapor-dominated systems, suggesting that the reservoir behavior under production can be understood in terms of desorption.

This report describes a computer program for solving a modified material balance equation which considers adsorption/desorption and compression

phenomena in porous media. The steam flow model of Herkelrath et al. and the pseudo-pressure substitution (Al-Hussainy, et al. (1966)) are used. The computer program has been used to check experimental studies in adsorption and to perform a field forecast for production/desorption.

## 2 Mathematical Model

The system consists of a homogeneous porous medium containing steam in pore space and of immobile adsorbed water on the solid (low water saturation). The relative permeability of steam is taken to be unity. The material balance equation, after substitution of Darcy's law, is:

$$\frac{\partial \phi \rho_v (1 - S_w)}{\partial t} + \phi \rho_w \frac{\partial S_w}{\partial t} - \frac{\partial}{\partial x} \left[ \frac{k}{\mu} \rho_v \left( \frac{dp}{dx} - \rho_v g \right) \right] + q = 0 \quad (1)$$

The second term in Eq. 1 describes mass transfer between adsorbed water and steam (phase change). It is a sink term in adsorption and a source term when desorption occurs. The fourth term represents production/injection from the system.

Adsorption phenomena can be described by an equilibrium model characterizing the adsorption capacity of the system (how much steam can be adsorbed/removed per unit weight of rock).

Adsorption reactions are exothermic. We neglect a heat balance in this study, assuming that temperature changes in the system are small (they are primary due to adsorption/desorption according to Herkelrath et al. (1983)). The temperature of steam determines the amount of adsorption and the shape of the isotherm. Conventional reservoir models for vapor-dominated systems include an energy balance as part of the process of computing mass transfer due to vaporization/condensation for steam water equilibrium, see Moench and Atkinson, 1978.

We assume that there is no hysteresis for desorption. This assumption is consistent with experimental data. See Bikerman (1970) concerning the

theories for hysteresis of adsorption and capillary condensation. With the assumption of an immobile adsorbed phase, the theory of hysteresis of wetting may be disregarded. Capillary condensation is an explanation for the shape of the adsorption isotherm based on the concept of pores of variable cross-section and size.

Adsorption is usually described by the function  $X=f(p,T)$  where  $X$  is the amount adsorbed, customarily expressed as gram water/gram rock. The relationship between amount adsorbed (liquid) and liquid saturation is:

$$S_w = \frac{1 - \phi}{\phi} \frac{\rho_r}{\rho_w} X \quad (2)$$

where  $\rho_r$  and  $\rho_w$  are density of rock and density of water, respectively.

The Langmuir isotherm model is:

$$X = \frac{PIPS}{a + b(p/p_s)} \quad (3)$$

where  $a$  and  $b$  are constants and  $p_s$  is the saturation pressure. This model appears to fit adsorption data for many rocks. In the test problem with soil, the Herkelrath and Moench (1980) empirical relation for the adsorption isotherm was used.

Steam is treated as a real gas and the pseudo-pressure approach is used to rewrite Eq. 1 in terms of a pseudo-pressure  $m(p)$  (see Al-Hussainy et al., 1966):

$$m(p) = \int_{p_m}^p \frac{p}{\mu(p)z(p)} dp \quad (4)$$

where  $p_m$  is an arbitrary pressure, usually at the lowest end of pressures of interest in the problem.

The resulting equation has a form similar to the diffusivity equation and has reduced nonlinearity:

$$A \frac{\partial m}{\partial t} + B \frac{\partial^2 m}{\partial x^2} + C \frac{\partial m}{\partial x} + qRT = 0 \quad (5)$$

where:

$$A = \phi M \mu C_g \left(1 - \frac{\rho_r}{\rho_w} \frac{1 - \phi}{\phi} X\right) + \left(\frac{ZRT}{p_v} - \frac{M}{\rho_w}\right) \rho_r (1 - \phi) \mu \frac{\partial X}{\partial p_v} \quad (6)$$

$$B = -M \quad (7)$$

$$C = \frac{M^2}{RT} \frac{2K g p_v C_g}{Z} \quad (8)$$

where  $C_g$  is the isothermal compressibility of steam,  $\rho_r$  the rock density, and  $Z$  is the real gas law deviation factor.

The boundary conditions which will be used are no-flow boundary, and constant pressure boundary.

The SI unit system used is  $p(\text{dynes/cm}^2)$ ,  $\rho(\text{g/cm}^3)$ ,  $k(\text{cm}^2)$  and  $\mu(\text{dyne.s/cm}^2)$ . The other variables must have consistent units.

### 3 Solution Procedure

The finite-difference equation is derived by discretizing the spatial derivatives in Eq. 5 with a variable-weighted method and the time derivative with an implicit method. A block-centered grid with uniform spacing is used. In the case of a no-flow boundary, the reflection technique is used to derive the appropriate difference equation for the boundary block.

The initial pressure distribution is taken to be uniform. To convert the pressure to pseudo-pressure and vice versa, a table of pressure vs pseudo-pressure is used. This table is developed for the range of pressure adsorption/desorption by using the trapezoidal rule to evaluate an  $m(p)$  for each pressure. The conversion is performed by table look-up and linear interpolation.

## 4 Program Development

The adsorption effect was originally incorporated into the material balance equation by dimensional analysis. An equation similar to that presented by Bumb and McKee (1988) was derived.

Several test cases were used to evaluate the reliability of the mathematical model and of the computer program. Aronofsky and Jenkins (1951) provide results for transient gas flow in porous media without adsorption. It was found that computed results for air flow were in good agreement with those presented by Aronofsky and Jenkins, see Figs. 1, 2 and 3.

Next, the laboratory experiments of Herkelrath et al. (1983) with transient steam flow and adsorption were tested. Eq. 1 was found to be a reasonable mathematical model, considering the adsorbed phase as a liquid. Computed results were in acceptable agreement with the experimental results, Figs. 4 and 5.

The program was also used to forecast the production history of a hypothetical Geysers field unit. The program is described in the next section.

## 5 Program Description

The program was written for the cases of either constant producing or injection pressure or rate at one end of a linear core closed at the other end. The constant pressure case is identified as  $IC=0$ , and the constant rate case is identified as  $IC=1$ , respectively. For a production forecast, an IF-ELSE



structure was used to switch from the IC=1 mode to the IC=0 mode. The program structure is described in the following.

In addition to an input data file, there is an input section in the program. The data in the input data file are pressure, specific volume and viscosity. The data were taken from Steam Tables and were used to build the p-m(p) table.

The program consists of the following parts:

### 1. Input Section

The input parameters are classified by fluid, reservoir, adsorption and numerical parameters. Some are located in subroutine INPUT, others in the main program. See section "User Manual".

### 2. Initialization

This part consists of subroutine TABLE and INIT. The real gas deviation factor, z, isothermal compressibility, and pseudo-pressure are evaluated for the range of pressure considered in the data input file. The initial pressure distribution is specified.

### 3. Solver

This part consists of the subroutines NEWDAT and COMPUT. The discretized equation for the cases IC=0 and IC=1 are solved in subroutine COMPUT. A tridiagonal coefficient matrix is used and the Thomas algorithm is used to solve the equation. New pressures are then determined from the new pseudo-pressures.

The subroutine NEWDAT is then used to calculate new coefficients from Eqs.6-8.

### 4. Math routines

This part of the program consists of subroutine TABSEQ for table look-up and linear interpolation and the subroutine THOMAS for solving the tridiagonal matrix.

The algorithm is described in the following:

read input parameters.  
read input data file. Prepare tables of  $z$ ,  $C_g$  and  $m(p)$  vs  $p$ .  
read initial pressure.

### Loop

determine  $m(p)$ ,  $\rho_v$ ,  $z$ ,  $C_g$  at every grid point in the reservoir.  
set coefficient matrix - grid point no. one if IC=1  
set right hand side vector.  
solve the system.  
determine new pressures at grid points from the pseudo-pressure obtained.  
If time==specified time, write output  
endif  
time=given time  
stop  
endif

**end of Loop**

## 6 Field Example Simulation

Although this program was prepared to match bench-scale laboratory transient flow experiments under desorption, the model may also be used to study potential field performance. To illustrate this useful feature, conditions similar to The Geysers were used to prepare example simulations. Vertical linear flow was considered. The reservoir model has the following characteristics: porosity 0.1, vertical permeability 300 md, temperature 500F, initial pressure 681 psia saturation, area of 400 acres, and 5000 ft vertical length. During the early production phase, a constant flow rate of 1,000,000 lb/hr is maintained. This is equivalent to approximately a 50MWe power plant. When the pressure in the producing block drops to 100 psig, the assumed power plant inlet pressure, then the production mode shifts to production at that constant pressure and flowrate declines.

The Langmuir isotherm model was found to fit experimental data for clayey rock, Fig. 6. The saturation pressure is  $p_s=680.86$  psia. The range of pressure considered is 80 psia to 681 psia. The input data file reads  $p$ (psia),  $v(ft^3/lbm)$  and  $\mu(cp)$  for that range of pressure with format 3F14.4.

The input parameters in the main program are:

1. Problem definition

Production starts at constant flow rate: IC=1.

2. Fluid parameters

R (*dyne/cm.mol.K*) : universal **gas** constant  
WM (*g/mol*) : Molecular weight  
TP (*K*) : temperature of steam  
PSAT (*dyne/cm<sup>2</sup>*) : saturation pressure  
DSTW (*g/cm<sup>3</sup>*) : density of adsorbed water

3. Reservoir parameters

PWELL(*dyne/cm<sup>2</sup>*) : specified production pressure  
RHOR. (*g/cm<sup>3</sup>*) : rock density  
PHI (--) : porosity  
XK (*cm<sup>2</sup>*) : permeability  
XL (*cm*) : height of the reservoir  
RATE (*lb/hr*) : specified rate  
CA (*cm<sup>2</sup>*) : cross-sectional area of the reservoir  
XG (*cm/s<sup>2</sup>*) : gravitational constant  
PINIT(*dyne/cm<sup>2</sup>*) : initial pressure

Most of these parameters are determined by the problem. The initial pressure distribution is taken to be the pressure of saturated steam at 500 F.

4. Adsorption parameters

AA and BB are the coefficients a and b in the Langmuir equation, **Eq. 3.**

If adsorption models other than the Langmuir model are used, the expressions for X and its derivative with respect to pressure, DXDP, must be changed.

## 5. Numerical parameters

The numerical model requires specification of the following parameters:

TIME (*time scale*) : the period of time of simulation  
N (-) : number of blocks  
DT (*time scale*) : timestep  
DX (*cm*) : block length  
WGT (-) : weight (numerical scheme)  
TIME (*time scale*) : the period of time of simulation

The time scale used in this application is hours.

All parameters must be specified in the main program. The expressions for X and DXDP are in the subroutine COMPUT.

Results of the field example simulation are presented in Figs. 7-9.

## 7 Discussion

The use of the Langmuir isotherm to represent adsorption-desorption data may appear surprising. This model (Eq. 3) was derived assuming a monolayer adsorbed and has been largely replaced by expressions for more complete adsorption models. Bumb and McKee (1988) observed that this model appeared to match experimental data for methane adsorption in coals and shales over the entire range of pressure to the saturation pressure ( $p/p_s = 1$ ). This was surprising because even more sophisticated models are not expected to match data beyond relative pressures of about 0.3. Eq. 3 was also found in this study to match available steam adsorption data in porous materials containing clays (tuff, silty sand, and greywacke). Thus the value of Eq. 3 is that it is an empirical representation of adsorption data, not that the original Langmuir model is valid.

Eq. 3 is shown on Fig. 6. The curve shape is concave downwards. As the relative pressure drops to 0.5, the mass adsorbed drops from about 0.0125 to 0.009 lb steam/lb rock, or about 25%. A 50% drop in pressure yields only 25% of the steam. The remaining 75% will desorb as pressure drops to atmospheric.

A remaining question is whether 0.0125 lb steam/lb rock is significant. Does the mass adsorbed in micropores compare with the mass of steam compressed in the pore space? The field example simulation answers this question. Figure 7 presents production rate vs time computed for the transient production from 400 acres of area of a vapor-dominated system 5000ft thick. The mass in place at start is about 1.7 billion lbs of steam (as vapor and adsorbed liquid). From Fig. 7, the desired rate of one million lbs/hr can be maintained for about 10 years, then the rate will decline. Although not shown on Fig. 7, cases have also been run assuming that the producing pressure is dropped from 100 psi to some lower pressure (say 50 psi) when the rate declines to some specific fraction of the desired rate.

The solid line on Fig. 7 shows computed rate including both expansion of steam in pores, and vaporization of adsorbed liquid (desorption). The dashed line presents computed rate if only desorption is considered. The bulk of the mass in this system is in the adsorbed liquid. The adsorbed mass is 50 to 100 times the mass of compressed steam in pore space. The

short dash line presents rate from compressed steam only.

This simple lumped parameter model shows that reservoir conditions may control the production rate from a vapor-dominated system. Fig. 7 was computed for a vertical permeability of **300** md. Fig. 8 presents pressure vs depth for both **300** and 50 md vertical permeabilities. Vertical permeability affects the pressure in the top block (250 ft depth), and would change Fig. 6. Results in Fig. 8 may also be used to compute the mean pressure at succeeding times. This information can be related to the cumulative production to permit performance matching. This result is shown in Fig. 9:  $p/z$  vs cum production. The shape of the computed solid curve is concave upwards. Remember the initial mass in place is 1.7 billions lbs, far off the right-hand side of the graph. Thus much of the mass in the system would be recovered at low pressures (and rates). Again the long dashes indicate that the behavior considering only adsorption is close to that of the entire system including compressed steam.

The transient flow program was originally prepared to aid analysis of experiments to measure adsorption on field core material. However the use as a simple simulator to study field problems is significant. Current effort is aimed at producing a PC version of the program that is menu driven.

The model does not include a heat balance. For the field example, desorption would cause a drop in temperature of less than 30F. However, reinjection to mine energy from hot rock requires consideration of a heat balance. This will be added to the program. Although not mentioned in this report, the shape of the adsorption isotherm, Fig. 6, has obvious connotations regarding reinjection and tracer injection.

Finally, the Langmuir isotherm equation may be used to derive a basis for field performance matching and forecasting, as well as interpretation of core measurements. These subjects will be presented in future reports.

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## **9 Nomenclature**

$\phi$ : porosity

$\rho_v$ : steam density

$S_w$ : Water saturation

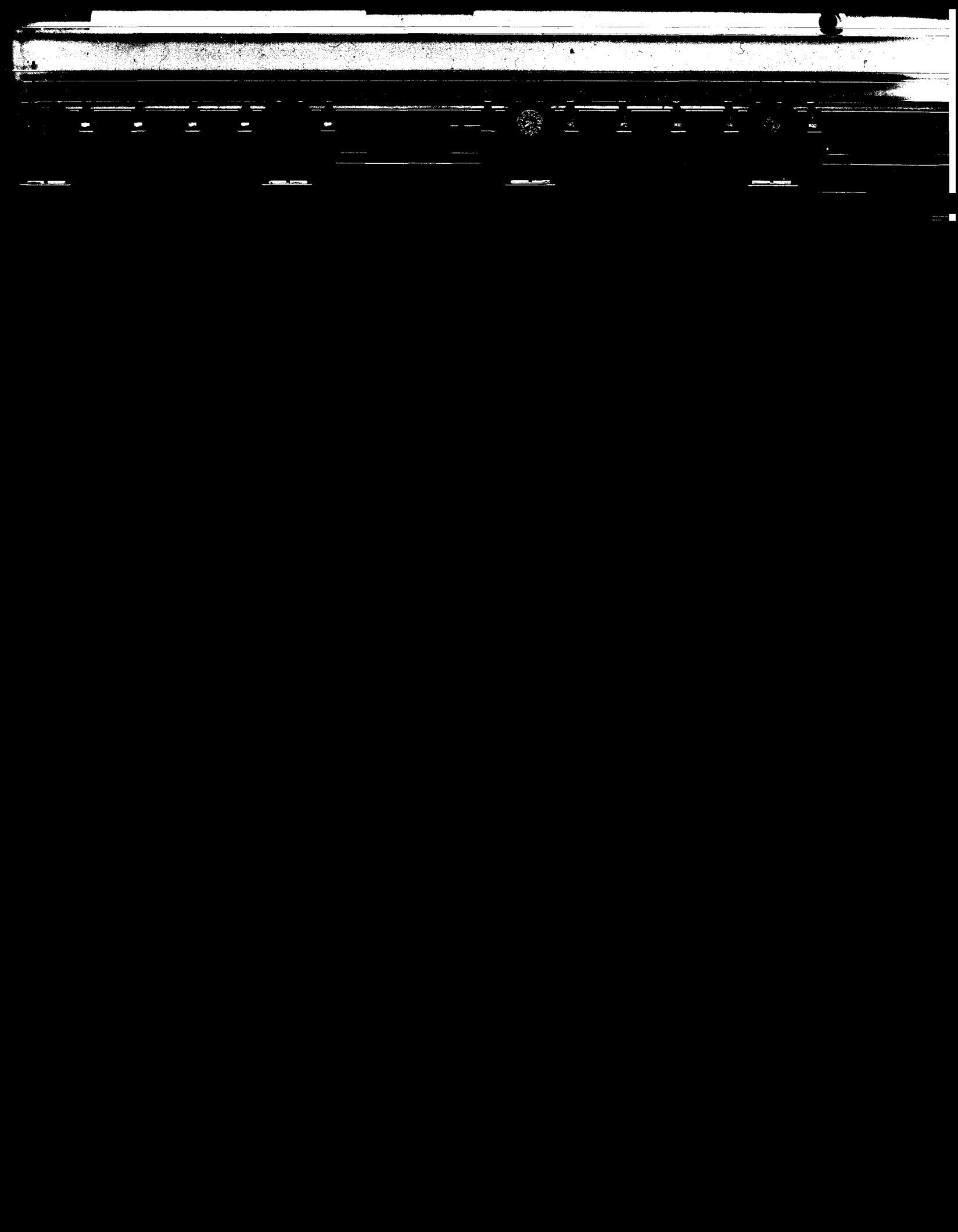
$\rho_w$ : water density

$k$ : permeability

$\mu$ : viscosity

$g$ : gravity





$X$  : Mass of water adsorbed  
 $p_s$ : saturation pressure  
 $m(p)$ : pseudo-pressure, **Eq. 4**  
 $\rho_r$ : **rock** density  
 $p$ : pressure  
 $p_m$  base pressure for  $m(p)$   
 $a$ : constant, **Eq. 3**  
 $b$ : constant, **Eq. 3**  
 $c_g$ : isothermal compressibility  
 $x$ : length variable  
 $z$ : gas law deviation factor  
 $M$ : molecular weight  
 $R$ : gas law constant

## 10 Appendix - - Program Listing

The variables that appear in the program are put in five Common blocks, corresponding to the five following files:

1. "DM.1"

WM,R,TP,PSAT,RHOR,PHI,XK,XL,AA,BB,DSTW,C1,C2,C3,  
N,DT,DX,WGT,TIME,STIME,XMSH(10),PRI,CA,XG,  
R(47),VL(47),VIC(47),PD(10),C4,XMWELL,PWELL,  
IC,D1(10),T1(10),U1(10),S1(10),RATE,CU,XQ,  
BA(10),BS(10),VG(10),RG(10),DEPTH(10),PINIT

2. "CM.2"

P(47),V(47),VISC(47)

3. "CM.3"

Z(47),DST(47),DDST(47),DP(47),CG(47),PMUZ(47),  
AVG(47),DPAVG(47),XM(47)

4. "DM.4"

PI(10),P0,P1,PP(46),Xmm(46),CGG(46),XMI(10),  
CGI(10),VISCI(10),ZI(10)

5. "DM.5"

A1(10),A2(10),X(10),DXDP(10),B,DI(9),U(9),T(9),  
S(9),XMN(10),A(10),C(10),XFLUX

PROGRAM ADSORPTION

IMPLICIT REAL\*8 (A-H,O-Z)

INCLUDE 'DM.1'  
 INCLUDE 'CM.2'  
 INCLUDE 'CM.3'  
 INCLUDE 'DM.4'  
 INCLUDE 'DM.5'

C PROBLEM DEFINITION

IC=1

C INPUT PARAMETERS FOR GAS/STEAM

WM= 18.015D0  
 R= 8.313E07  
 TP= 533.16  
 PSAT= 680.8642\*6.894757E04  
 DSTW= (1./0.02043)\*1.601846\*0.01

C INPUT PARAMETERS FOR RESERVOIR MODEL

RHOR= 2.650D0  
 PHI= 0.1D0  
 XK= 300.\*9.8697E-12  
 XL= 5000.\*30.480  
 PWELL= 114.7D0\*6.894757E04  
 RATE= 1000000.  
 CA= 16187425690.  
 XG= 980.D0  
 PINIT= 680.8642D0\*6.894757E04

C ADSORPTION PARAMETERS

BB= 53.D0  
 AA= 31.D0

C PARAMETERS FOR NUMERICAL MODEL

N= 10  
 DT= 3600.\*24.\*7.\*4.  
 DX= XL/10.D0  
 WGT= 1.  
 TIME= 3600.\*24.\*7.\*4.\*12.\*26.  
 STIME= 0.  
 XMSH(1)= 0.5\*DX  
 DO 666 I= 2/10

666 XMSH(I)= XMSH(I-1)+DX

C

COUNT= 0.  
 CU= 0.  
 XQ= RATE  
 SWI= 0.

WRITE (6,\*) ' INPUT PARAMETERS '  
 \*WRITE (6,100) WM, R, TP, PSAT, RHOR, PHI, XK, XL, CA, XG, N,  
 DT, DX, WGT, TIME, AA, BB, DSTW, RATE, PWELL

CALL INPUT  
 CALL TABLE:  
 CALL INIT

1000 CALL NEWDAT (IC)  
 CALL COMPUT (IC)  
 TID= STIME/(3600.\*24.\*7.\*4.\*12.)

IF (PI(1).LE.PWELL) THEN  
 IC= 0  
 PI(1)= PWELL  
 CALL TABSEQ (PP,XMM,46,PWELL,XMI(1))  
 CU= CU+0.5\*(XFLUX+XQ)\*DT/3600.  
 XQ= XFLUX

ELSE  
 IF(STIME.NE.0.) THEN  
 CU= RATE\*STIME/3600.

```

ELSE
  CU= RATE*DT/3600.
ENDIF
ENDIF
IF (TID.EQ.COUNT) THEN
  WRITE: (6,*) ' ***** '
  WRITE: (6,*) ' TYPE OF FLOW '
  WRITE: (6,*) IC
  WRITE: (6,*) ' TIME STEP = 1 MONTH '
  WRITE: (6,650)
  IF (COUNT.EQ.0.) THEN
    WRITE (6,670)
  ELSE
    WRITE (6,660)
    WRITE (6,700) TID
  ENDIF
  WRITE: (6,*) ' FLOW RATE AT WELL (lb/hr) '
  WRITE: (6,900) XFLUX
  WRITE: (6,*) ' PWELL (PSIA) '
  PSF= PI(1)*1.450377E-05
  WRITE: (6,900) PSF
  WRITE: (6,*) ' P LAST BLOCK (PSIA) '
  PBT= PI(10)*1.450377E-05
  WRITE: (6,900) PBT
  WRITE: (6,*) ' PRESSURE DISTRIBUTION (PSIA) WITH DEPTH (FT) '
  DO 33 I= 1,10
    DEPTH(I)= XMSH(I)*0.03280840
    PD(I)= PI(I)*1.450377E-05
    WRITE(6,2000) DEPTH(I), PD(I)
33 CONTINUE
    WRITE (6,*) ' cumulative production '
    WRITE (6,900) CU
    COUNT= COUNT+1.
  ENDIF
  STIME= STIME+DT
  IF (STIME.LT.TIME) GO TO 1000
100 FORMAT (//
*10X, ■ MCLEcular WEIGHT.....: ', F12.4, ' G/MOL' /
*10X, ■ GAS CONSTANT, (UNIVERSAL) .....: ', E12.4, ' DYNE/CM.MOL.K' /
*10X, ■ GAS TEMPERATURE.....: ', F12.4, ' K' /
*10X, ■ SATURATION PRESSURE.....: ', E12.4, ' DYNE/CM2' /
*10X, ■ ROCK DENSITY.....: ', F12.4, ' G/CM3' /
*10X, ■ POROSITY.....: ', F12.4, ' /
*10X, ■ PERMEABILITY.....: ', E12.4, ' CM2' /
*10X, ■ CORE LENGTH.....: ', E12.4, ' CM' /
*10X, ■ CROSS-SECTIONAL AREA.....: ', E12.4, ' CM2' /
*10X, ■ GRAVITATIONAL CONSTANT.....: ', E12.4, ' CM/S2' /
*10X, ■ NUMBER OF GRID POINTS.....: ', 112, ' /
*10X, ■ TIME STEP.....: ', E12.4, ' S' /
*10X, ■ SPACE STEP.....: ', F12.4, ' CM' /
*10X, ■ WEIGHT.....: ', F12.4, ' /
*10X, ■ SIMULATION TIME.....: ', E12.4, ' S' /
*10X, ■ ADSORPTION PARAMETER.....: ', F12.4, ' /
*10X, ■ ADSORPTION PARAMETER.....: ', F12.4, ' /
*10X, ■ DENSITY OF ADSORBED WATER.....: ', F12.4, ' G/CM3 ' /
*10X, ■ WELL RATE.....: ', F12.4, ' LB/H' /
*10X, ■ WELL PRESSURE.....: ', F12.4, ' DYNE/CM2' )
650 FORMAT (//, 25X, ' SIMULATION TIME ' )
660 FORMAT (29X, ' IN YEARS ', //)
670 FORMAT (33X, ' DT ', //)
700 FORMAT (25X, F14.4, //)
750 FORMAT (2E22.4)
900 FORMAT (F22.4)
950 FORMAT (E22.8)
2000 FORMAT (2F22.4)
END

```

SUBROUTINE INPUT

```

IMPLICIT REAL*8 (A-H,O-Z)
INCLUDE 'DM.1'
INCLUDE 'CM.2'

```

C READ P, v, VISCOSITY DATA. COMPUTE Z AND CG FACTORS.  
C INPUT: P(psia), V(ft<sup>3</sup>/lbm), VISC(cpoise)

```

DO 10 I=1,47
  READ (5,200) PR(I), VL(I), VIC(I)
  P(I) = PR(I) * 6.894757304
  V(I) = VL(I) * 62.428
  VISC(I) = VIC(I) * 0.01
10 CONTINUE
200 FORMAT (3F14.4)
RETURN
END

```

SUBROUTINE TABLE

```

IMPLICIT REAL*8 (A-H,O-Z)
INCLUDE 'DM.1'
INCLUDE 'CM.2'
INCLUDE 'CM.3'

```

```

DO 11 I=1,47
  Z(I) = WM * P(I) * V(I) / (R * TP)
  DST(I) = 1. / V(I)
  IF (I.GE.2) THEN
    DDST(I) = DST(I) - DST(I-1)
    DP(I) = P(I) - P(I-1)
    CG(I) = DDST(I) / (DST(I) * DP(I))
  ENDIF
11 CONTINUE

```

C COMPUTE M(P)

```

DO 12 I=1,47
  PMUZ(I) = P(I) / (VISC(I) * Z(I))
  IF (I.GE.2) THEN
    AVG(I) = 0.5 * (PMUZ(I-1) + PMUZ(I))
    DPAVG(I) = DP(I) * AVG(I)
    IF (I.EQ.2) THEN
      XM(I) = DPAVG(I)
    ELSE
      XM(I) = XM(I-1) + DPAVG(I)
    ENDIF
  ENDIF
12 CONTINUE
RETURN
END

```

SUBROUTINE INIT

```

IMPLICIT REAL*8 (A-H,O-Z)
INCLUDE 'DM.1'
INCLUDE 'CM.2'
INCLUDE 'CM.3'
INCLUDE 'DM.4'
INCLUDE 'DIY.5'

```

C INITIALIZE. FIND CORRESPONDING Z, VISCOSITY AND CG

```

DO 13 I= 1,10
  PI(I)= PINIT
13  CONTINUE
  WRITE (6,*) ' INITIAL PRESSURE DISTRIBUTION '
DO 100 I= 1,10
100 WRITE (6,200) XMSH(I),PI(I)
DO 91 I= 2,47
  PP(I-1)= P(I)
  XMM(I-1)= XM(I)
  CGG(I-1)= CG(I)
91  CONTINUE
200 FORMAT(2F22.4)
  RETURN
  END

```

SUBROUTINE NEWDAT (IA)

```

IMPLICIT REAL*8 (A-H,O-Z)
INCLUDE 'DM.1'
INCLUDE 'CM.2'
INCLUDE 'CM.3'
INCLUDE 'DM.4'
INCLUDE 'DM.5'

DO 30 N= 1,10
  IF(STIME.EQ.0.) THEN
    CALL TABSEQ(PP,XMM,46,PI(N),XMI(N))
  ELSE
    IF(IA.EQ.0) THEN
      IF(N.GE.2) XMI(N)= XMN(N)
    ELSE
      XMI(N)= XMN(N)
    ENDIF
  ENDIF
  CALL TABSEQ(P,VISC,47,PI(N),VISCI(N))
  CALL TABSEQ(P,Z,47,PI(N),ZI(N))
  CALL TABSEQ(PP,CGG,46,PI(N),CGI(N))
30  CONTINUE
  RETURN
  END

```

SUBROUTINE COMPUT (IA)

```

IMPLICIT REAL*8 (A-H,O-Z)

INCLUDE 'DM.1'
INCLUDE 'CM.2'
INCLUDE 'CM.3'
INCLUDE 'DM.4'
INCLUDE 'DM.5'

```

C COMPUTE MATRIX COEFFICIENT

```

DO 17 I= 1,10
  X(I)= PI(I)/(AA*PSAT+BB*PI(I))
  DXDP(I)= AA*PSAT/(AA*PSAT+BB*PI(I))**2
*  A1(I)= PHI*WM*VISCI(I)*CGI(I)
*          *(1.-X(I)*RHOR*(1.-PHI)/(DSTW*PHI))
*          -WM*DXDP(I)*(1.-PHI)*VISCI(I)*RHOR/DSTW
*  A2(I)= DXDP(I)*(1.-PHI)*VISCI(I)*RHOR
*          *(ZI(I)*R*TP/PI(I))
  A(I)= A1(I)+A2(I)
  C(I)= 2.*XK*PI(I)*XG*CGI(I)*WM**2/(ZI(I)*R*TP)
17  CONTINUE
  B= XK*WM
  IF(IA.EQ.0) THEN

```

```

DO 188 I= 2,10
  IF(I.EQ.2) THEN
    DI(I-1)= 1.+2.*B*WGT*DT/ (A(I)*DX**2)
    U(I-1)= -B*WGT*DT/(A(I)*DX**2)
    *      +C(I)*WGT*DT/ (2.*DX*A(I))
    S(I-1)= (1.-2.*B*(1.-WGT)*DT/ (A(I)*DX**2))*XMI(I)
    *      +(B*(1.-WGT)*DT/(A(I)*DX**2)
    *      -(1.-WGT)*C(I)*DT/ (2.*DX*A(I)))*XMI(I+1)
    *      +(B*DT/(A(I)*DX**2)+C(I)*DT/(2.*DX*A(I)))*XMI(I-1)
  ELSEIF (I.EQ.10) THEN
    DI(I-1)= 1.+B*WGT*DT/(A(I)*DX**2)+C(I)*WGT*DT/(2.*A(I)*DX)
    T(I-1)= -B*WGT*DT/(A(I)*DX**2)-C(I)*WGT*DT/(2.*A(I)*DX)
    *      S(I-1)= (1.-B*(1.-WGT)*DT/(A(I)*DX**2))*XMI(I)
    *      - (1.-WGT)*C(I)*DT*XMI(I)/(2.*DX*A(I))
    *      +B*(1.-WGT)*DT*XMI(I-1)/(A(I)*DX**2)
    *      +C(I)*(1.-WGT)*DT*XMI(I-1)/(2.*A(I)*DX)
  ELSE
    DI(I-1)= 1.+2.*B*WGT*DT/(A(I)*DX**2)
    T(I-1)= -WGT*B*DT/(A(I)*DX**2)-C(I)*WGT*DT/(2.*DX*A(I))
    U(I-1)= -B*WGT*DT/(A(I)*DX**2)+C(I)*WGT*DT/(2.*DX*A(I))
    *      S(I-1)= B*(1.-WGT)*DT*(XMI(I+1)+XMI(I-1))/(A(I)*DX**2)
    *      +XMI(I)*(1.-2.*B*(1.-WGT)*DT/(A(I)*DX**2))
    *      +(1.-WGT)*C(I)*DT*(XMI(I-1)-XMI(I+1))/(2.*DX*A(I))
  ENDIF
188  CONTINUE
    CALL THOMAS(1,9,T,DI,U,S)
    DO 90 I=1,9
90   XMN(I+1)= S(I)
  ELSE
DO 189 I= 1,10
  IF(I.EQ.1) THEN
    D1(I)= 1.+B*WGT*DT/(A(I)*DX**2)-C(I)*WGT*DT/(2.*A(I)*DX)
    U1(I)= -B*WGT*DT/(A(I)*DX**2)+C(I)*WGT*DT/(2.*A(I)*DX)
    *      S1(I)= (1.-B*(1.-WGT)*DT/(A(I)*DX**2))*XMI(I)
    *      +(1.-WGT)*C(I)*DT*XMI(I)/(2.*A(I)*DX)
    *      +B*(1.-WGT)*DT*XMI(I+1)/(A(I)*DX**2)
    *      -(1.-WGT)*C(I)*DT*XMI(I+1)/(2.*DX*A(I))
    *      -RATE*R*TP*453.592*DT/(CA*DX*3600.*A(I))
  ELSEIF (I.EQ.10) THEN
    D1(I)= 1.+B*WGT*DT/(A(I)*DX**2)+C(I)*WGT*DT/(2.*A(I)*DX)
    T1(I)= -B*WGT*DT/(A(I)*DX**2)-C(I)*WGT*DT/(2.*A(I)*DX)
    *      S1(I)= (1.-B*(1.-WGT)*DT/(A(I)*DX**2))*XMI(I)
    *      -(1.-WGT)*C(I)*DT*XMI(I)/(2.*DX*A(I))
    *      +B*(1.-WGT)*DT*XMI(I-1)/(A(I)*DX**2)
    *      +(1.-WGT)*C(I)*DT*XMI(I-1)/(2.*A(I)*DX)
  ELSE
    D1(I)= 1.+2.*B*WGT*DT/(A(I)*DX**2)
    T1(I)= -WGT*B*DT/(A(I)*DX**2)-C(I)*WGT*DT/(2.*DX*A(I))
    U1(I)= -B*WGT*DT/(A(I)*DX**2)+C(I)*WGT*DT/(2.*DX*A(I))
    *      S1(I)= B*(1.-WGT)*DT*(XMI(I+1)+XMI(I-1))/(A(I)*DX**2)
    *      +XMI(I)*(1.-2.*B*(1.-WGT)*DT/(A(I)*DX**2))
    *      +(1.-WGT)*C(I)*DT*(XMI(I-1)-XMI(I+1))/(2.*DX*A(I))
  ENDIF
189  CONTINUE
    CALL THOMAS(1,10,T1,D1,U1,S1)
    DO 91 I=1,10
91   XMN(I)= S1(I)
  ENDIF

```

C NEW PRESSURE IN CORE. NEW FLOW RATE

```

IF(IA.EQ.0) THEN
  IN= 2
ELSE
  IN= 1
ENDIF

```



```

DO 40 I= IN,10
    CALL TABSEQ(XMM,PP,46,XMN(I),PI(I))
40 CONTINUE
CALL TABSEQ(P,V,47,PI(2),VOL)
RO1= (1./VOL)
XF= CA*RO1*XK*(PI(2)-PI(1))/(VISCI(2)*DX)
XFLUX= XF*3600./453.592
RETURN
END

```

```

C
C SEQUENTIAL SEARCH AND LINEAR INTERPOLATION
C

```

```

SUBROUTINE ,TABSEQ (X,Y,N,XX,YY)

REAL*8 X(*),Y(*),XX,YY

I= 1
100 I= I+1
IF(I.GT.N) GO TO 98
IF(XX.GT.X(I)) GO TO 100
YY= Y(I-1)+(Y(I)-Y(I-1))*(XX-X(I-1))/(X(I)-X(I-1))
RETURN
99 YY= Y(1)
WRITE(6,88)
WRITE(6,89)XX
88 FORMAT(1X,' WARNING - ARGUMENT OUT OF TABLE ')
89 FORMAT(F22.6)
RETURN
98 YY= Y(N)
WRITE(6,89)XX
RETURN
END

```

```

SUBROUTINE: THOMAS (IL,IU,BB,DD,AA,CC)
REAL*8 BB(1),AA(1),DD(1),CC(1)

LP= IL+1
DO 10 I= LP,IU
R= BB(I)/DD(I-1)
DD(I)= DD(I)-R*AA(I-1)
10 CC(I)= CC(I)-R*CC(I-1)
CC(IU)= CC(IU)/DD(IU)
DO 20 I= LP,IU
J= IU-I+1L
20 CC(J)= (CC(J)-AA(J)*CC(J+1))/DD(J)
RETURN
END

```

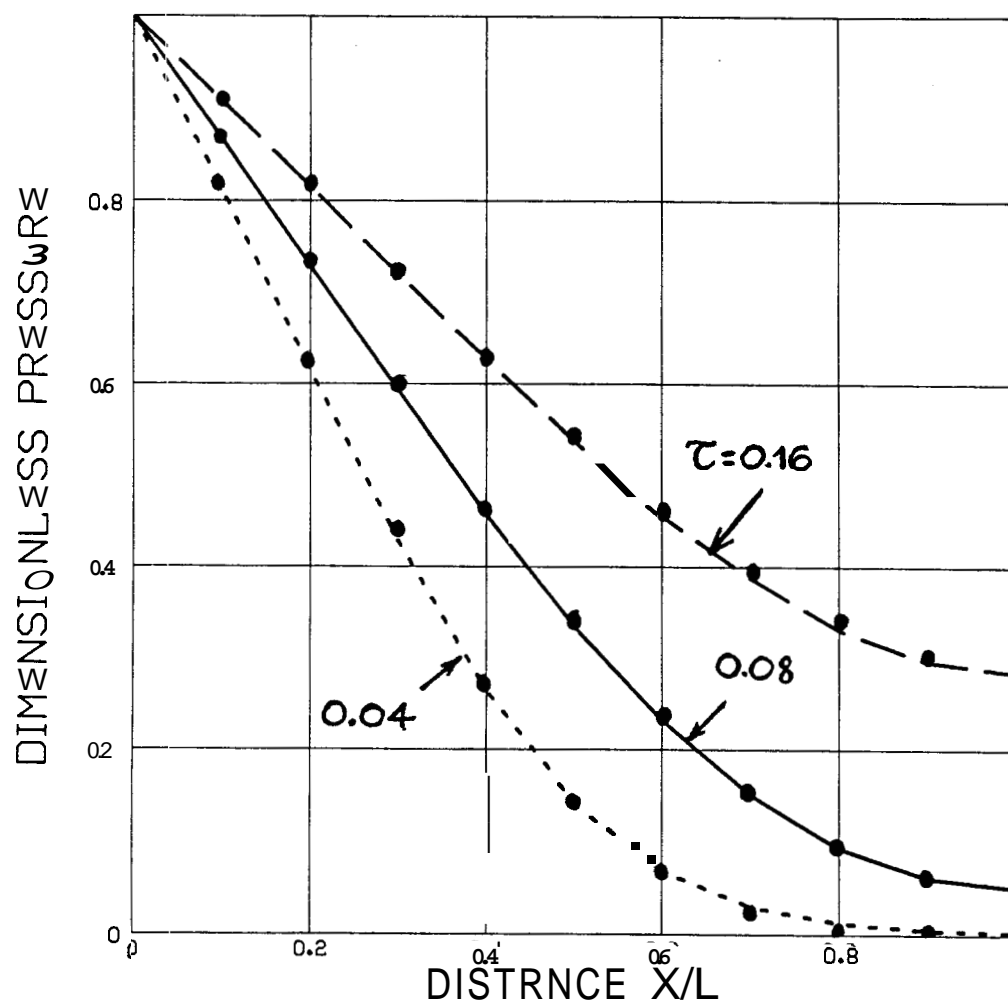


Fig.1: Pressure rise in Finite Tube with closed end for pressure ratio 2/1. Solid line is computed with finite difference program and points were Jenkins - Aronofsky (1951).

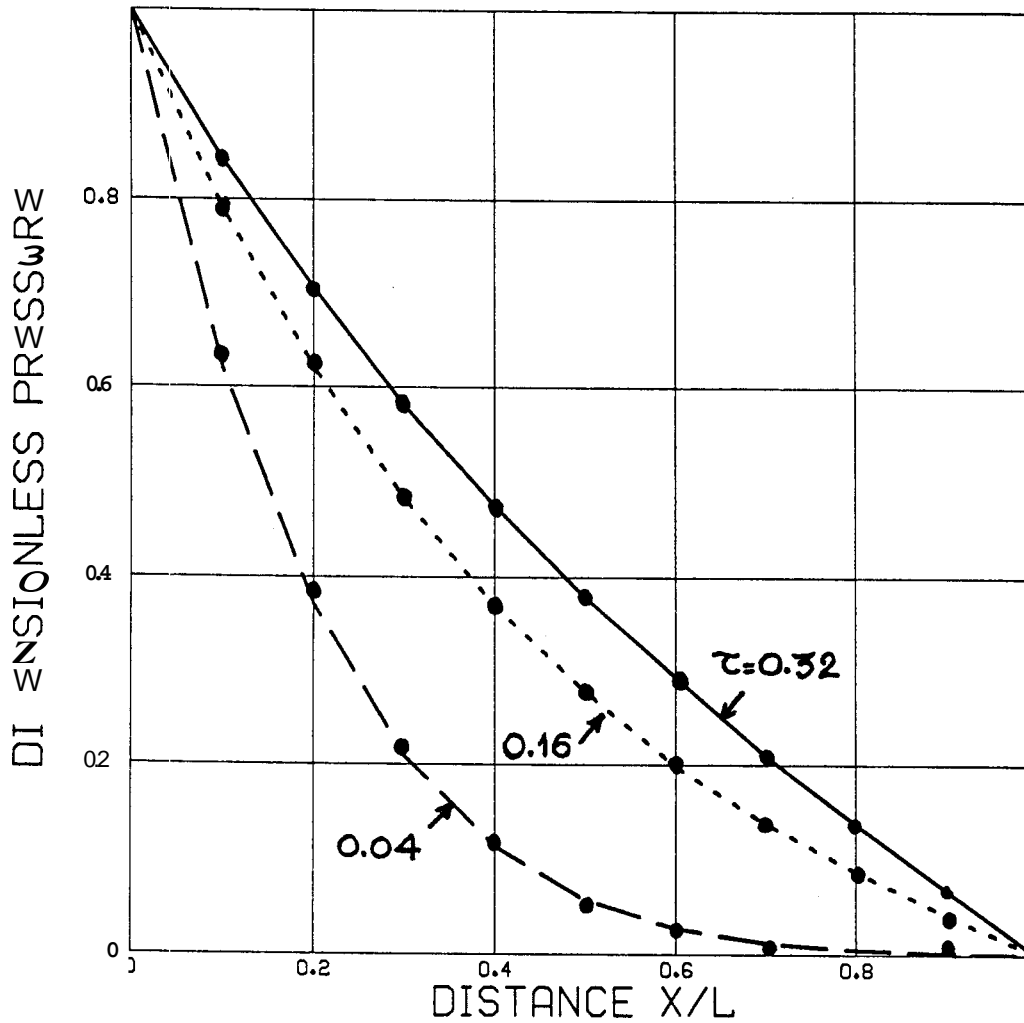


Fig.2: Pressure distribution in finite tube with constant end pressure for pressure ratio 1/2. Solid line is computed with finite difference program and points were Jenkins - Aronofsky (1951).

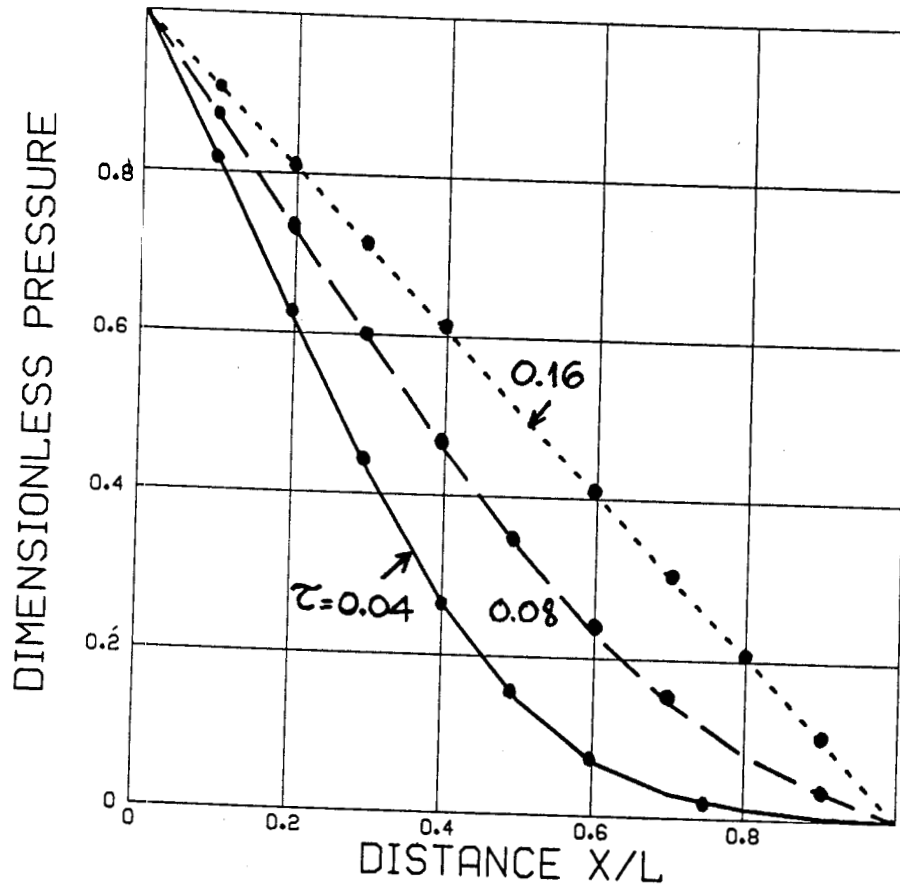


Fig.3: Pressure distribution in finite tube with constant end pressure for pressure ratio 2/1.

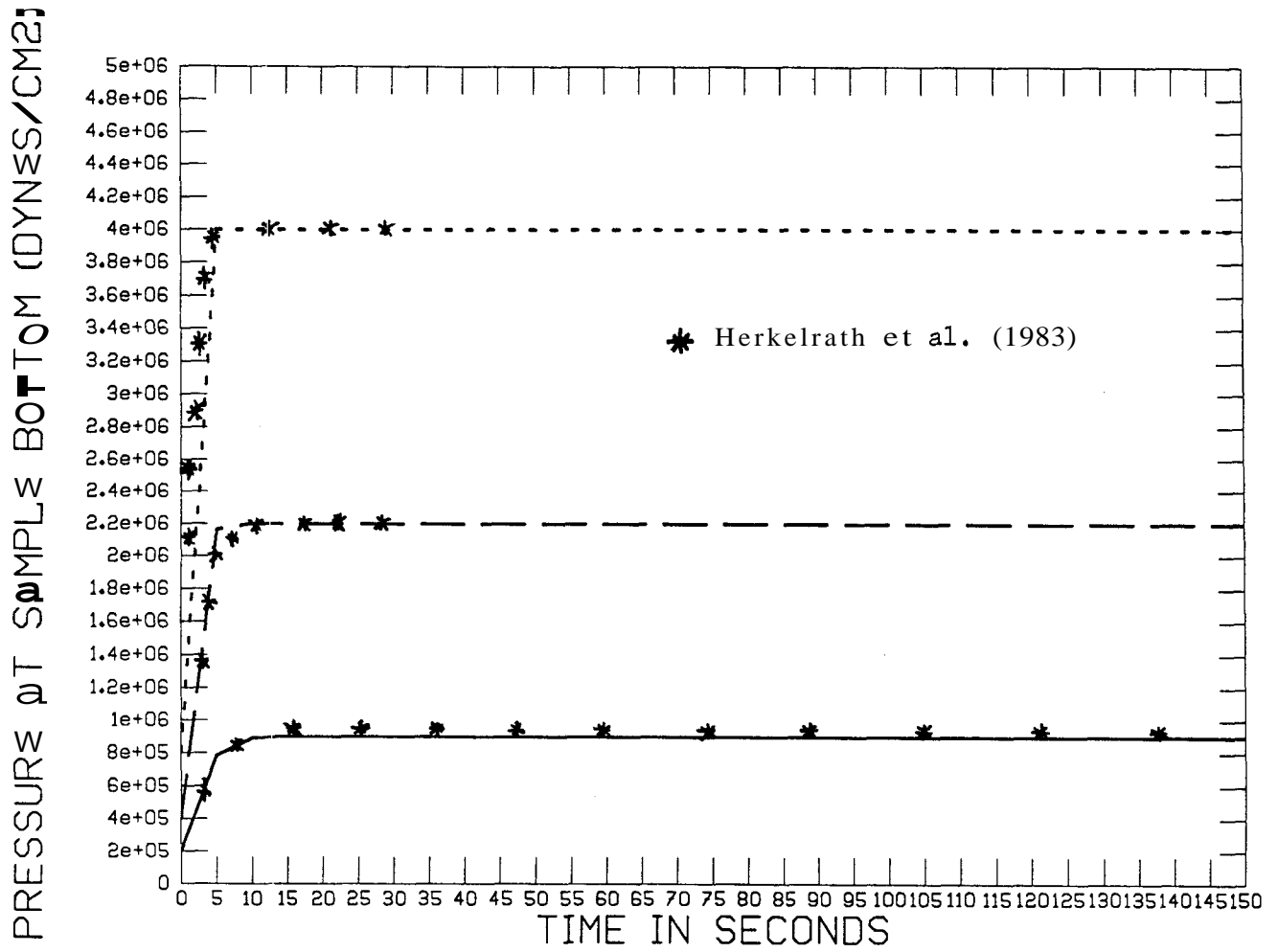


Fig.4: Steam pressure response at the closed end of a porous cylinder to a step increase in pressure imposed at the end neglecting adsorption.

PRESSURE AT SOURCE (DYNES/C<sup>2</sup>)

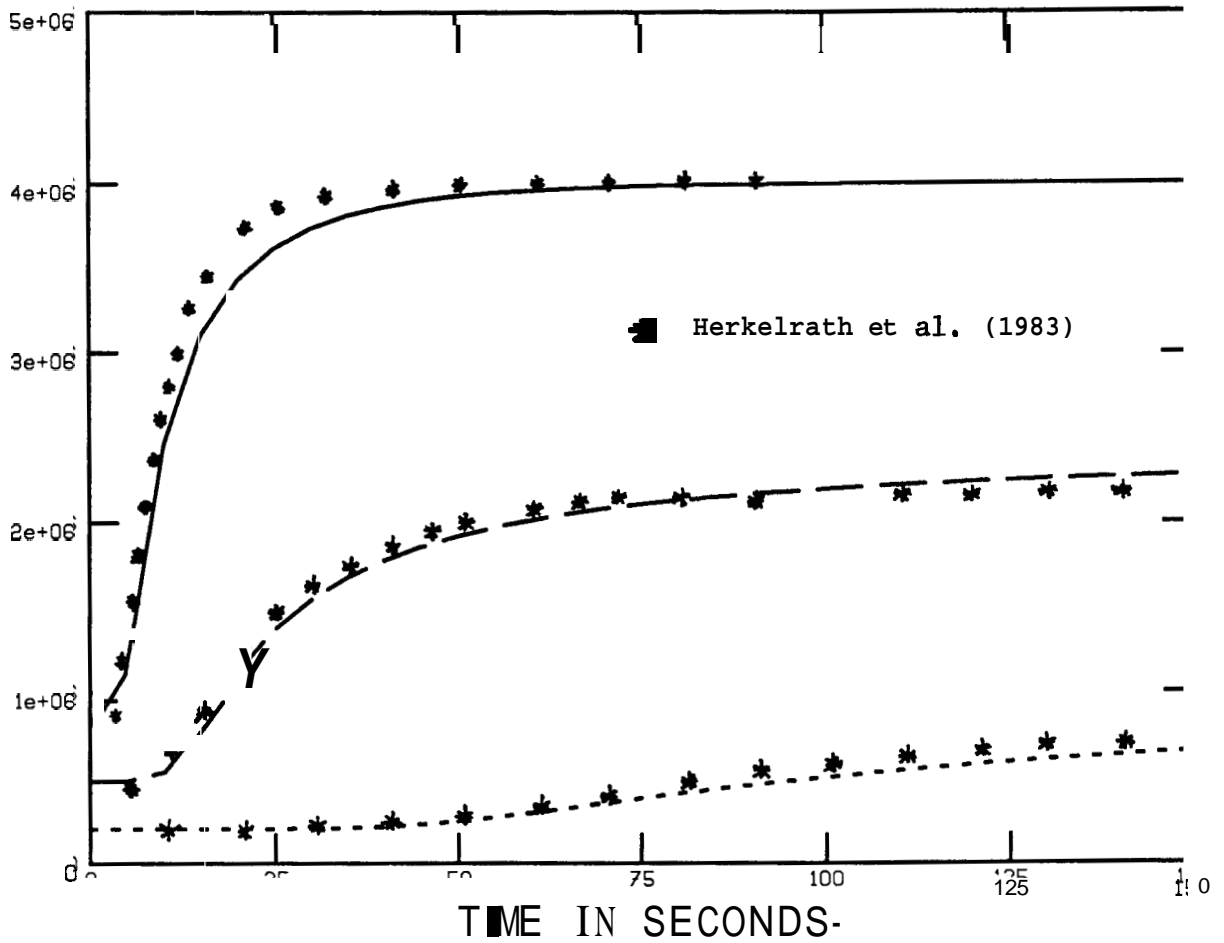


Fig.5: Computed Steam Pressure response at the closed end of a porous cylinder caused by a step increase in pressure at the other end (Herkelrath, et al. (1983)).

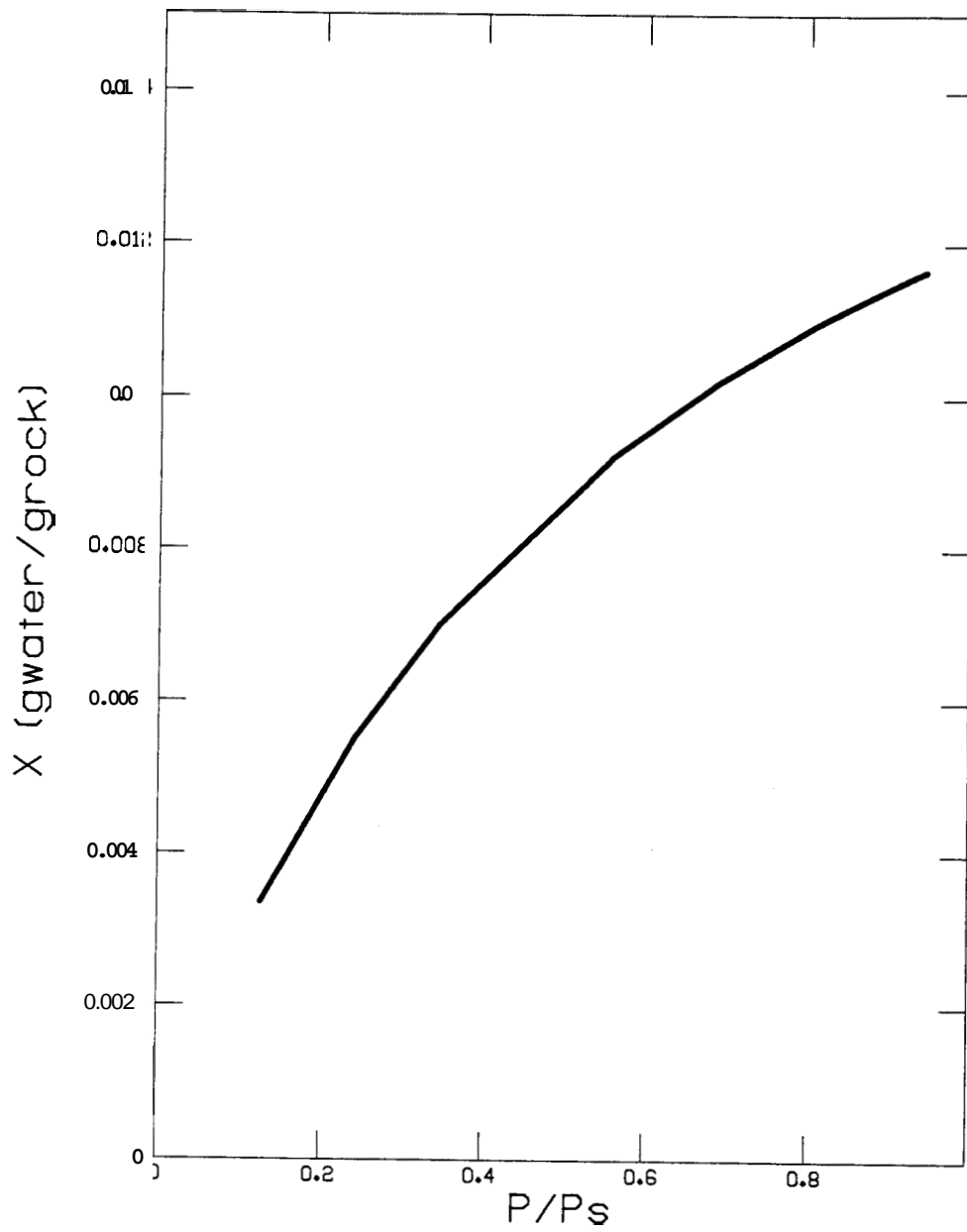


Fig.6: Langmuir Adsorption isotherm for dirty sandstone.

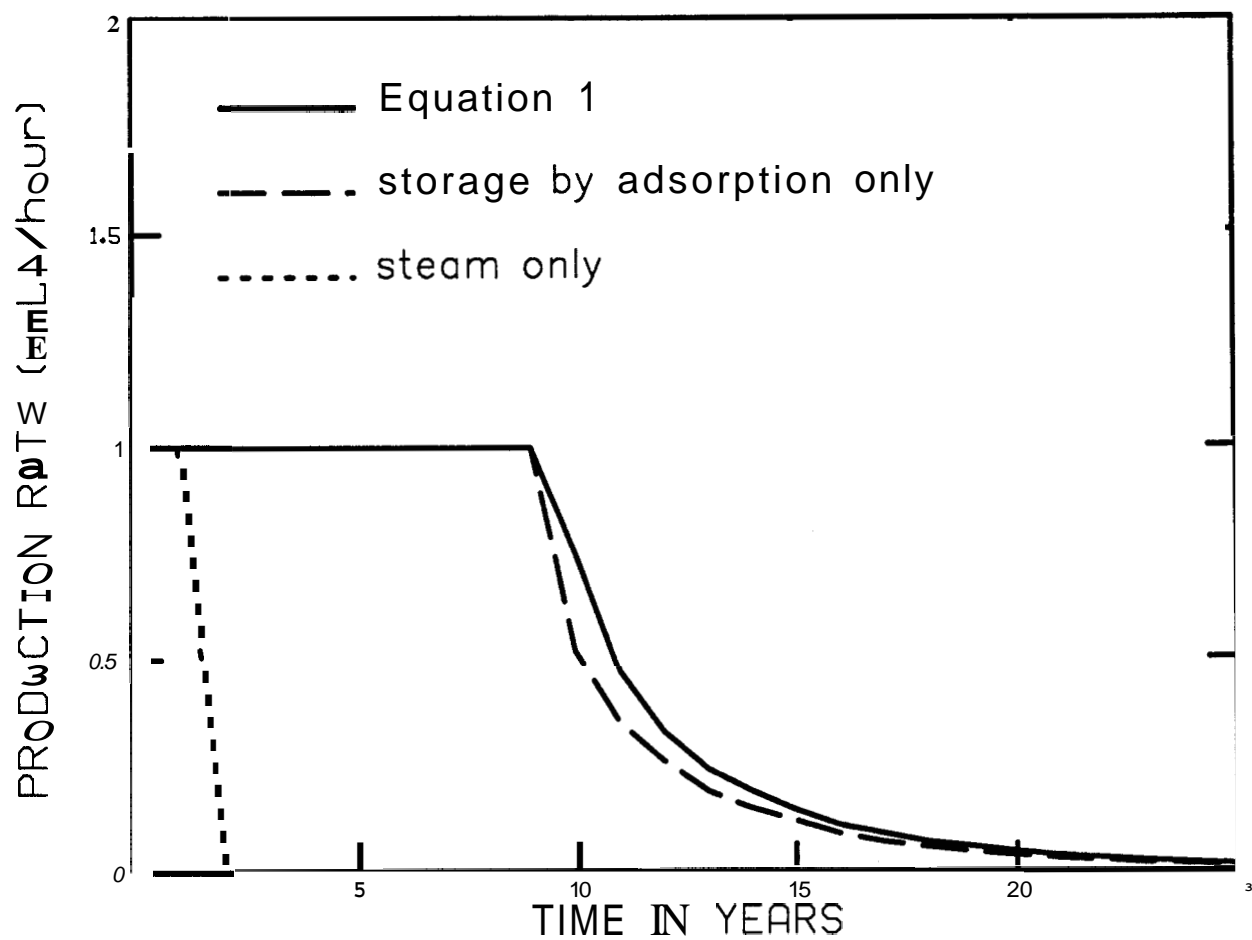


Fig.7: Production history according to different theories,



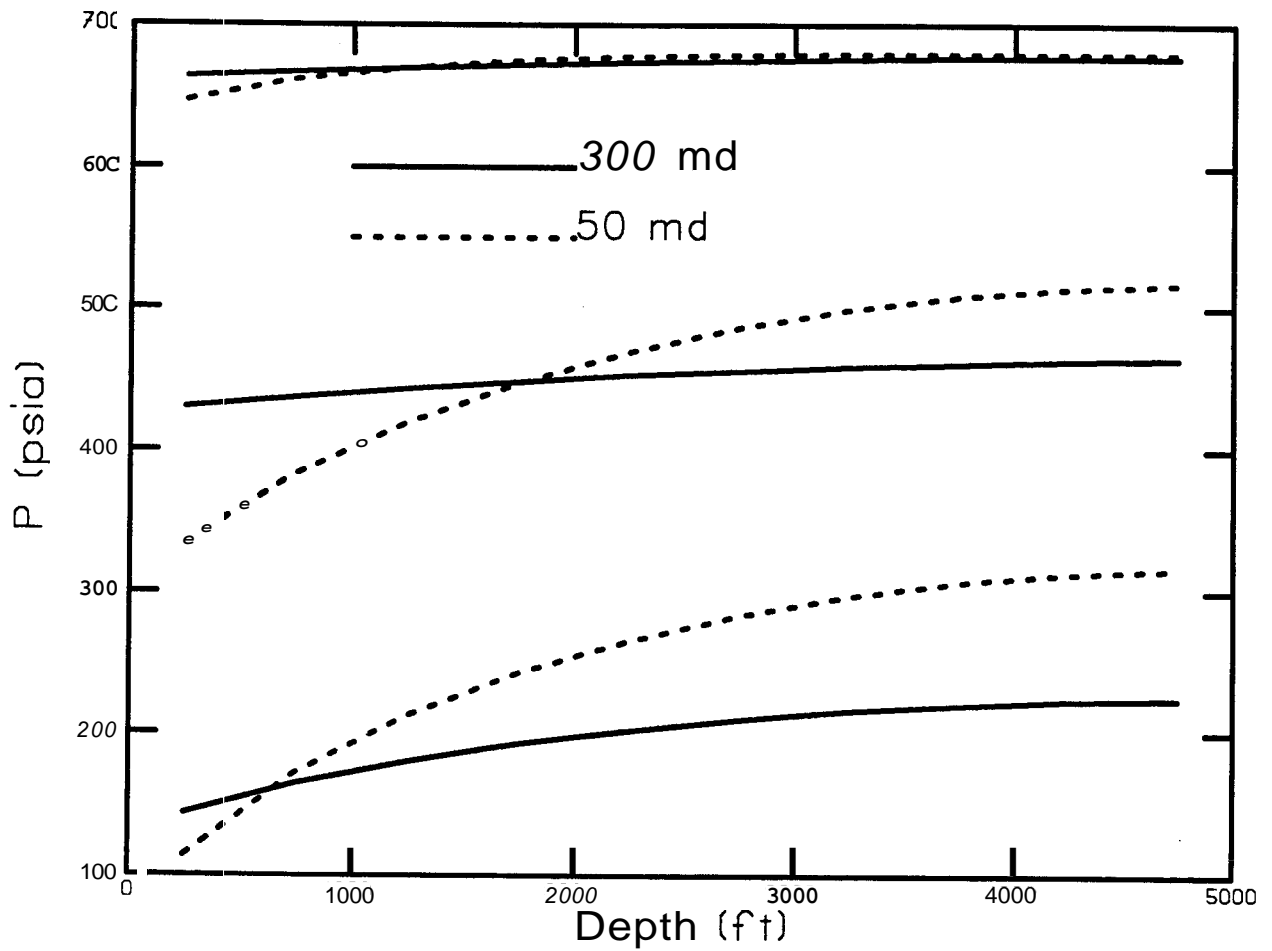


Fig.8:: Pressure distribution in the reservoir for different permeabilities (1 month, 3 years, 9 years).

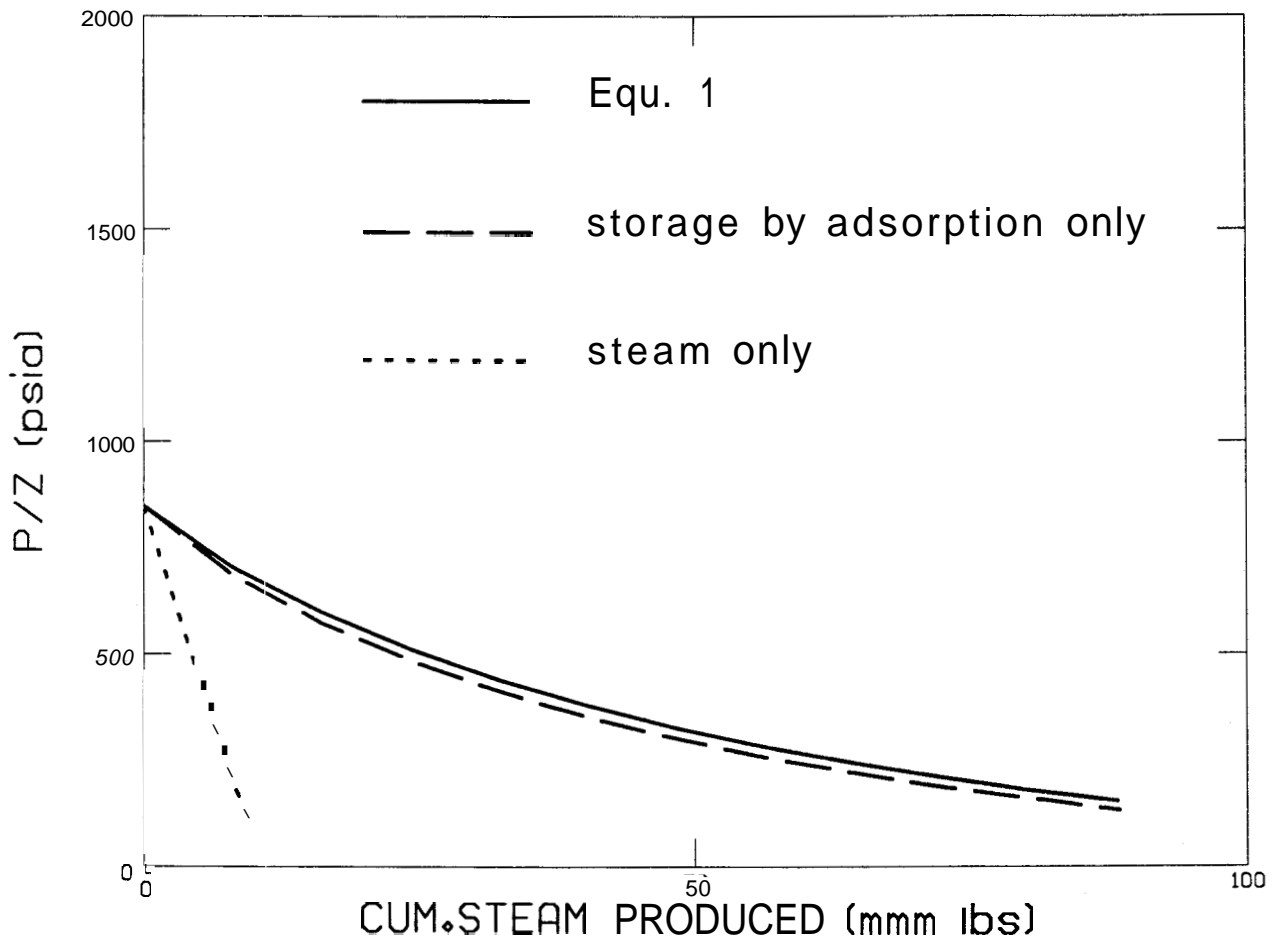


Fig.9: p/z vs cumulative mass produced. The initial mass in place is 1.7 billion lbs steam.

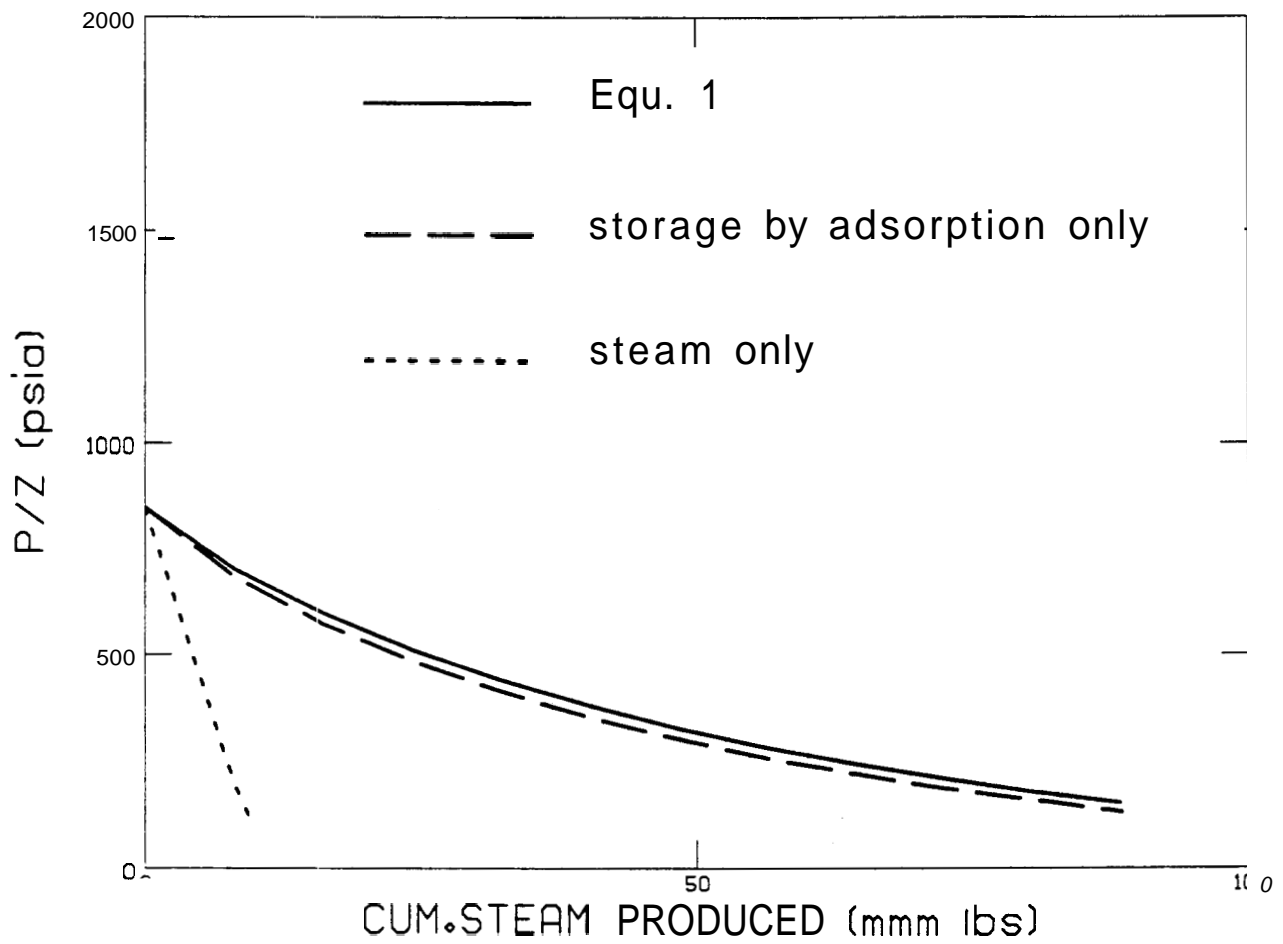


Fig.9: p/z vs cumulative mass produced. The initial mass in place is 1.7 billion lbs steam.