SGP-TR-100

Collection and Evaluation of Flowing Pressure and Temperature Data from Geothermal Wells

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ABSTRACT

Two-phase flow **occurs** in geothermal wellbores, ***so*** it is important to have the capability of modeling vertical two-phase flow for proper well and reservoir management. Investigators have used several correlations to this end and testing of these correlations have been reported in the literature. However, a large data set covering a wide range of flowrate, fluid enthalpy, wellhead pressure and well depth, has not appeared in a single study, that could then be available to test specific models against. This report is intended to fill that gap by providing as complete a data set as possible on flowing pressure and temperature profiles from ten geothermal wells around the world. It **also** provides calculated pressure and temperature profiles for these wells using the Orkiszewski **(1967)** correlations. Analysis of pressure profiles and flow pattern transitions for the ten geothermal wells in our study is also presented. The analysis suggests general applicability of Orkiszewski's **(1967)** correlations for geothermal wellbore flow under a variety of situations. Most of the geothermal wells tested in this study flowed in the slug flow regime.

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1. INTRODUCTION

Two-phase vertical geothermal wellbore flow studies are important for well and reservoir management purposes. Several studies have appeared in the past on how to model two-phase flow in geothermal wellbores with limited testing of the models. This report is intended to provide a compilation of data for two-phase calculations from ten geothermal wells around the world, covering a wide range of flowrate, well-head pressure, fluid enthalpy and depth. Our data set covers:

- Flowrate **12.9-68.6** kg/sec
- Wellhead pressure **2.3-56.5** bar-g
- Fluid enthalpy **965-1966 kJ/kg**
- Depth **913-2600** m

Such a collection of data should be helpful for investigators in the future to test an existing or new model rigorously to determine general applicability of a given model.

In this study, we provide calculated pressure and temperature profiles for the ten wells using the Orkiszewski **(1967)** correlations. **A** computer program used by Ortiz-R. **(1983)** with minor modifications was used for this purpose. **A** brief description of the computer program is presented in Chapter **2.**

This wellbore simulator has been used in the Stanford Geothermal Program for different studies. e.g., Gudmundsson, Ortiz-R., and Granados-G. **(1984)** and Gudmundsson **(1984)** used the simulator to study wellbore calcite deposition and discharge analysis problems. Gudmundsson, Ortiz-R., and Granados-G. **(1984)** used the Orkiszewski **(1967)** model for two-phase flow in geothermal wells after a slight modification in the way the liquid distribution coefficient τ was calculated. They found that wellbore calcite deposition results in slow output decline at early time, but rapid decline at late times. Gudmundsson **(1984)** presented a step-by-step procedure for discharge analysis of two-phase geothermal wells. Gudmundsson, Ambastha and

Thorhallsson **(1984)** used the simulator to analyse discharge characteristics of well 9 in Reykjanes field, Iceland. The measured output of this well was 180 kg/sec at a well-head pressure of 20 bar-g. Calculations showed that the well deliverability depends greatly on the wellbore diameter and the enthalpy of the steam-brine mixture.

Calculated and measured pressure and temperature profiles appear in Chapter 3. A summary of the effort in this study is presented in Chapter **4.** The computer program listing with typical input and output sheets are presented in Appendix **A** and **B,** respectively. Appendix C contains relevant measured pressure and temperature data from the ten wells. Analysis of pressure profiles and flow pattern transitions appear as papers in Appendix D.

Last but not least, we appreciate the cooperation on this study with CFE in Mexico, METU in Turkey, and MWD in New Zealand.

2. DESCRIPTION OF COMPUTER PROGRAM

A computer program used by Ortiz-R. (1983) with minor modifications was used in this study. Modification of the computer program involved **flow** regime transition criteria. In particular, the bubble flow regime criterion presented **by** Ortiz-R. (1983) as expression (12) in his report is replaced by

$$L_{b/s} > v_{sg}/v_{sT} \tag{1}$$

to make it consistent with the original Orkiszewski (1967) method. Further details on this criterion are mentioned in Ambastha and Gudmundsson (1986a).

The input system of the computer code has been changed from formatted input to unformatted input for easier data entry. The order in which the input data is entered remains the same. The output file system has been modified to get more information about a particular run than was being obtained before. In particular, the program now opens two files to get flowing pressure and temperature data vs. depth so that it is convenient to get such graphs from a run. The units of pressure, temperature and depth are in bar-g, degree C and meter respectively. It also opens files to report data on both dimensionless liquid and gas numbers and diameter number as the calculation proceeds in the sections of the wellbore where two-phase flow occurs. Specific file names opened for these purposes are mentioned in the documentation part of the program.

The rest of the details of the computer program are the same as in Ortiz-R. (1983). This wellbore simulator was fist developed by Fandriana et al . (1981), and later modified by Ortiz-R. (1983). The program allows calculations to **start** from the wellhead or bottomhole. Steam table values are used to interpolate steam/water properties. Wellbore heat transmission **is** considered in the program by using an overall heat transfer coefficient. Wellbore string design with many diameters can be handled in the program. However, the effects of noncondensable gases and solids in the flowstream are neglected in the program.

A complete listing of the modified program appears in Appendix A. Appendix B contains typical input and output sheets for one of the runs in this study.

3. PRESSURE AND TEMPERATURE PROFILES

Measured pressure and temperature data for all ten wells appear in Appendix C, with the exception of measured temperature data for Utah State 14-2 which was not available. Data were obtained from various sources mentioned in Ambastha and Gudmundsson (1986b). Data used to calculate pressure and temperature profiles is provided in Table 1 of Ambastha and Gudmundsson (1986b). One can obtain more information about the wells by referring to the original sources. For consistency, calculations were done from surface to bottom. Measured and calculated pressure and temperature profiles appear in Figs. 1-19.

HGP-A well is a special case for which measured pressure and temperature profiles, and discharge tests are available for four different rates. Data presented in Table 1 of Ambastha and Gudmundsson (1986b) belongs to the measurements for the highest rate. Relevant data for all four rates appear in Table 1 of this report.

Analysis of pressure profiles and flow pattern transitions for wells considered in this study is presented in two papers attached in Appendix D. Again, data in Tables 2 and 3 of Ambastha and Gudmundsson (1986b) belong to the measurements for the highest rate in well HGP-A. Supplements to Tables 2 and 3 in that paper appear as Tables 2 and 3 of this report.

Analysis of temperature profile matches separately or in conjunction with pressure profiles has not been carried out in this study. This may be part of a future project.

TABLE 1
Data used to calculate pressure and temperature profiles from wellhead to bottom for HGP A well

Steam rate klb/hr	Total Flowrate (Steam & Water) kg/s	Mixture Enthalpy kJ/kg	Wellhead Pressure bar-g	Wellbore String Design	Total Depth m
70	13.9	1966	3.2	0.802 ft from 0-680 m 0.5833 ft from 680 m-bottom	1966
66	13.6		6		
58	12.8		14.9		
50	11.6		25.2		

TABLE 2
Values representing two-phase nature of flow at/near wellhead for HGP A well

Steam rate klb/hr	Total Mass Flux kg/s-m^2	Quality at Wellhead	Steam Mass Flux kg/s-m^2	Wellhead Pressure bar-g	Measured Pressure Gradient bar/m	Calculated Pressure Gradient bar/m	Ratio
70	296	0.63	187	3.2	0.0042	0.0049	1.17
66	279	0.61	171	6	0.0029	0.0036	1.24
58	245	0.57	140	14.9	0.0057	0.0029	0.51
50	211	0.54	114.5	25.2	0.0093	0.0033	0.35

TABLE 3
Comparison of measured and calculated pressure profiles for HGP A well

Steam rate klb/hr	Data Points	Measured Pressure Range bar-g	Mean Error bar-g	Standard Deviation of Error bar-g	Mean Percent Error	Standard Deviation of Percent Error
70	17	3.2-16.7	0.6	0.4	6.1	2.7
66		6-20.1	-0.15	0.64	0.7	5.8
58		14.9-34	-2.64	1.2	-10.7	3.7
50		25.2-52.6	-4.64	2.6	-11.3	4.7

4. SUMMARY

This report has provided researchers with data sets for several measured pressure and temperature profiles covering a wide range of conditions. This should be helpful to validate new and existing two-phase geothermal wellbore flow models under a variety of situations. As concluded in Ambastha and Gudmundsson (1986b), the Orkiszewski (1967) correlations seem to have general applicability for geothermal wellbore flow. As suggested in Ambastha and Gudmundsson (1986a), most of the geothermal wells tested in this study flowed in the slug flow regime and further research for geothermal two-phase flow applications should be directed towards the slug flow regime.

Analysis of pressure profiles in Ambastha and Gudmundsson (1986b) indicates that

1. Good matches between calculated and measured pressure profiles were obtained using the correlations if the steam mass flux is larger than 100 kg/s-m^2.
2. Gas content and fluid enthalpy are important parameters in determining the depth of flashing and hence the agreement between calculated and measured pressure profiles.

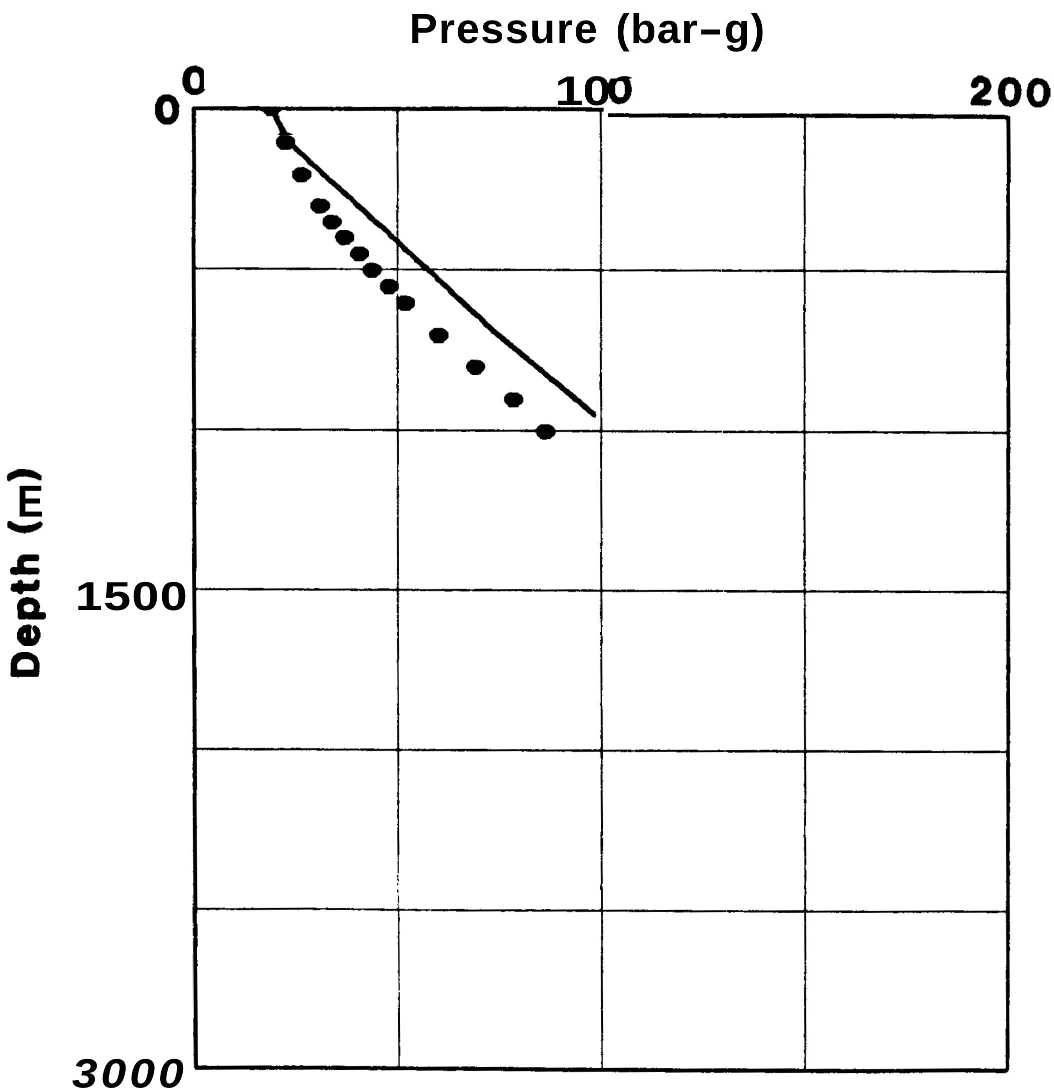

Fig. 1 - Measured and calculated pressure profiles for Ngawha 11.

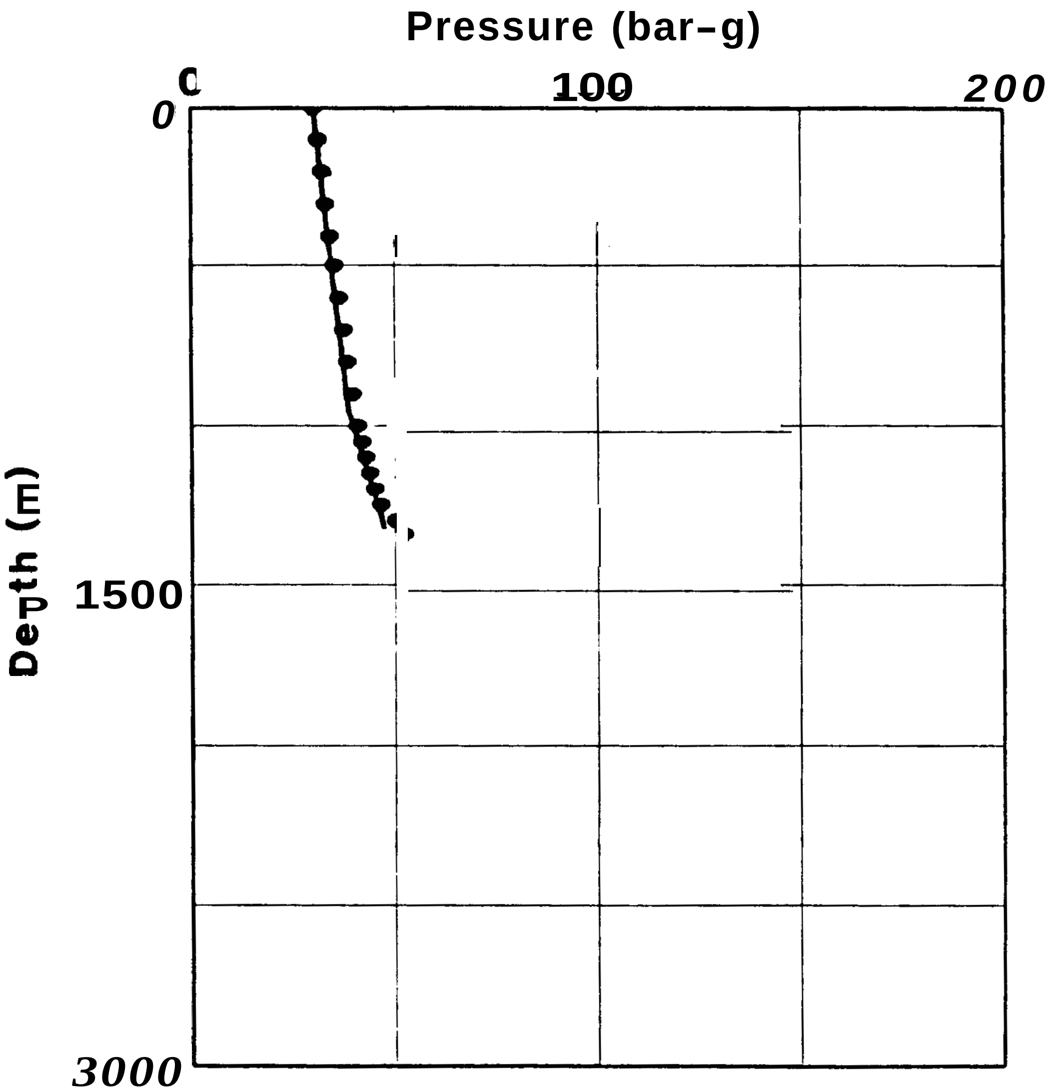

Fig. 2 - Measured and calculated pressure profiles for Los Azufres 18.

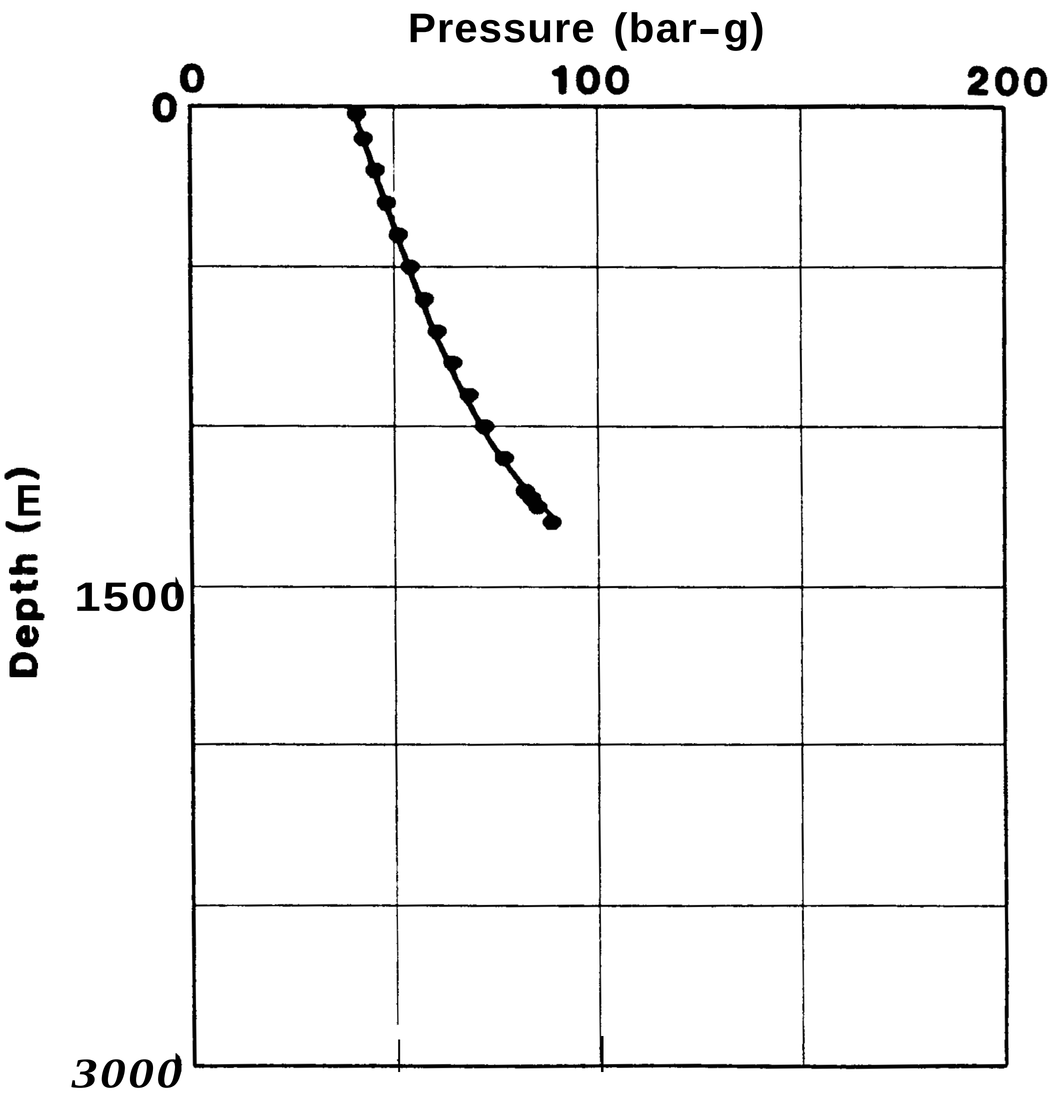

Fig. **3** - Measured and calculated pressure profiles for Cerro-Prieto 90.

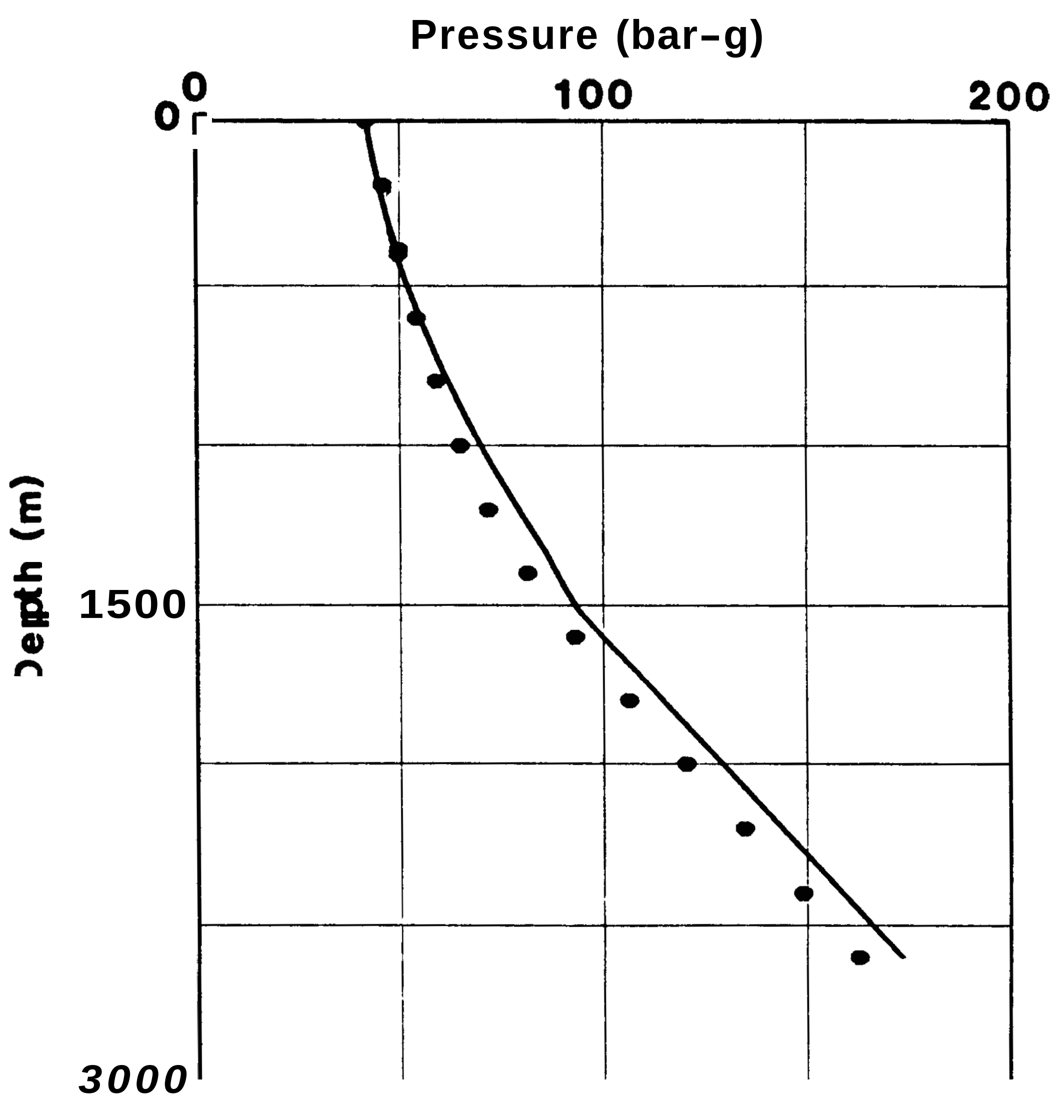

Fig. 4 - Measured and calculated pressure profiles for **Okoy** 7.

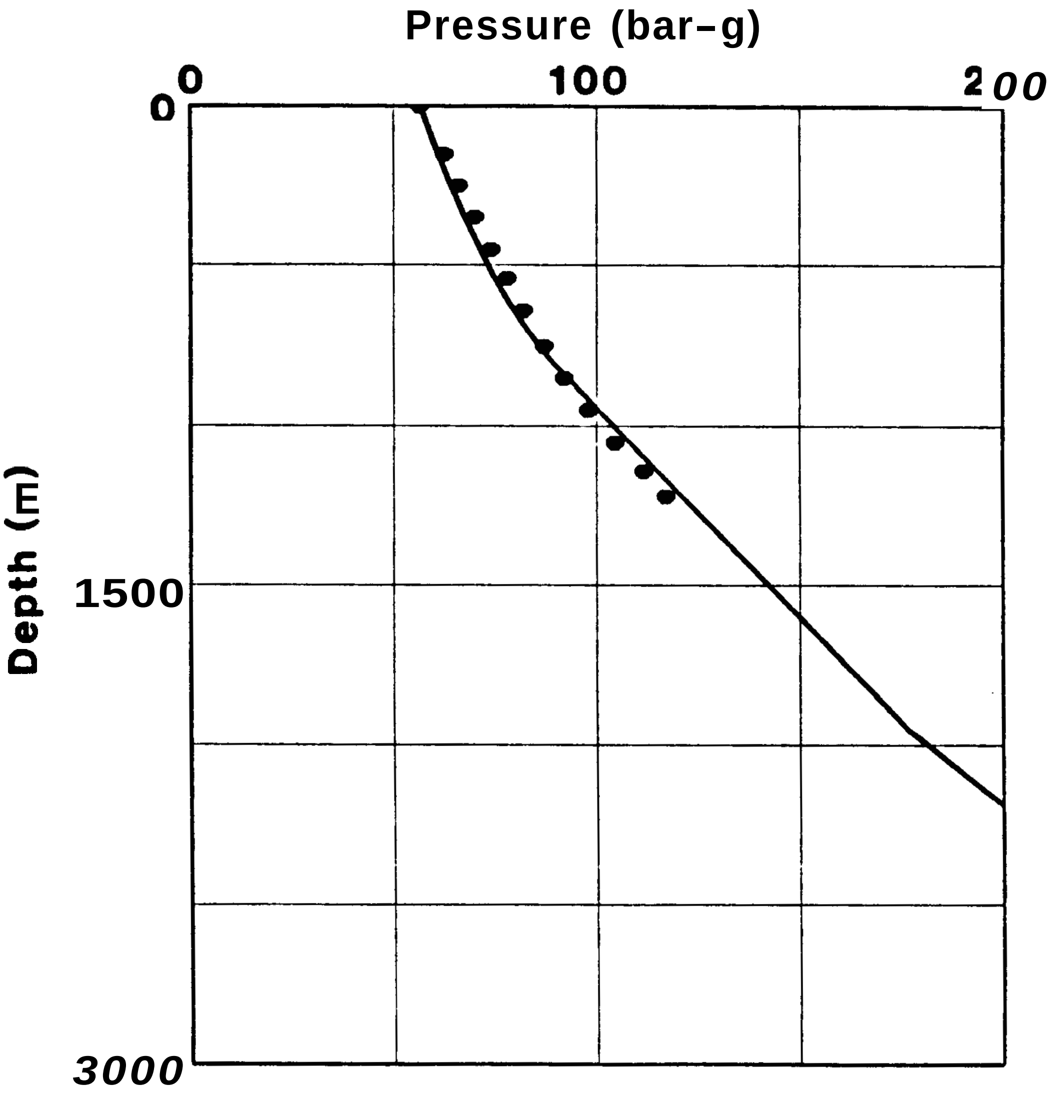

Fig. *5* - Measured and calculated pressure profiles for Cerro-Prieto 91.

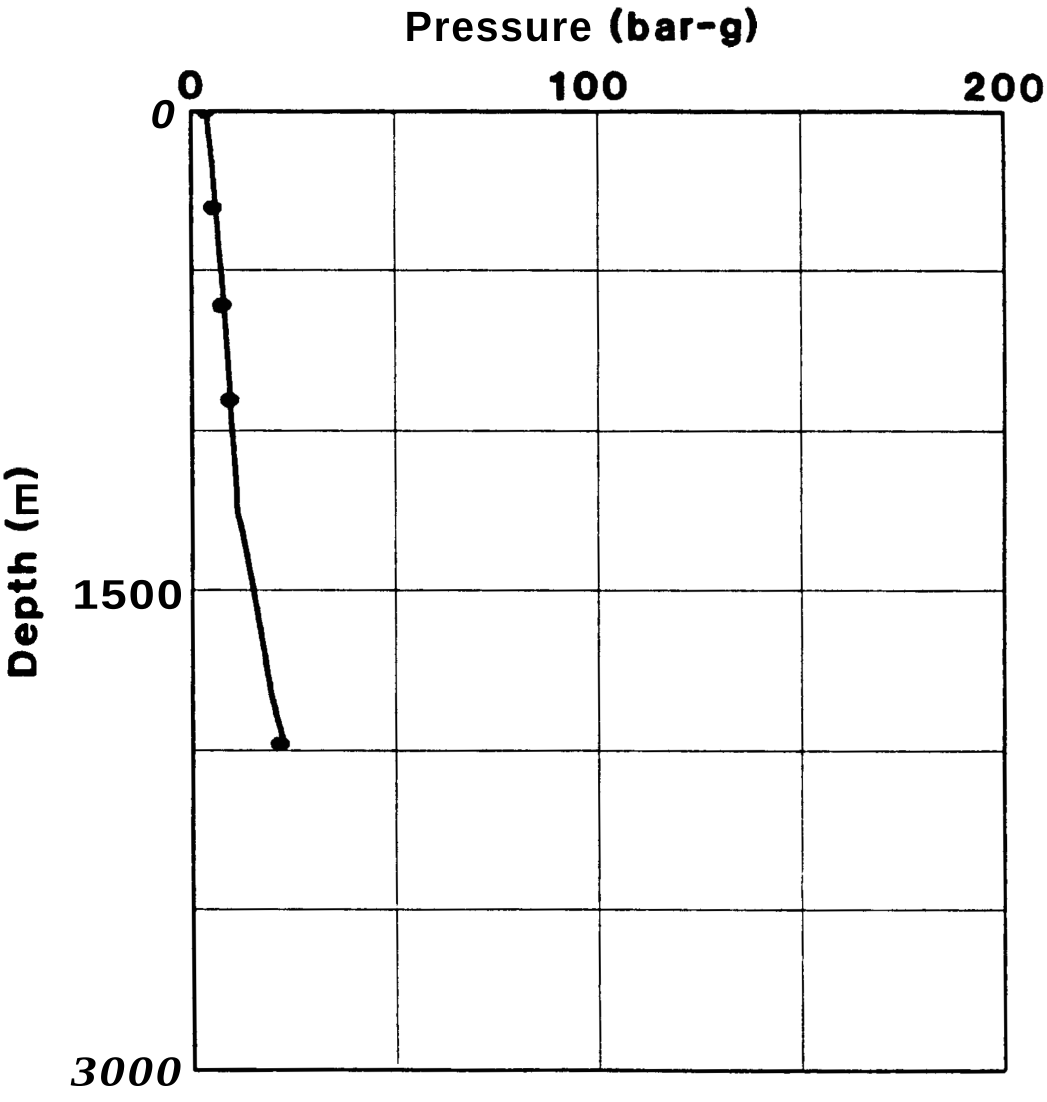

Fig. 6 - Measured and calculated pressure profiles for Mofete 2.

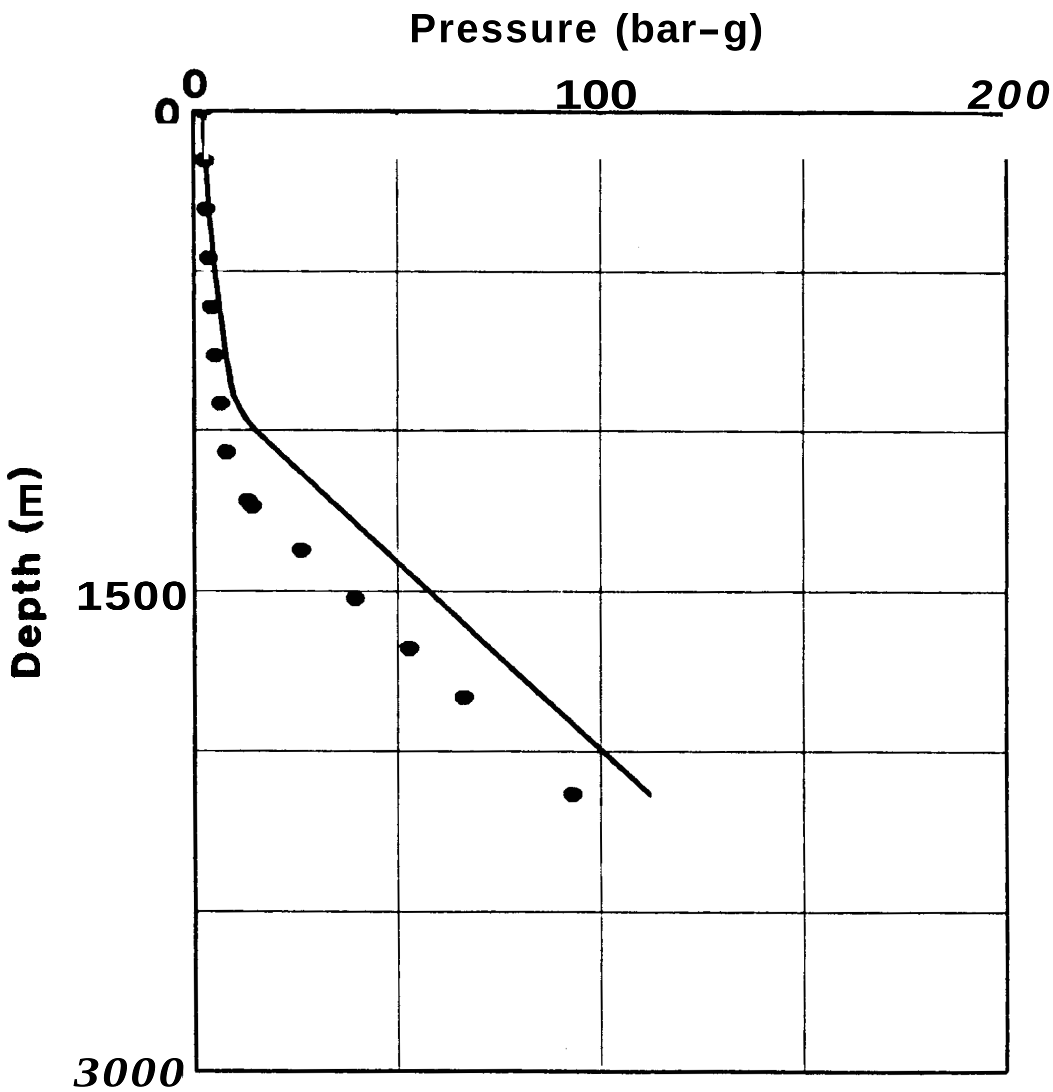

Fig. **7** - Measured and calculated pressure profiles **for** East Mesa *6*.

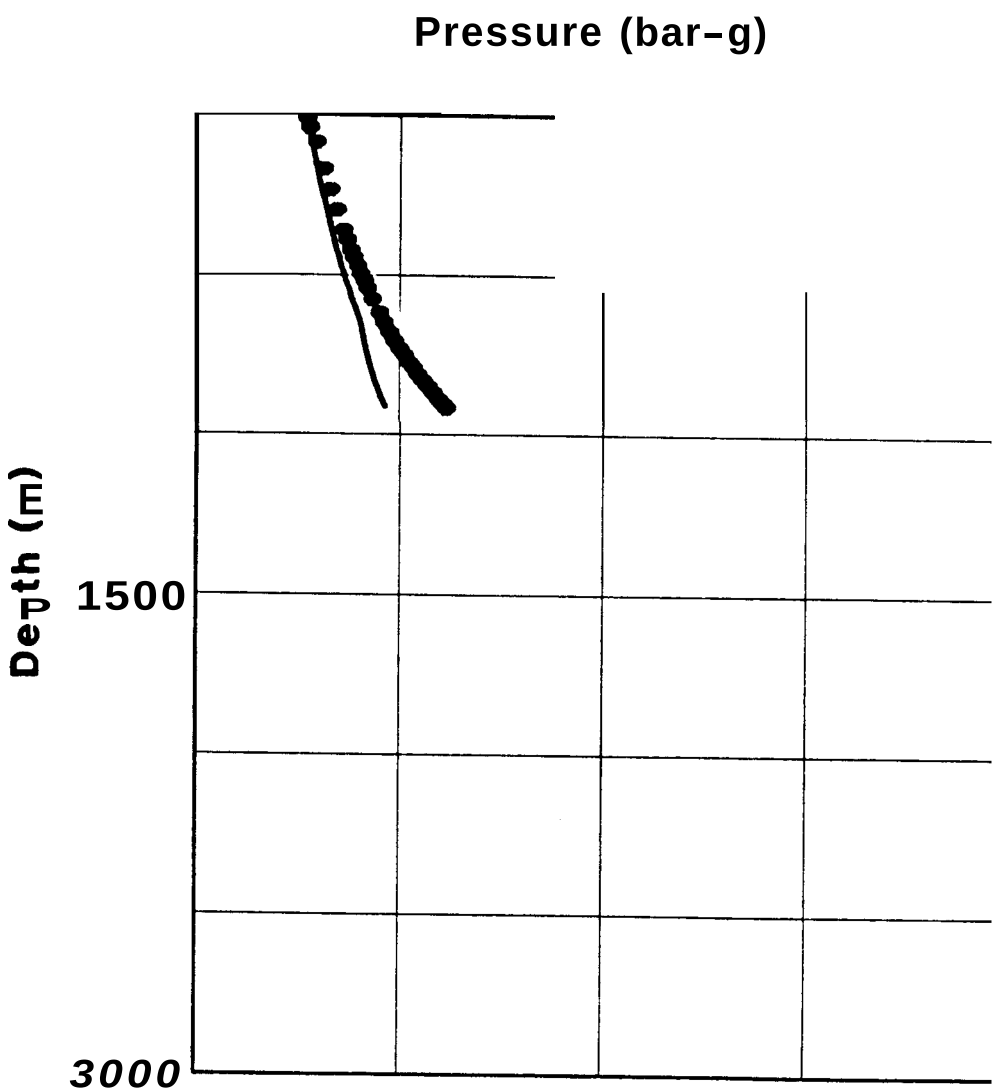

Fig. 8 - Measured and calculated pressure profiles for Utah State **14.**

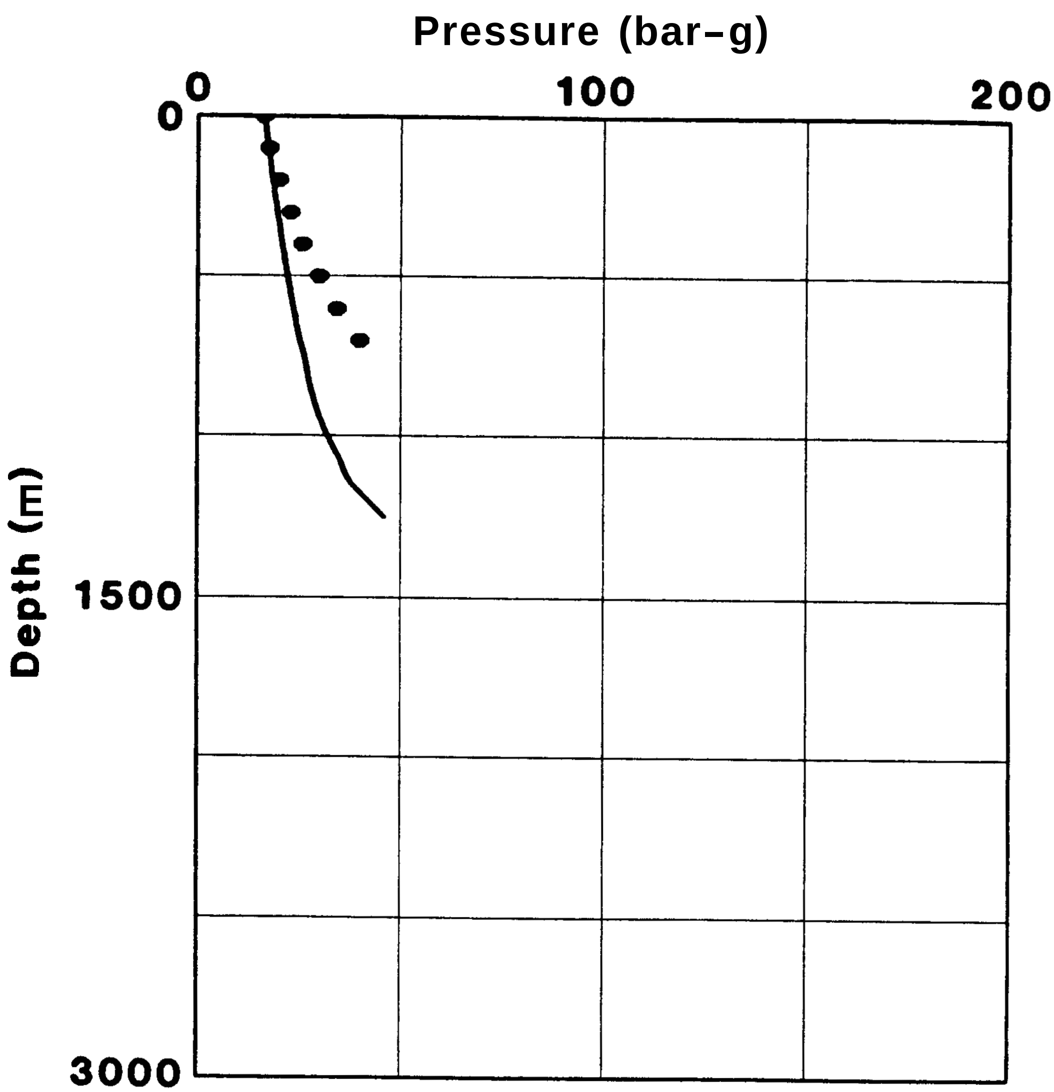

Fig. 9 - Measured and calculated pressure profiles for Krafla 9.

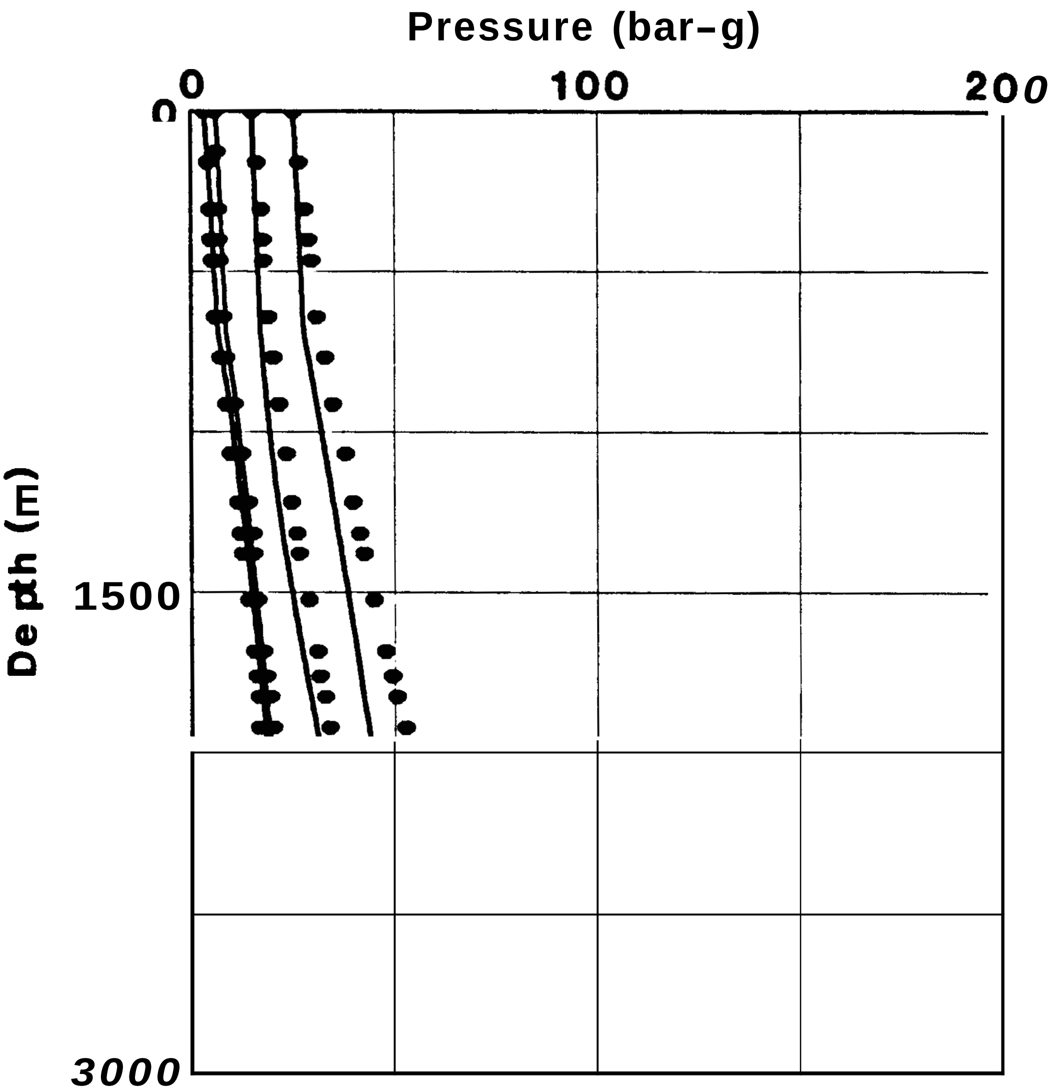

Fig. 10 - Measured and calculated pressure profiles for HGP A well

(Steam rate = 70, 66, 58, 50 Klb/hr.)

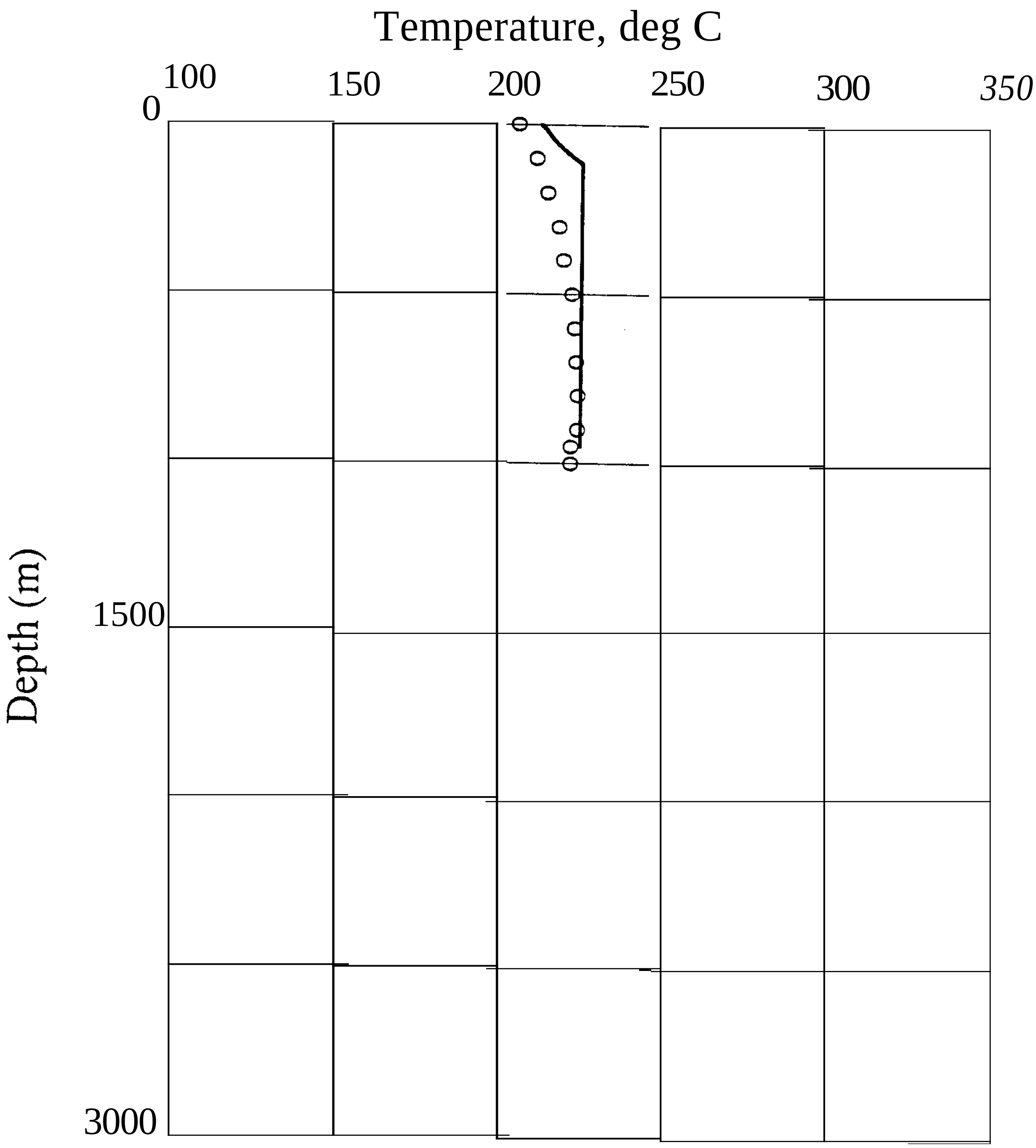

Fig. 11 - Measured and calculated temperature profiles for Ngawha 11

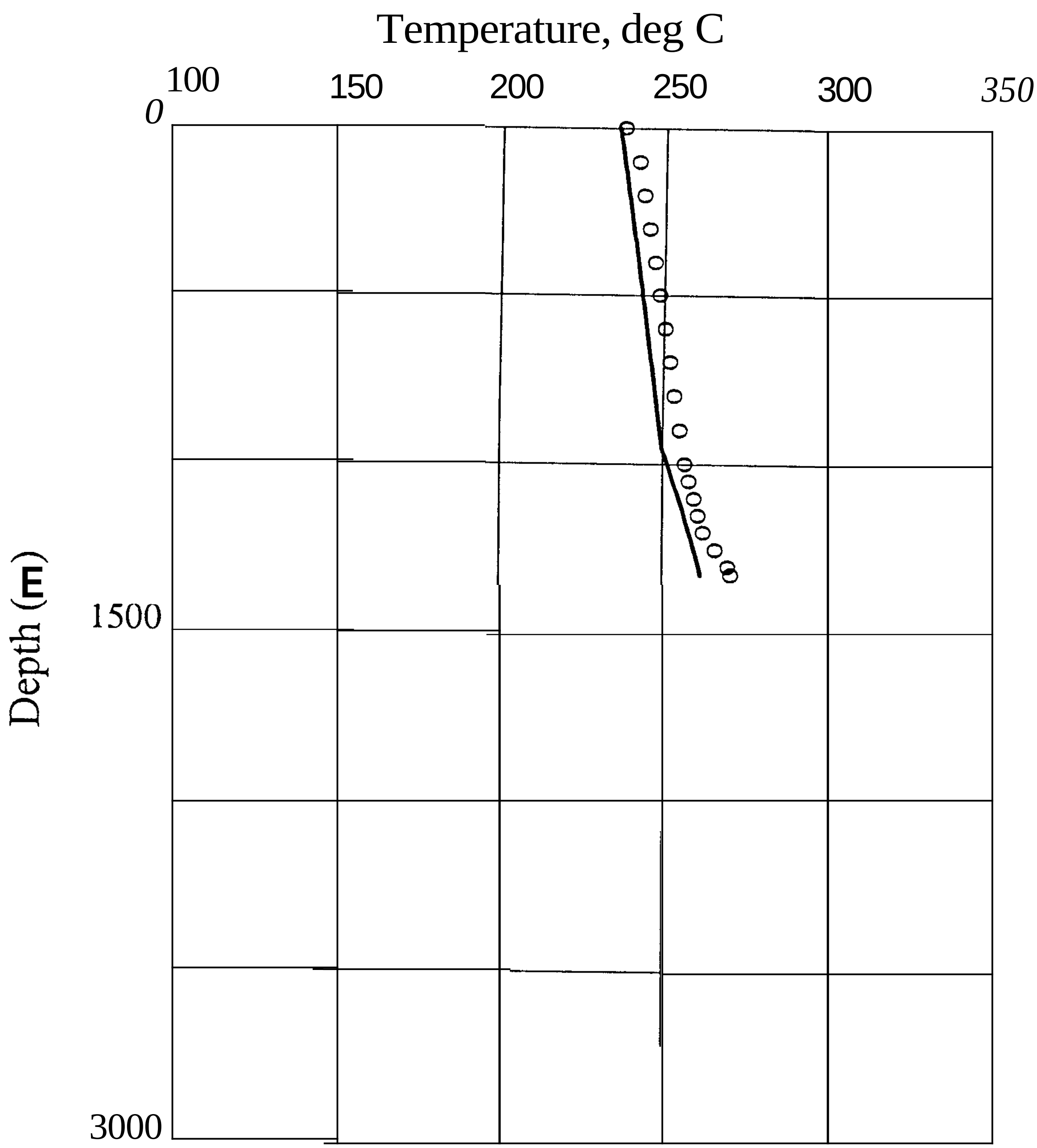

Fig. 12 - Measured and calculated temperature profiles for Los Azufres 18

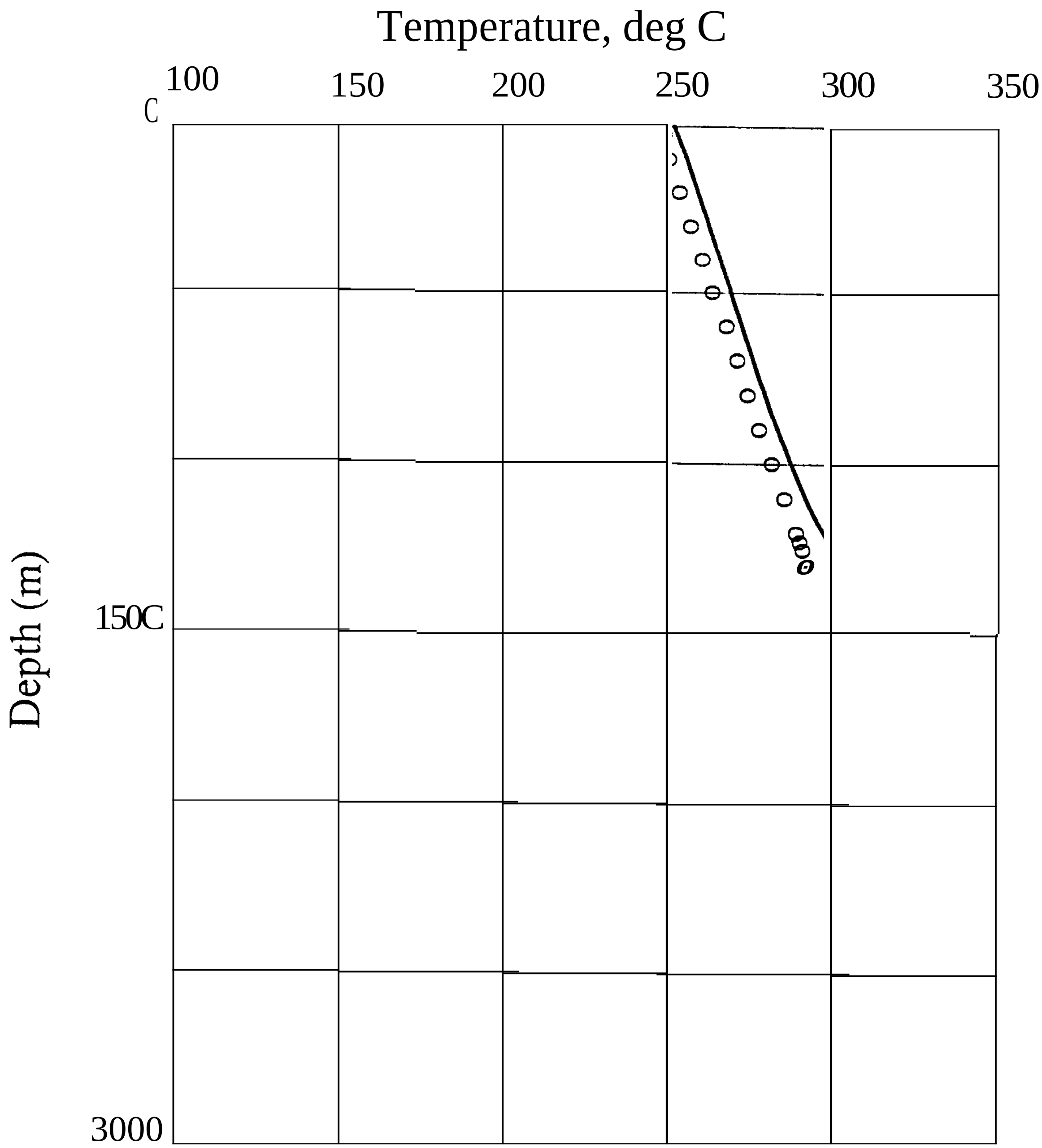

Fig. 13 - Measured and calculated temperature profiles for Cerro-Prieto 90

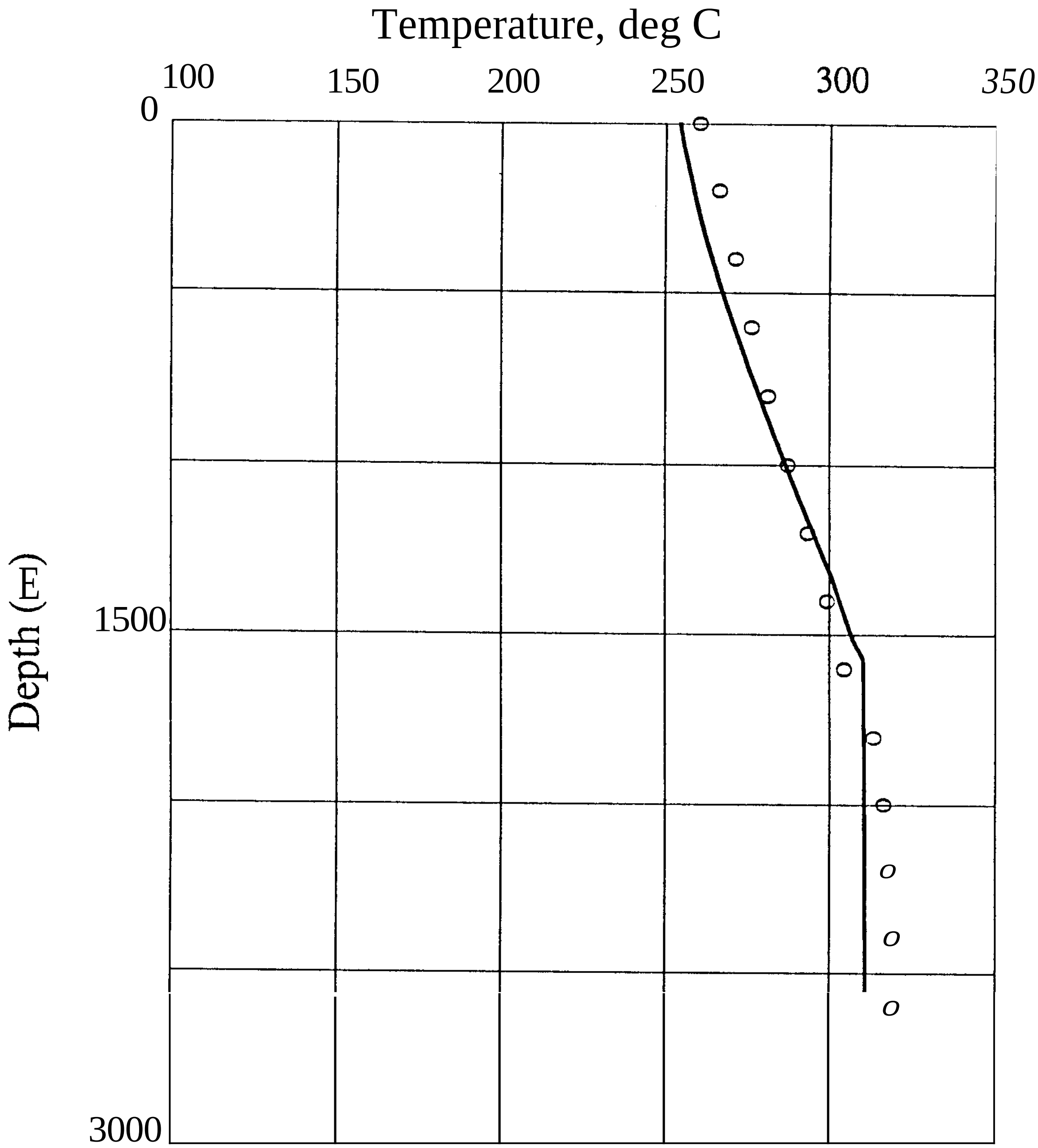

Fig. 14 - Measured and calculated temperature profiles for Okoy 7

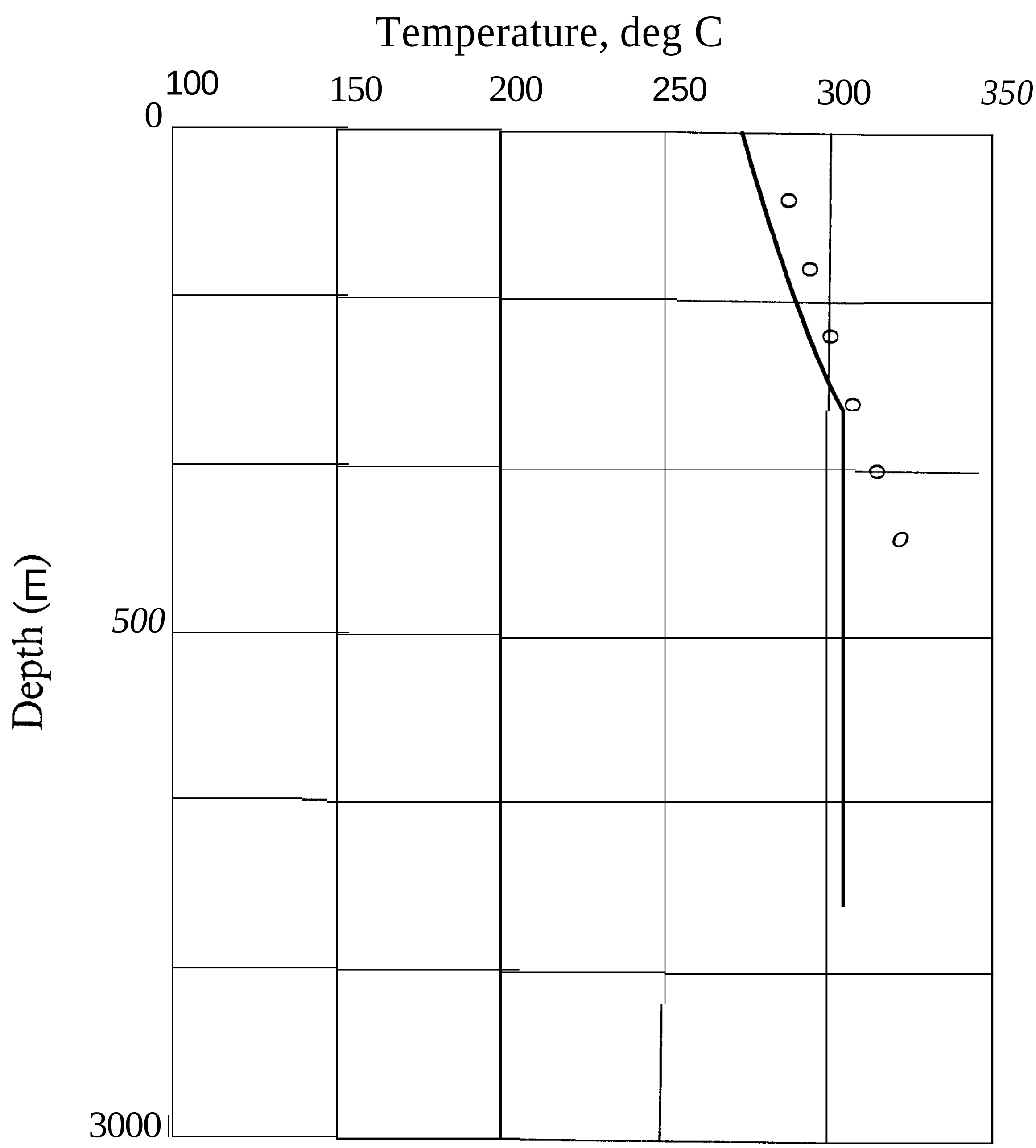

Fig. 15 - Mcasured and calculated temperature profiles for Cerro-Prieto 91

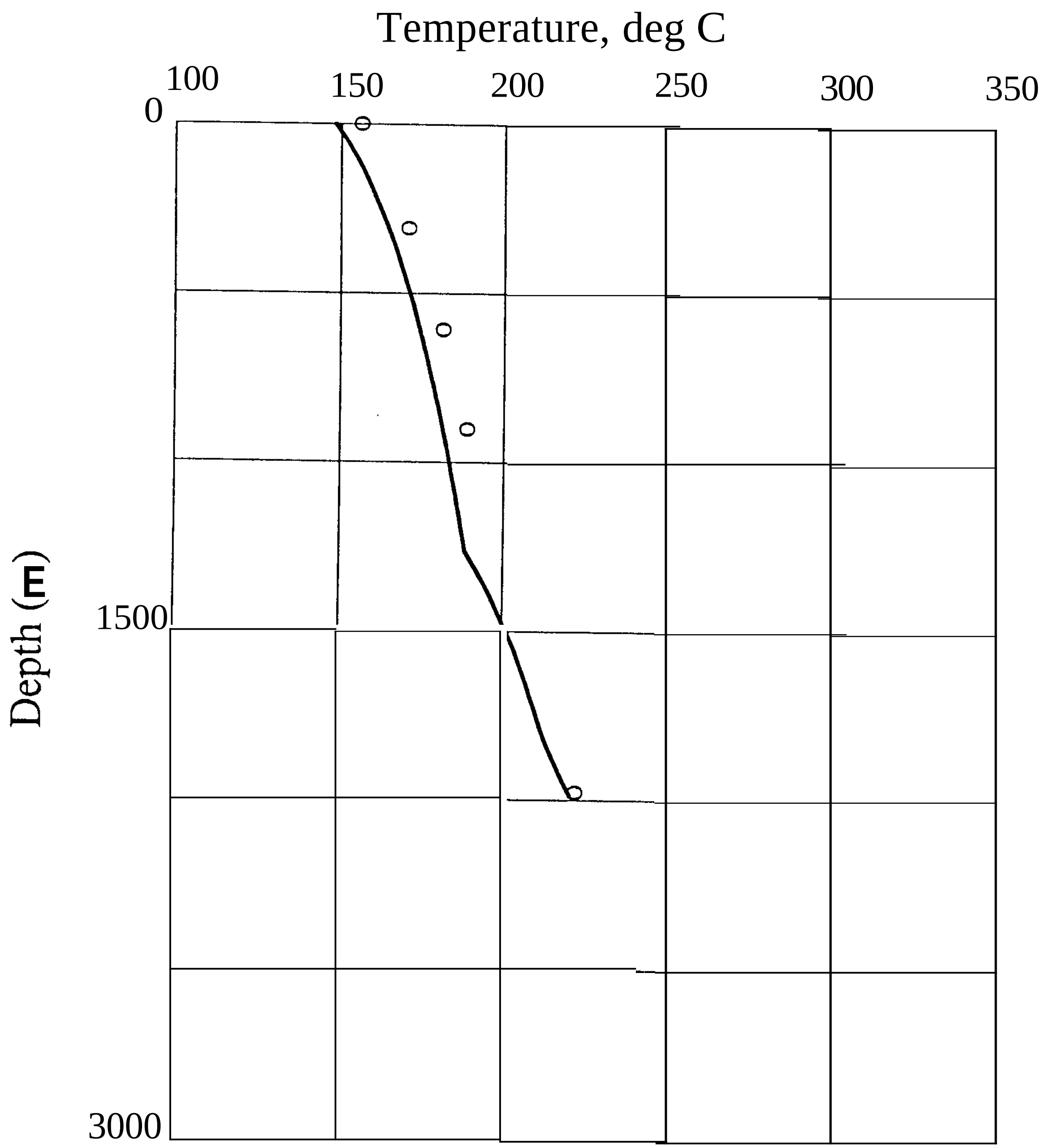

Fig. 16 - Measured and calculated temperature profiles for Mofete 2

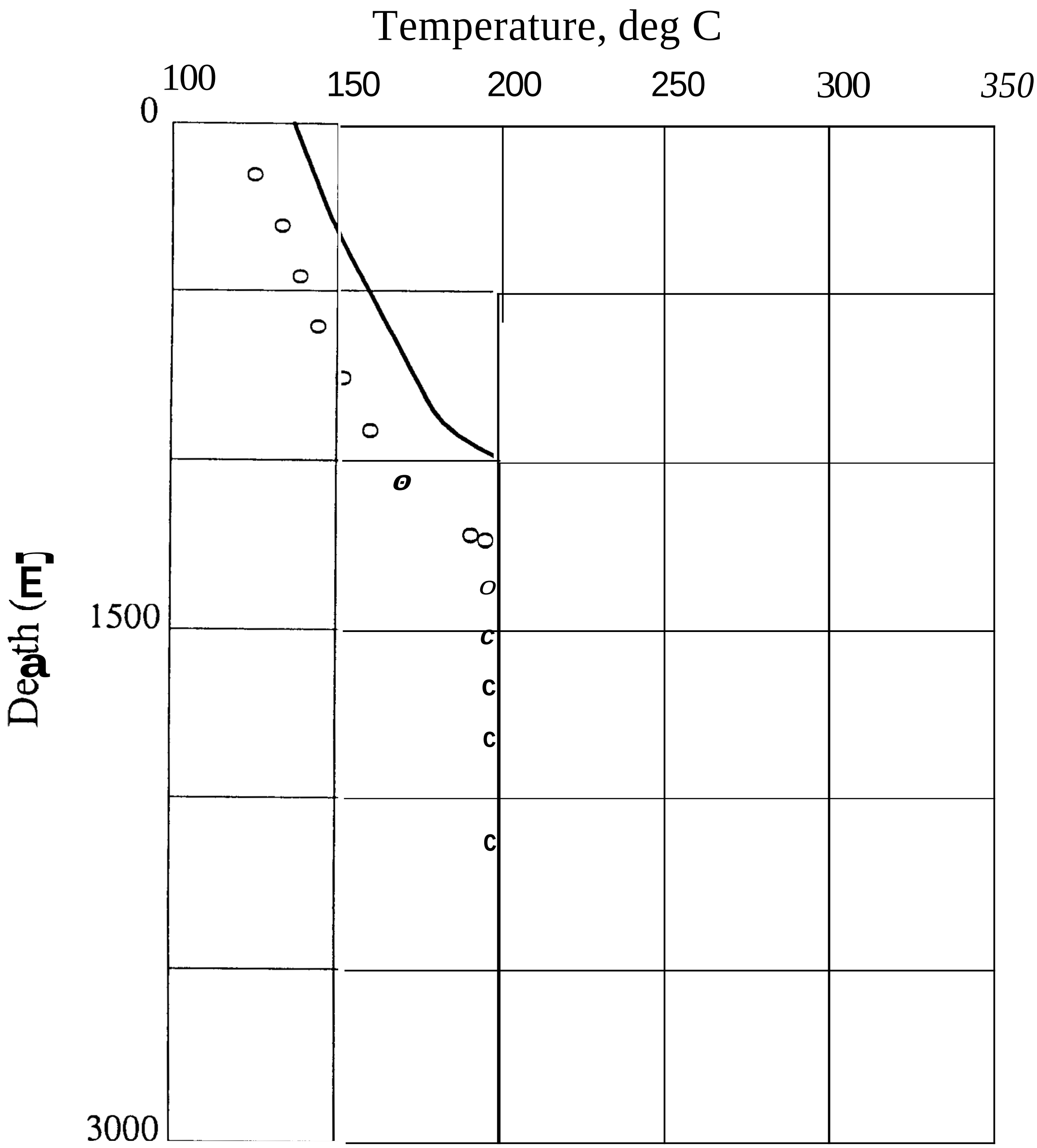

Fig. 17 - Measured and calculated temperature profiles for East Mesa 6

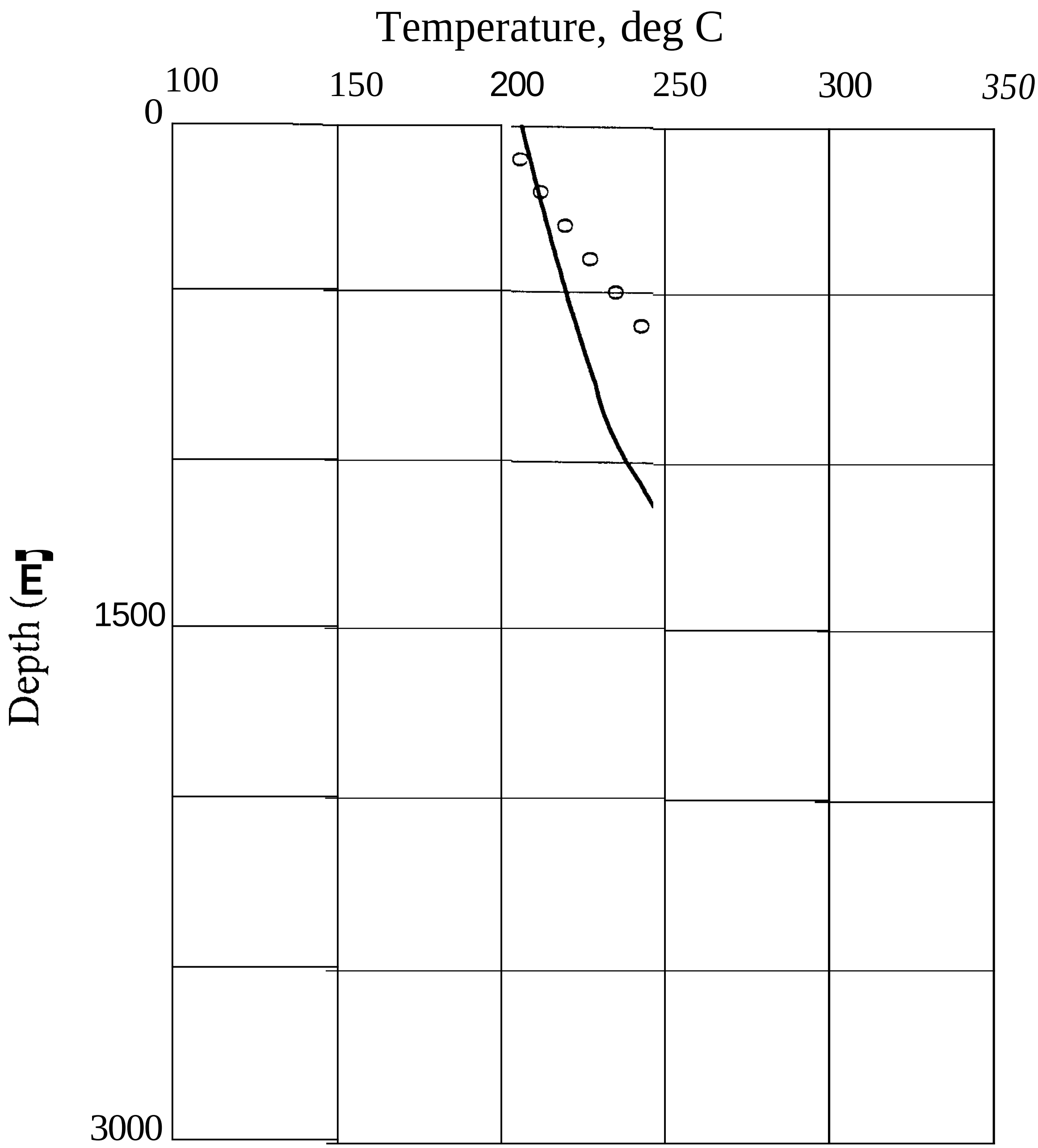

Fig. 18 - Measured and calculated temperature profiles for Krafla 9

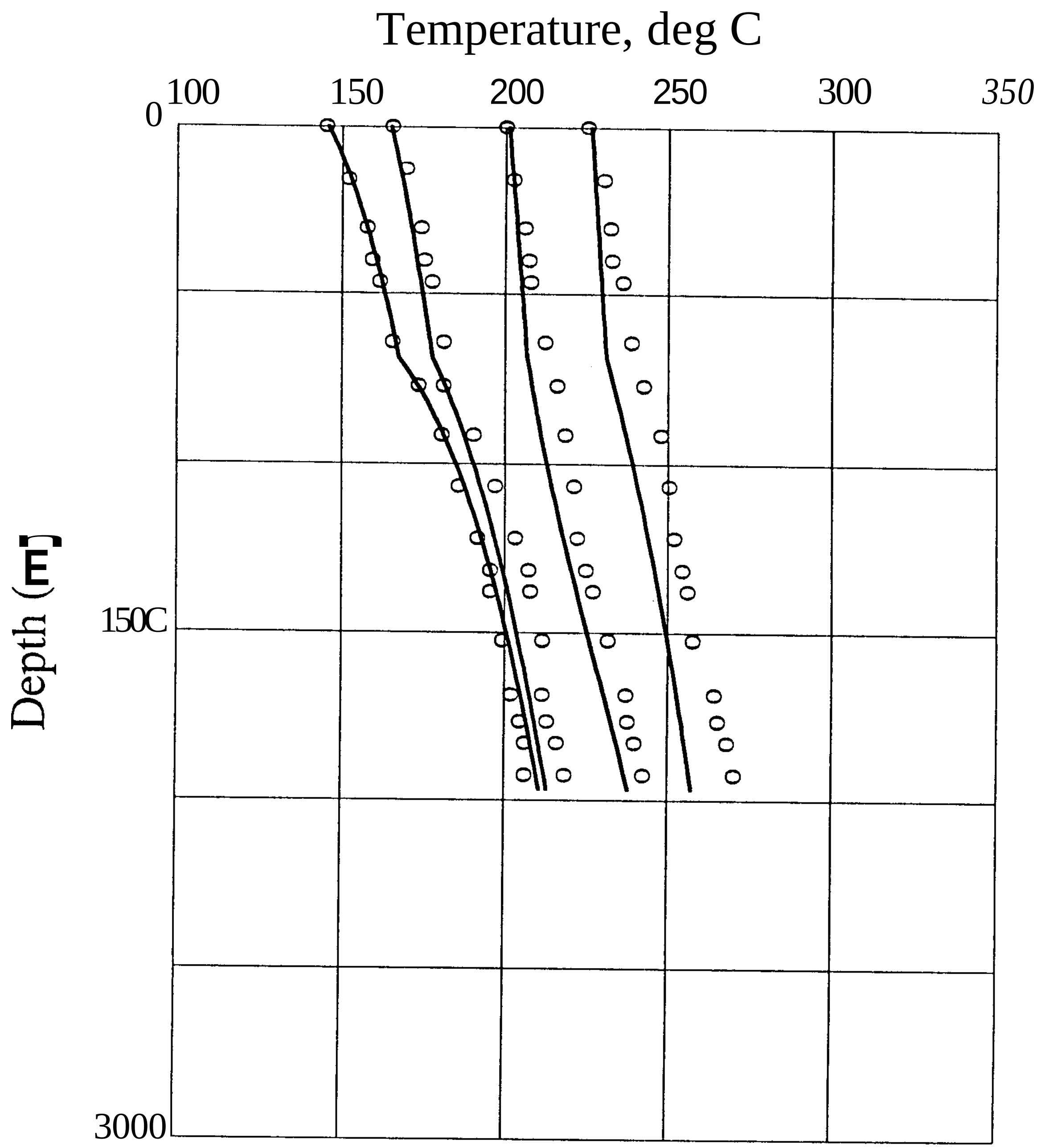

Fig. 19 - Measured and calculated temperature profiles for **HGP-A** well (Steam rate = 70, 66, ***58,*** *50* Klb/hr.)

NOMENCLATURE

$L_{b/s}$	Bubble-slug boundary term
v_{sg}	Superficial gas velocity, ft/sec
v_{sT}	Total superficial velocity, ft/sec
τ	Liquid distribution coefficient

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APPENDIX A: Computer Program Listing

Modification to original Ortiz-R. (1983) program is mentioned at the top of the program listing. Updated document also contains list of output **files** opened by the program for various purposes.

ortiz.f Wed Aug 6 16:33:18 1986 1

```
C *****************************************************************
C *                                                               *
C * THIS PROGRAM CALCULATES THE FLOWING PRESSURE AND TEMPERATURE  *
C * OF A TWO-PHASE GEOTHERMAL WELL. THE DIRECTION OF CALCULATION  *
C * CAN EITHER BE FROM THE WELLHEAD OR WELLBOTTOM. THE PROGRAM    *
C * WAS DEVELOPED BY JAIME ORTIZ-R. AND IS DESCRIBED IN SGP-TR-66 *
C * "TWO-PHASE FLOW IN GEOTHERMAL WELLS: DEVELOPMENT AND USES OF  *
C * A COMPUTER CODE," JUNE 1983. THIS VERSION OF THE PROGRAM WAS  *
C * RUN ON THE IBM-3081 COMPUTER OF CIT AT STANFORD UNIVERSITY.   *
C * THE WORK WAS FUNDED BY THE U.S. DEPARTMENT ENERGY THROUGH     *
C * CONTRACT DE-AT03-80SF11459 TO THE STANFORD GEOTHERMAL PROGRAM *
C *                                                               *
C * THE ORIGINAL VERSION BY JAIME ORTIZ-R. HAS BEEN MODIFIED      *
C * BY ANIL KUMAR AMBASTHA SLIGHTLY TO BE CONSISTENT WITH ORIGINAL *
C * ORKISZEWSKI (1967) TWO-PHASE FLOW CORRELATIONS.  THE          *
C * MODIFICATION IS DISCUSSED IN SGP-TR-100 "COLLECTION AND       *
C * EVALUATION OF FLOWING PRESSURE AND TEMPERATURE DATA FROM      *
C * GEOTHERMAL WELLS" AUG. 1986. VARIOUS FILES ARE OPENED TO GET RAW*
C * DATA FOR SEVERAL GRAPHS THAT AID IN PROPER ANALYSIS OF DATA.  *
C * THIS VERSION OF PROGRAM HAS BEEN EXTENSIVELY RUN AND TESTED ON *
C * STANFORD UNIV. PETROLEUM ENGINEERING DEPARTMENT VAX COMPUTER. *
C *****************************************************************
C *                                                               *
C *              INPUT VARIABLES                                  *
C *    P(1)    = FLOWING PRESSURE, PSIA                           *
C *    T(1)    = FLOWING TEMPERATURE, DEG. F.                     *
C *    DIA     = PIPE DIAMETER, FT.                               *
C *    ND      = NUMBER OF DIFFERENTS DIAMETERS + 1               *
C *    ZDIAM   = DEPTH OF DIFFERENTS DIAMETERS ENDINGS            *
C *    DIST    = PIPE LENGTH, FT.                                 *
C *    AROUG   = ABSOLUTE PIPE ROUGHNESS, FT.                     *
C *    WGR     = WATER GRAVITY                                    *
C *   WT      = TOTAL MASS FLOW RATE, LB/HR                       *
C *   ENM1    = ENTHALPY OF FLUID AT INITIAL POINT, BTU/LB        *
C *   HCO     = HEAT TRANSFER COEFFICIENT, BTU/(HR.SQFT. @F)      *
C *   ENTH    = ENTHALPY, BTU/LB                                  *
C *   ANG     = ANGLE OF FLOW FROM HORIZONTAL, DEG.               *
C *   NPT     = NUMBERS OF POINTS WITH SHUT-IN TEMPERATURES       *
C *   ROKT    = SHUT-IN TEMPERATURE, DES. F.                      *
C *   DEPT    = DEPTH OF SHUT-IN TEMPERATURE, FT.                 *
C *   DWELLB = DEPTH OF WELLBORE (FT)                             *
C *   DWELLH = DEPTH OF WELLHEAD (FT)                             *
C *   ISIGN  = +1/-1, (+1=ITERATION FRDM THE WELLHEAD,            *
C *                    -1=ITERATION FROM BOTTOMHOLE.   )          *
C *                                                               *
C *****************************************************************
C
C

*     OUTPUT FILE SYSTEM
*     ******************

*     pressure ---- pressure (barg) vs. depth (m) data
*     temp ---- Temperature (deg C) vs. depth (m) data
*     flow ---- NLV vs. NGV data in two-phase flow region
*     dia ---- Diameter number data in two-phase flow region
*     ***********************************************************
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION DEPT(30),ROKT(30)
      DIMENSION P(250),T(250),Z(250),ENTH(250)
      DIMENSION DIAM(10),ZDIAM(10),AROUG(10)
      DIMENSION ITITLE(20),REG(5)
      DATA REG/ 4HBBLE, 4HSLUG, 4HMIST, 4HTRAN, 4HMONO/
C
C     READ INPUT PARAMETERS
```

```
*      **********************
       OPEN(UNIT-7,FILE="pressure")
       OPEN(UNIT-8,FILE-"temp")
       OPEN(UNIT=9,FILE="flow")
       OPEN(UNIT=10,FILE="dia")
       READ(5,1300)(ITITLE(I),I=1,18)
 1300  FORMAT(18A4)
       READ(5,*) P(1),T(1),Z(1)
       READ(5,*)WGR,WT,ENM1,HCO
       READ(5,*)INC
       READ(5,*) ANG,DWELLB,DWELLH
       READ(5,*)ISIGN
       READ(5,*) ND
       ND=ND+1
       READ(5,*) (DIAM(I),I=1,ND)
       READ(5,*)(AROUG(I),I=1,ND)
       READ(5,*) (ZDIAM(I),I=1,ND)
       READ (5,*) NPT
       READ (5,*) (DEPT(I),I=1,NPT)
       READ (5,*) (ROKT(I),I=1,NPT)
C
       WRITE(6,3000)(ITITLE(I),I=1,18)
 3000  FORMAT(1H1,///,5X,18A4)
       WRITE(6,3010)
 3010  FORMAT(//,5X,'INPUT DATA AS FOLLOW:')
       WRITE(6,3050)WGR,WT,HCO
 3050  FORMAT(//,7X,'WATER GRAVITY',T35,F15.4,
      3 /,7X,'TOTAL MASS FLOWRATE,LB/HR',T35,F15.4,
      4 /,7X,'HEAT TRANSF COEFF,BTU/HR/SQFT/F',T35,F15.4)
       IF(ISIGN.EQ.-1) GO TO 10
       WRITE(6,3020)
 3020  FORMAT(//,5X,'AT THE WELLHEAD :')
       WRITE(6,3040)Z(1),P(1),T(1)
 3040  FORMAT(/,7X,'DEPTH,FT',    T24,F10.2 ,
      1/,7X,'PRESSURE,PSIA',T24,F10.2,/,7X,
      2' TEMPERATURE,F' ,T24,F10.2)
       WRITE(6,3075)
 3075  FORMAT(//,5X,'PIPE DIAMETER USED AS FOLLOW:',/)
       GO TO 11
   10  WRITE(6,3030)
 3030  FORMAT(//,5X,'AT THE WELLBOTTOM:')
       WRITE(6,3040)Z(1),P(1),T(1)
       WRITE(6,3075)
   11  CONTINUE
       ND1 = ND-1
       IF(ND1.LE.O) GO TO 8
       DO 7 II=1,ND1
       WRITE(6,3076)ZDIAM(II),ZDIAM(II+1), IAM(II+1) ,AROUG(II+1)
 3076  FORMAT(7X,'FROM',F8.1,' FT  TO ',F8.1,' FT, PIPE DIAMETER (FT) =',
      1F9.4,/,T41,'ABS ROUGHNESS (FT) =' ,F9.4,/)
  7    CONTINUE
    8  CONTINUE
       WRITE(6,3005)INC
 3005  FORMAT(/, 5X,'TOTAL LENGTH DIVIDED IN ' ,13,' INTERVALS')
       WRITE(6,3060)
 3060  FORMAT(//,5X,'DOWNHOLE SHUT-IN TEMPERATURE AS FOLLOW:',
      1//,7X,'DEPTH,FT',T25,'TEMP,F',/)
       DO 20 I=1,NPT
   20  WRITE(6,3070)DEPT(I) ,ROKT(I)
 3070  FORMAT(2X,F12.2,5X,F10.2)
       WRITE(6,501)
  501  FORMAT(1X,//)
C
C      CHECK FOR DENSE STATE OF GEOTHERMAL FLUID
```

```
      IF (T(1).GT.705.OR.P(1).GT.3208.) GO TO 100
C
C     CONVERT ALL VARIABLES INTO ITS USABLE FORMS.
      SIGN   = DFLOAT(ISIGN)
      PIE    = 3.14159D0
      ANG    = ANG*PIE/180.
      AROG   = AROUG(1)
      DIA    = DIAM(1)
      AREA   = PIE*DIA*DIA/4.
      DIST   = DWELLB-DWELLH
      DELZ   = DIST/DFLOAT(INC)
      DELL   = DELZ/DSIN(ANG)
      ISTATE = 0
      IONE   = 1
      FRIMON-0.0
      POTMON=0.0
      FRITP -0.0
      POTTP -0.0
      ACCTP -0.0
      IPIPE  = 2
      CENT   = 0.0
      CENT2  = 0.0
      DM     = 21.
      IF(ISIGN.EQ.1) DM=0.00
C
C     TEST FOR COMPRESSED LIQUID
      PSAT-FPSAT(T(1))
      IF(PSAT-P(1)) 201,200,600
C
C     * THIS IS A COMPRESSED LIQUID (SINGLE PHASE FLOW) *
C
 201  IF (DABS(PSAT-P(1))/P(1) .LT.1.D-3) GO TO 200
      CALL COWAT (T(1),P(1),WDEN,ENTH1)
      IF (ISTATE.EQ.0) ENTH(1) = ENTH1
      WRITE(6,3080)
 3080 FORMAT('1',/,10X,'* LIQUID FLOW *',
     1T52,'FRICTION',T64,'ACCELE.',T73,'POTENTIAL',T109,'qw/A',
     2/,7X,'DEPTH,FT',T18,'PRES,PSIA',T32,'TEMP,F',T40,
     3'EN,BTU/LB',T51,'Psi/100ft',T62,'Psi/100ft',T73,'Psi/100ft',
     4T109,'ft/s',/)
      WRITE(6,3090)Z(1),P(1),T(1),ENTH(1)
 3090 FORMAT(4X,4(1X,F10.2),3(1X,F10.4),21X,F10.4)
      WRITE(7,*)Z(1)/3.28084,(P(1)-14.7)/14.503774
      WRITE(8,*)Z(1)/3.28084,(T(1)-32.)/1.8
  253 CONTINUE
      DPE=DELZ*0.35
C
C     CHECK IF THIS IS THE FIRST POINT OR A TRANSFER FROM TWOPHASE.
      IF (ISTATE.NE.0) IONE = KFLASH
      IF ( ISTATE.NE.0 .AND. ISIGN.EQ.1 ) DELZ=(DWELLB-ZFLASH)/
     1                                     DFLOAT(INC-K)
      DELL = DELZ/DSIN(ANG)
C
C     START TO CALCULATE PRESSURE DROP IN THE COMPRESSED LIQUID REGION.
      DO 30 K=IONE,INC
   29 ZMID = Z(K) + SIGN*DELZ/2.
      TR = FLAGR(DEPT,ROKT,ZMID,1,NPT)
      IF (ISIGN.EQ. 1.AND. ZMID.LE.ZDIAM(IPIPE)) GO TO 39
      IF (ISIGN.EQ.-1.AND. ZMID.GE.ZDIAM(IPIPE)) GO TO 39
      IPIPE = IPIPE +1
      AROG-AROUG(IPIPE)
      DIA- DIAM(IPIPE)
      AREA = PIE*DIA*DIA/4.
 39   CONTINUE
C
```

```
C     ITERATION TO  CALCULATE  TEMPERATURE AND PRESSURE VALUES
      DO 31 I=1,500
      XI= DFLOAT(I-1)
      TAV= T(K) + SIGN*XI*.005
      Q = PIE*HCO*DIA*DELL*(TAV-TR)/(WT*2.)
      ENAV=ENTH(K) +SIGN*(Q-DELZ/1556.)
      IF(Q .LE. 0. ) ENAV=ENTH(K)
C
C     CALC. PRESSURE DROP USING THE ASSUMED FLOWING TEMPERATURE.
      DO 32 J=1,100
      PAV=P(K)+SIGN*DPE/2.
      CALL PVTW(TAV,PAV,WGR,DENL,VISL)
      ED=AROG/DIA
      VSL=WT/DENL/AREA/3600.
      REYN=1488.*DIA*VSL*DENL/VISL
      CALL FRFACT(REYN,ED,FM)
      DPDL=(FM*DENL*VSL*VSL/(32.2*2.*DIA)+DENL*DSIN(ANG))/144.
      DPC=DPDL*DELL
      IF (J .LE. 90) GO TO 4949
      IF (J .GT. 91) GO TO 4848
      WRITE(6,4747)
 4747 FORMAT(1X,/,1X,' J' ,T9,' DPE' ,T21,' DPC' ,T33,'PAV')
 4848 WRITE(6,1515)J,DPE,DPC,PAV
 1515 FORMAT(1X,I3,3(2X,F10.4))
 4949 CONTINUE
      IF (DABS(DPC-DPE).LT.0.001) GO TO 35
      DPE=(DPC+DPE)/2.
   32 CONTINUE
C     SYSTEM DOES NOT CONVERGE AFTER 100 ITERATIONS
      WRITE (6,34)
   34 FORMAT (' NO CONVERGENCE AT PRESSURE ITERATION',/)
      GO TO 999
   35 CONTINUE
      CALL COWAT(TAV,PAV,WDEN,ENL)
      IF (I .LE. 400) GO TO 5050
      IF(I.GT.401) GO TO 5151
      WRITE(6,5252)
 5252 FORMAT(1X,/,1X,' I' ,T12,'ENAV' ,T25,'ENL' ,T37,'TAV')
 5151 WRITE(6,1616)I,ENAV,ENL,TAV
 1616 FORMAT(1X,I3,3(2X,F10.3))
 5050 CONTINUE
      IF (DABS(ENAV-ENL).LT..1) GO TO 36
   31 CONTINUE
C     SYSTEM DOESN'T CONVERGE FOR 50000 P AND T ITERATIONS
      WRITE (6,37)
   37 FORMAT (' NO CONVERGENCE AT TEMPERATURE ITERATION',/)
      GO TO 999
   36 T(K+1)=T(K)+XI*SIGN*0.01
      P(K+1)=P(K)+DPC*SIGN
C     CHECK IF FLUID IS IN SATURATED REGION
      PSAT=FPSAT( T(K+1) )
      IF( DABS(PSAT-P(K+1))/PSAT .LT. 1.D-3 ) GO TO 50
      IF(CENT .EQ. 1. )GO TO 45
      IF (P(K+1)-PSAT) 40,50,60
C
C     CHANGE FROM COMPRESSIBLE FLUID TO SATURATED STEAM
C     WITHIN THE INCREMENT.  RECALCULATE AGAIN
   45 CONTINUE
      IF( P(K+1)-PSAT ) 42,50,46
   40 CONTINUE
      DELZ=DABS(P(K)-PSAT)/DPDL
      DELL=DELZ/DSIN(ANG)
      CENT=1.0
      DPE=DPDL*DELZ
      GO TO 29
```

```
   42 CONTINUE
      DELZ=DELZ-0.2
      DELL = DELZ/DSIN(ANG)
      GO TO 29
   46 CONTINUE
      DELZ=DELZ+0.3
      DELL=DELZ/DSIN(ANG)
      GO TO 29
   60 FRIT=(FM*DENL*VSL**2./(32.2*2.*DIA*144.))*DELL
      ACCT=0.0
      POTT=(DENL*DSIN(ANG)/144.)*DELZ
      FRIMON=FRIMON+FRIT
      POTMON=POTMON+POTT
      Z(K+1)=Z(K)+DELZ*SIGN
      CALL COWAT(T(K+1),P(K+1),AD,ENTH(K+1))
      WRITE(6,3090)Z(K+1),P(K+1),T(K+1),ENTH(K+1),
     lFRIT*(100./DELL),ACCT*(100./DELL),POTT*(100./DELZ),VSL
      WRITE(7,*)Z(K+1)/3.28084,(P(K+1)-14.7)/14.503774
      WRITE(8,*)Z(K+1)/3.28084,(T(K+1)-32.)/1.8
   30 CONTINUE
      WRITE(6,2626)FRIMON,POTMON,FRITP,POTTP,ACCTP
      GO TO 999
C
C     THIS IS THE COMPRESSED LIQUID FLASHING POINT
   50 Z(K+1)=Z(K)+DELZ*SIGN
      FRIT=(FM*DENL*VSL**2./(32.2*2.*DIA*144.))*DELL
      ACCT=0.0
      POTT=(DENL*DSIN(ANG)/144.)*DELZ
      FRIMON=FRIMON+FRIT
      POTMON=POTMON+POTT
      CALL COWAT (T(K+1),P(K+1),FL,FE)
      WRITE (6,51)
   51 FORMAT(/,10X,'FLASH POINT....')
      WRITE (6,3090) Z(K+1),P(K+1),T(K+1),FE,
     lFRIT*(100./DELL),ACCT*(100./DELL),POTT*(100./DELZ)
      WRITE(7,*)Z(K+1)/3.28084,(P(K+1)-14.7)/14.503774
      WRITE(8,*)Z(K+1)/3.28084,(T(K+1)-32.)/1.8
      KFLASH = K+1
      ENTH (K+1) = FE
      ZFLASH = Z(K+1)
      ISTATE =1
      XS=0.0
C
C     **TWO-PHASE FLASHING FLOW**
C
C     CHECK IF THIS IS A TRANSFER FROM COMPRESSED LIQUID REGION.
  200 IF (ISTATE.EQ.1) IONE = KFLASH
      IF(ISTATE.EQ.0) DPDL=0.009
      IF ( ISTATE.EQ.l .AND. ISIGN.EQ.-1 ) DELZ=(ZFLASH-DWELLH)/
     1                                    DFLOAT(INC-K)
      IF (ISTATE.EQ.1)GO TO 282
      CALL SATUR(T(1),DENS,EHS,EHW,VISS)
      ENTH(1)=ENM1
      XS=(ENTH(1)-EHW)/(EHS-EHW)
  282 DELL = DELZ/DSIN(ANG)
      WRITE(6,2010)
 2010 FORMAT('1',/,10X,'• TWO-PHASE FLOW *',
     1T52,'FRICTION',T64,'ACCELE.',T73,'POTENTIAL',T109,'qw/A',
     2T119,'qs/A',/,7X,'DEPTH,FT',T18,'PRES,PSIA',T32,'TEMP,F',T40,
     3'EN,BTU/LB',T51,'Psi/100ft',T62,'Psi/100ft',T73,'Psi/100ft',
     CT85,'STM.FRAC',T97,'REGIME',T109,'ft/s',T119,'ft/s',/)
C
      DO 210 K = IONE,INC
      IF(ISIGN.EQ.-1.AND.ISTATE.EQ.1) GO TO 254
      IF(K.NE.l) GO TO 254
```

```
      WRITE(6,5454)Z(1),P(1),T(1),ENTH(1),XS
 5454 FORMAT(4X,4(1X,F10.2),34X,F10.4)
      WRITE(7,*)Z(1)/3.28084,(P(1)-14.7)/14.503774
      WRITE(8,*)Z(1)/3.28084,(T(1)-32.)/1.8
  254 CENT1=0.0
      ZMID = Z(K) + SIGN*DELZ/2.
      TR = FLAGR (DEPT,ROKT,ZMID,1,NPT)
      IF (ISIGN.EQ.1 .AND. ZMID.LE.ZDIAM(IPIPE)) GO TO 69
      IF (ISIGN.EQ.-1 .AND. ZMID.GE.ZDIAM(IPIPE)) GO TO 69
      IPIPE = IPIPE +1
      AROG=AROUG(IPIPE)
      DIA= DIAM(IPIPE)
      AREA = PIE*DIA*DIA/4.
   69 CONTINUE
C
C     ITERATE TO FIND THE PRESSURE DROP
      DPC=DPDL*DELL
      DO 219 M=1,100
      DPE=DPC
      PAVG=P(K)+SIGN*(DPE/2.)
      TAVG=FTSAT(PAVG)
  550 CONTINUE
      Q=3.14159*HCO*DIA*(DELL/2.)*(TAVG-TR)/WT
      IF (TR.GE.TAVG)  Q  -0.0
      ENAV=ENTH(K)+SIGN*(Q-DELZ/2./778.)
      IF( Q .LE. 0. ) ENAV=ENTH(K)
      CALL SATUR(TAVG,DENS,ENS,ENW,VISS)
      X=(ENAV-ENW)/(ENS-ENW)
      IF ( X.LT.1.) GO TO 202
      CENT1=CENT1+1.
      IF(CENT1.EQ.100) GO TO 220
      TAVG=T(K)+SIGN*CENT1*0.05
      PAVG=FPSAT( TAVG )
      DPE=2.*(PAVG-P(K))*SIGN
      GO TO 550
  202 IF ( ISTATE.EQ.1) GO TO 204
      IF (X.GT..001)GO TO 204
C
C     CALCULATE THE DEPTH OF THE FLASHING POINT
      CENT2=1.
      ENAV=ENTH(K)
      TFP=TAVG
      DO 5051 N=1,200
      IF(N.LT.190) GO TO 9090
      IF(N.GT.191) GO TO 3434
      WRITE(6,3034)
 3034 FORMAT(4X,'N',T14,'TFP',T24,'ENAV',T36,'ENW',
     1T47,'ENS',T56,'X')
 3434 WRITE(6,8585)N,TFP,ENAV,ENW,ENS,
 8585 FORMAT(1X,I5,4(1X,F10.3),1X,F10. )
 9090 CONTINUE
      TFP=TFP-0.05
      CALL SATUR(TFP,DENS,ENS,ENW,VISS
      X=(ENAV-ENW)/(ENS-ENW)
      IF(X.GE.-1.D-3) GO TO 5052
 5051 CONTINUE
      WRITE(6,6060)
 6060 FORMAT(1X,/,1X,'NO CONVERGENCE FINDING FLASH POINT')
      GO TO 999
 5052 TAVG=(T(K)+TFP)/2.
      PAVG-FPSAT(TAVG)
      CALL SATUR(TAVG,DENS,ENS,ENW,VISS)
      X=(ENAV-ENW)/(ENS-ENW)
      GO TO 204
 4204 CONTINUE
```

```
      PFP=FPSAT(TFP)
      Z(K+1)=Z(K)+(PFP-P(K))/DPDL
      P(K+1)=PFP
      T(K+1)=TFP
      CALL COWAT(TFP,PFP,DENA,ENAV)
      ENTH(K+1)=ENAV
      KFLASH = K+1
      ZFLASH = Z(K+1)
      XLEN=(Z(K+1)-2(K))
      FRIT-(SDPF/144.)*XLEN
      ACCT-(SEKK*(DPDL))*XLEN
      POTT=(SDENTP*DSIN(ANG)/144.)*XLEN
      FRITP=FRITP+FRIT
      POTTP=POTTP+POTT
      ACCTP=ACCTP+ACCT
      WRITE(6,51)
      WRITE (6,3090) Z(K+1),P(K+1),T(K+1),ENAV,
     1FRIT*(100./XLEN),ACCT*(100./XLEN),POTT*(100./XLEN)
      WRITE(7,*)Z(K+1)/3.28084,(P(K+1)-14.7)/14.503774
      WRITE(8,*)Z(K+1)/3.28084,(T(K+1)-32.)/1.8
      WRITE(6,3080)
      ISTATE = 1
      GO TO 253
C
 204  CALL PVTW(TAVG,PAVG,WGR,DENW,VISW)
      SUR=FSURW( TAVG,PAVG )
      WS = X*WT
      WW=WT-WS
      VSW=WW/DENW/AREA/3600.
      VSS=WS/DENS/AREA/3600.
      HLNS=VSW/(VSW+VSS)
      VM=VSW+VSS
      XGN=1.938*VSS*((DENW/SUR)**0.25)
      XLN=1.938*VSW*((DENW/SUR)**0.25)
C
      CALL ORKIS(HLNS,XLN,XGN,ANG,DENW,DENS,VM,DIA,VSS,VSW,
     1PAVG,AROG,VISW,VISS,SUR,HL,DPDL,IFP,SDPF,SEKK,
     2SDENTP,XBL,XSL,XML,SIG)
      XND=120.872*DIA*DSQRT(DENW/SUR)
      IF(ISIGN.EQ.-1) DM=SDENTP
      DPDL=-DPDL
      DPC=DELL*DPDL
      IF(M.LT.50) GO TO 1818
      IF(M.GE.51) GO TO 8181
      WRITE(6,7171)
 7171 FORMAT(/,1X,' M',T7,' DPE',T14,' DPC',T22,'TAVG',T29,
     1'ENAV' ,T38,'X',T42,'VSW',T48,'VSS',T52,'HLNS',T59,
     2'HL',T63, 'DENW',T69,'DENS',T76, 'XLN',T82,'XGN',T87,
     3'VISW',T93,'SDPF',T98,'SEKK',T103,'SDENTP',T109, 'IFP',T112,
     4'XBL',T117,'XSL',T122,'XML',T129,'SIG')
 8181 WRITE(6,2121)M,DPE,DPC,TAVG,ENAV,X,VSW,VSS,
     1HLNS,HL,DENW,DENS,XLN,XGN,VISW,SDPF,SEKK,SDENTP,IFP,XBL,
     2XSL,XML,SIG
 2121 FORMAT(1X,I3,2F7.3,2F7.2,F6.3,2F6.2,2F5.2,2F6.2,2F6.1,
     1F6.3,F6.2,F5.2,F7.3,I2,F4.1,2F5.0,F8.4)
 1818 CONTINUE
      IF(CENT2.EQ.1.) GO TO 4204
      IF (DABS(DPE-DPC)/DPE.LT.1.D-3) GO TO 130
  219 CONTINUE
  220 CONTINUE
C     SYSTEM DOES NOT CONVERGES AFTER 100 ITERATIONS.
      WRITE(6,1111)CENT1,DPE-DPC
 1111 FORMAT(5X,'cent1 ',F5.0,1X,'DIFFE ',F10.3)
      WRITE (6,221) Z(K),P(K),T(K)
  221 FORMAT (' TWO-PHASE FLASHING FLOW',/,
```

```
     C' NO CONVERGENCE AT DEPTH= ',F10.3,' PRESSURE= ',
     CF10.3,' TEMPERATURE- ',F10.3)
      GO TO 999
C
 130  CONTINUE
      FRIT=(SDPF/144.)*DELL
      ACCT-(SEKK*(DPDL))*DELL
      POTT=(SDENTP*DSIN(ANG)/144.)*DELL
      FRITP=FRITP+FRIT
      POTTP=POTTP+POTT
      ACCTP=ACCTP+ACCT
      ENTH(K+1)=ENTH(K) + DABS(ENTH(K)-ENAV)*2*SIGN
      Z(K+1)=Z(K)+DELZ*SIGN
      P(K+1)= P(K) + SIGN*DPC
      T(K+1)=FTSAT(P(K+1))
      CALL SATUR(T(K+1),DENS,ENS,ENW,VISS)
      X= (ENTH(K+1)-ENW)/ (ENS-ENW)
 111  WRITE(6,2000) Z(K+1), P(K+1),T(K+1),ENTH(K+1),
     1FRIT*(100./DELL),ACCT*(100./DELL),POTT*(100./DELL),
     2X,REG(IFP),VSW,VSS
 2000 FORMAT(4X,4(1X,F10.2),4(1X,F10.4),T99,A4,2F10.4)
      WRITE(7,*)Z(K+1)/3.28084,(P(K+1)-14.7)/14.503774
      WRITE(8,*)Z(K+1)/3.28084,(T(K+1)-32.)/1.8
      WRITE(9,*)XGN,XLN
      WRITE(10,*)XND
 210  CONTINUE
      WRITE(6,2626)FRIMON,POTMON,FRITP,POTTP,ACCTP
 2626 FORMAT(///,T30,'** PRESSURE ANALYSIS **',/,
     C /,25X,'TOTAL FRICTION, LIQUID      =',F10.4,' PSI',
     1 /,25X,'TOTAL POTENTIAL, LIQUID     =',F10.4,' PSI',
     2//,25X,'TOTAL FRICTION, TWO-PHASE   =',F10.4,' PSI',
     3 /,25X,'TOTAL POTENTIAL, TWO-PHASE  =',F10.4,' PSI',
     4 /,25X,'TOTAL ACCELE., TWO-PHASE    =',F10.4,' PSI')
      GO TO 999
C
 600  IF ((PSAT-P(1))/P(1).LT.1.D-3) GO TO 200
      WRITE(6,2020)
 2020 FORMAT(///,15X,'SUPER HEATED STEAM, RUN TERMINATED',//)
      TSAT=FTSAT(P(1))
      WRITE(6,8899) P(1),TSAT
 8899 FORMAT(1X,'FOR ',F10.2,' TEMP SAT = ',F10.2
      GO TO 999
 100  WRITE (6,2040)
 2040 FORMAT (' PRESSURE OR TEMPERATURE IS ABOVE CRITICAL POINT
     1: PROGRAM EXECUTION IS TERMINATED ')
 999  CONTINUE
      WRITE(6,2001)
 2001 FORMAT(1X,///)
      STOP
      END
C
C
      SUBROUTINE ORKIS(HLNS,XLN,XGN,ANG,DL,DG,VM,D,VSG,VSL,
     1P,RTUB,VL,VG,SUR,HL,DPDL,IREG,DPF,EKK,DENTP,
     2XBL,XSL,XML,SIG)
      IMPLICIT REAL*8(A-H,O-Z)
      REL=1488.*DL*VM*D/VL
      KOUNT=1
      CENT3=1.
      FAC=2.*32.2*D
      REG=1488.*DG*VSG*D/VG
      ED=RTUB/D
C     CHECK FOR SINGLE PHASE FLOW
      IF(VSG.LT..00001)GO TO 2500
      IF(VSL.LT..00001)GO TO 2600
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      XSL=50.+36.*XLN
      XML=75.+84.*XLN**.75
      HGNS=VSG/VM
      XBL=1.071-.2218*VM**2/D
      IF(XBL.LT..13)XBL=.13
      IF(HGNS.LT. XBL) GO TO 1
      IF(XGN .LT. XSL) GO TO 4
      IF(XGN .GT. XML) GO TO 5
      KOUNT=2
      GO TO 4
C
C     BUBBLE FLOW CALCULATIONS
    1 VS=.8
      HL=1.-.5*(1.+VM/VS-DSQRT((1.+VM/VS)**2-4.*VSG/VS))
      IF(HL.LT.HLNS)HL=HLNS
      RELB=1488.*DL*VSL*D/HL/VL
      CALL FRFACT(RELB,ED,FF)
      DPF=FF*DL*VSL*VSL/HL/HL/FAC
      EKK=0.
      DENTP=DL*HL+DG*(1.-HL)
      IREG=1
      GO TO 2000
C
C     SLUG FLOW CALCULATIONS
    4 SIG=.045*DLOG10(VL)/D**.799-.709-.162*DLOG10(VM)-.888*DLOG10(D)
      TLI=-0.065*VM-0.1
      IF(SIG.LE.TLI)SIG=TLI
C     ITERATING FOR VB
      VB1=.5*DSQRT(32.2*D)
      I=0
   10 REB=1488.*DL*VB1*D/VL
      I=I+1
      IF(I.GT.10)print *,'iteration limit exceeded for bubble velocity'
      IF(I.GT.10)GO TO 12
      XX-DSQRT(32.2*D)
      TX=(.251+8.74D-06*REL)*XX
      VB=TX/2.+DSQRT(TX*TX+(13.59*VL)/(DL*DSQRT(D)))/2.
      IF(REB.LE.3000.)VB=(.546+8.74D-06*REL)*XX
      IF(REB.GE.8000.)VB=(.35+8.74D-06*REL)*XX
   11 IF(DABS(VB-VB1).LE..001)GO TO 12
      VB1=VB
      GO TO 10
   12 CONTINUE
      DENTP=(DL*(VSL+VB)+DG*VSG)/(VM+VB)+DL*SIG
      IF(SIG.EQ.TLI.AND.CENT3.EQ.1.) GO TO 13
      TLI=-VB*(1.-DENTP/DL)/(VM+VB)
      CENT3=CENT3+1.
      IF(SIG.GE.TLI)GO TO 13
      IF((SIG-TLI).GT.-1.D-05) GO TO 13
      SIG-TLI
      GO TO 12
   13 CONTINUE
      HL=(DENTP-DG)/(DL-DG)
      CALL FRFACT(REL,ED,FF)
      XX=FF*DL*VM*VM/FAC
      DPF=XX*((VSL+VB)/(VM+VB)+SIG)
      EKK=0.
      IREG-2
      IF(KOUNT.EQ.2)GO TO 51
      GO TO 2000
C
C     MIST FLOW CALCULATIONS
C     TRIAL AND ERROR CALCULATION FOR ED AND CORRECTED VSG
    5 VSGP-VSG
      EDG-ED
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   80 REYG=1488.*DG*VSGP*D/VG
      PR=454.*.0002048*DG/DL*(VSGP*VL/SUR)**2
      EDC=.0749*SUR/DG/VSGP/VSGP/D
      IF(PR.GT..005)EDC=.3713*SUR*PR**.302/DG/VSGP/VSGP/D
      VSGP=VSG/(1.-EDC)**2
      IF(DABS(EDC-EDG).LE.1.D-7)GO TO 60
      EDG=EDC
      GO TO 80
   60 ED-EDC
      IF(ED.LT..05)GO TO 70
      FF=1./(4.*DLOG10(.27*ED))**2 .067*ED**1.73
      GO TO 90
   70 CALL FRFACT(REYG,ED,FF)
   90 DPF=FF*DG*VSGP*VSGP/FAC
      DENTP=DL*HLNS+DG*(1.-HLNS)
      HL=HLNS
      EKK=VSGP*VM*DENTP/P/32.2/144
      IF(EKK.GT..95)EKK=.95
      IREG-3
      IF(KOUNT.EQ.2)GO TO 52
      GO TO 2000
C
C     CALCULATIONS FOR THE TRANSIT ON REG ON
   51 DPS=-(DPF+DENTP*DSIN(ANG))/144.
      DENMS=DENTP
      DPFS=DPF
      GO TO 5
   52 DPM=-(DPF+DENTP*DSIN(ANG)*XGN/XML)/144./(1.-EKK)
      DENMM-DENTP*(XGN/XML)
      DPFM=DPF
      A-(XML-XGN)/(XML-XSL)
      B=(XGN-XSL)/(XML-XSL)
      DENTP=DENMS*A+DENMM*B
      DPF=DPFS*A+DPFM*B
CC      WRITE(6,5252)A,B,DPS,DPM,DPFS,DPFM,DENMS,DENMM
CC 5252 FORMAT(1X,8(1X,F10.3))
      DPDL=A*DPS+B*DPM
      IREG=4
      GO TO 3000
C
C     FOR SINGLE PHASE LIQUID
 2500 CALL FRFACT(REL,ED,FF)
      DENTP=DL
      EKK=0.
      HL=HLNS
      IREG=5
      DPF=FF*DL*VSL*VSL/FAC
      GO TO 2000
 2600 CALL FRFACT(REG,ED,FF)
      EKK=0.
      DENTP-DG
      DPF=FF*DG*VSG*VSG/FAC
      IREG=3
 2000 DPDL=-(DPF+DENTP*DSIN(ANG))/144./(1.-EKK)
 3000 CONTINUE
      RETURN
      END
C
      SUBROUTINE FRFACT( REY,ED,FF)
      IMPLICIT REAL*8(A-H,O-Z)
      FF1 = 64./REY
      FGI = .0056+.5/REY**.32
      I=1
    5 DEN=1.14-2.*DLOG10(ED+9.34/(REY*DSQRT(FGI)))
      FF =(1./DEN)**2
```

```
      DIFF=DABS(FGI-FF)
      IF(DIFF-.0001)8,8,6
    6 FGI=(FGI+FF)/2.
      I = I+1
      IF (I-10) 5,5,7
    7 FF=FGI
    8 IF(FF-FF1)9,10,10
    9 FF=FF1
   10 RETURN
      END
C
      SUBROUTINE COWAT(TF,PP,DENL,EBP)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(23),SA(12)
      DATA A/
     16.824687741D3,-5.422063673D2,-2.096666205D4,3.941286787D4,
     2-6.733277739D4,9.902381028D4,-1.093911774D5,8.590841667D4,
     3-4.511168742D4,1.418138926D4,-2.017271113D3,7.982692717D0,
     4-2.616571843D-2,1.522411790D-3,2.284279054D-2,2.421647003D2,
     51.269716088D-10,2.074838328D-7,2.174020350D-8,1.105710498D-9,
     61.293441934D1,1.308119072D-5,6.047626338D-14/
      DATA SA/
     18.438375405D-1,5.362162162D-4,1.720000000D0,7.342278489D-2,
     24.975858870D-2,6.537154300D-1,1.150D-6,1.51080D-5,
     31.41880D-1,7.002753165D0,2.995284926D-4,2.040D-1    /
      TC=((TF+40.)/1.8)-40.
      TKR=(TC+273.15)/647.3
      PBAR=PP/14.5038
      PNMR=PBAR/2.212D2
      Y=1.-SA(1)*TKR*TKR-SA(2)/TKR**6
      Z=Y+(SA(3)*Y*Y-2.*SA(4)*TKR+2.*SA(5)*PNMR)**.5
      DENL=0.0
      YD=-2.*SA(1)*TKR+6.*SA(2)/TKR**7
      SNUM=0.
      DO 10 I=1,10
   10 SNUM=SNUM+(I-2)*A(I+1)*TKR**(I-1)
      PRT1=A(12)*(Z*(17.*(Z/29.-Y/12.)+5.*TKR*YD/12.)+SA(4)*TKR-
     1(SA(3)-1.)*TKR*Y*YD)/Z**(5./17.)
      PRT2=PNMR*(A(13)-A(15)*TKR*TKR+A(16)*(9.*TKR+SA(6))*(SA(6)-TKR)**5
     2+A(17)*(20.*TKR**19+SA(7))/(SA(7)+TKR**19)**2)
      PRT3=(12.*TKR**11+SA(8))/(SA(8)+TKR**11)**2*(A(18)*PNMR+A(19)*
     3PNMR*PNMR+A(20)*PNMR*PNMR*PNMR)
      PRT4=A(21)*TKR**18*(17.*SA(9)+19.*TKR*TKR)*(1./(SA(10)+PNMR)**3+
     4SA(11)*PNMR)
      PRT5=A(22)*SA(12)*PNMR**3+21.*A(23)/TKR**20*PNMR**4
      ENTR=A(1)*TKR-SNUM+PRT1+PRT2-PRT3+PRT4+PRT5
      EJG=ENTR*70.1204D0
      EBP=EJG*429.923D-3
      RETURN
      END
C
      FUNCTION FLAGR(X,Y,XARG,IDEG,NPTS)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION X(1),Y(1)
      N-NPTS
      N1=IDEG+1
      L=1
      IF(NPTS.LT.0)L=2
      IF(NPTS.LT.0)N=-N
      GO TO (10,20),L
   10 DO 11 MAX =N1,N
      IF(XARG.LT.X(MAX)) GO TO 12
   11 CONTINUE
      MAX-N
      GO TO 12
```

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```
   20 DO 21 MAX=N1,N
      IF(XARG.GT.X(MAX)) GO TO 12
   21 CONTINUE
      MAX=N
   12 MIN=MAX-IDEG
      FACTOR=1.
      DO 2 I=MIN,MAX
      IF(XARG.NE.X(I)) GO TO 2
      FLAGR=Y(I)
      RETURN
    2 FACTOR=FACTOR*(XARG-X(I))
      YEST=0.
      DO 5 I=MIN,MAX
      TERM=Y(I)*FACTOR/(XARG-X(I))
      DO 4 J=MIN,MAX
    4 IF(I.NE.J) TERM=TERM/(X(I)-X(J))
    5 YEST=YEST+TERM
      FLAGR=YEST
      RETURN
      END
C
      FUNCTION FPSAT(TF)
      IMPLICIT REAL * 8 (A-H,O-Z)
      REAL * 8 XK(9)
      DATA XK/-7.691234564,-2.608023696D1,-1.681706546D2,6.423285504D1,
     1-1.189646225D2,4.167117320D0,2.097506760D1,1.D9,6.D0/
      TC=((TF+40.)/1.8)-40.
      TKR=(TC+273.15)/647.3
      TKRM=1.-TKR
      SUM=0.
      DO 10 I=1,5
   10 SUM=SUM+XK(I)*TKRM**I
      DENO=1.+XK(6)*TKRM+XK(7)*TKRM*TKRM
      CONS=TKRM/(XK(8)*TKRM*TKRM+XK(9))
      PNMR=DEXP((1./TKR)*SUM/DENO-CONS)
      PBAR=PNMR*2.212D2
      PPSI=PBAR*14.5038
      FPSAT=PPSI
      RETURN
      END
C
      FUNCTION FTSAT(P)
      IMPLICIT REAL • 8 (A-H,O-Z)
      T=116.845*P**0.22302
      DO 17 I=1,200
      PCA-FPSAT(T)
      XSIG=-1.0
      IF((PCA-P).LT.0.) XSIG=1.
      IF(DABS(PCA-P)/P .LT. 1D-3) GO TO 43
      T=T+XSIG*.03
   17 CONTINUE
   43 FTSAT=T
      RETURN
      END
C
      SUBROUTINE SATUR(TF,DES,EHS,EHW,VIS)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION TD(33),XVS(33),XES(33),XEW(33)
      DIMENSION XVW(33)
C
      DATA XVW/1.0121D0,1.0171D0,1.0228D0,1.0290D0,1.0359D0,1.0435D0,
     C1.0515D0,1.0603D0,
     O1.0679D0,1.0798D0,1.0906D0,1.1021D0,1.1144D0,1.1275D0,1.1415D0,
     C1.1565D0,1.1726D0,
     P1.1900D0,1.2087D0,1.2291D0,1.2512D0,1.2755D0,1.3023D0,1.3321D0,
```

```
     C1.3655D0,1.4036D0,
     Q1.4475D0,1.4992D0,1.5620D0,1.6390D0,1.7410D0,1.8940D0,2.220D0/
      DATA TD/50.D0,60.D0,70.D0,80.D0,90.D0,100.D0,110.D0,120.D0,
     C130.D0,140.D0,150.D0,160.D0,
     2170.D0,180.D0,190.D0,200.D0,210.D0,220.D0,230.D0,240.D0,250.D0,
     C260.D0,270.D0,280.D0,290.D0,
     3300.D0,310.D0,320.D0,330.D0,340.D0,350.D0,360.D0,370.D0/
      DATA XVS/12045.D0,7677.6D0,5045.3D0,3408.3D0,2360.9D0,
     C1673.0D0,1210.1D0,891.71D0,
     4668.32D0,508.66D0,392.57D0,306.85D0,242.62D0,193.85D0,
     C156.35D0,127.19D0,104.265D0,
     586.062D0,71.472D0,59.674D0,50.056D0,42.149D0,35.599D0,
     C30.133D0,25.537D0,21.643D0,
     618.316D0,15.451D0,12.967D0,10.779D0,8.805D0,6.943D0,4.93D0/
      DATA XES/2592.D0,2609.D0,2626.D0,2643.D0,2660.D0,2676.D0,
     C2691.D0,2706.D0,2720.D0,
     72734.D0,2747.D0,2758.D0,2769.D0,2778.D0,2786.D0,2793.D0,
     C2798.D0,2802.D0,2803.D0,2803.D0,
     82801.D0,2796.D0,2790.D0,2780.D0,2766.D0,2749.D0,2727.D0,
     C2700.D0,2666.D0,2623.D0,2565.D0,
     92481.D0,2331.D0/
      DATA XEW/209.3D0,251.1D0,293.0D0,334.9D0,376.9D0,419.1D0,
     C461.3D0,503.7D0,546.3D0,
     X589.1D0,632.2D0,675.5D0,719.1D0,763.1D0,807.5D0,852.4D0,
     C897.7D0,943.7D0,990.3D0,
     Y1037.6D0,1085.8D0,1135.0D0,1185.2D0,1236.8D0,1290.D0,
     C1345.D0,1402.D0,1462.D0,
     Z1526.D0,1596.D0,1672.D0,1762.D0,1892.D0/
      TC=((TF+40.)/1.8)-40.
C
      XDS=FLAGR(TD,XVS,TC,2,33)
      DES=1./XDS*62.428
      XHS=FLAGR(TD,XES,TC,2,33)
      EHS=XHS*1000./2324.4
      XHW=FLAGR(TD,XEW,TC,2,33)
      EHW=XHW*1000./2324.4
      VTS=.407*TC+80.4-(1858.-5.9*TC)/XDS
      VIS=VTS/10000.
C
C      XDW=FLAGR(TD,XVW,TC,2,33)
C      DEW=1./XDW*62.428
      RETURN
      END
C
      FUNCTION FSURW(TF,PP)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION STVA(10),STV74(10),STV280(10)
      DATA STVA/
     10.D0,1000.D0,2000.D0,3000.D0,4000.D0,5000.D0,
     C6000.D0,7000.D0,8000.D0,9000.D0/
      DATA STV74/
     275.D0,63.D0,59.D0,57.D0,54.D0,52.D0,52.D0,51.D0,50.D0,49.D0/
      DATA STV280/
     353.D0,46.D0,40.D0,33.D0,26.D0,21.D0,21.D0,22.D0,23.D0,24.D0/
      TEM1=TF
      P=PP
      STW74=FLAGR(STVA,STV74,P,2,10)
      STW280=FLAGR(STVA,STV280,P,2,10)
      STW=(STW74-STW280)/(280.-74.)*(TEM1-74.)*(-1.)+STW74
      IF(TEM1.LT.74.)STW=STW74
      IF(TEM1.GT.280.)STW=STW280
      SURW-STW
      FSURW-SURW
      RETURN
      END
```

```
C
      SUBROUTINE PVTW(TF,PP,SGW,DEN,VIS)
      IMPLICIT REAL*8(A-H,O-Z)
      TA=TF-60.D0
      BW=1.D0+1.2D-4*TA+1.D-6*TA*TA-3.33D-6*PP
      DEN=62.43D0*SGW/BW
      VIS=DEXP(1.003D0-1.479D-2*TF+1.982D-5*TF*TF)
      RETURN
      END
```

APPENDIX B: Typical Input and Output Sheets

Input and output **sheets** attached are for Cerro-Prieto 90 well.

```
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                           TYPICAL INPUT SHEET
                           -------------------
CERRO-PRIETO M-90  (TOP TO BOTTOM)
590.      484.3    0000.0
1.     356840. 577.44   00.00
43
90.         4260.7     0.0
+1
0 1
.5808     .5808
.0006      .0006
0000.0      4260.7
02
0000. 4000.
100. 400.
```

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1

CERRO-PRIETO M-90 (TOP TO BOTTOM)

INPUT DATA AS FOLLOW:

WATER GRAVITY	1.0000
TOTAL MASS FLOWRATE, LB/HR	356840.0000
HEAT TRANSF COEFF, BTU/HR/SQ	0.

AT THE WELLHEAD :

DEPTH, FT	0.
PRESSURE, PSIA	590.00
TEMPERATURE, F	484.30

PIPE DIAMETER USED AS FOLLOW.

FROM 0. FT TO 4260.7 FT PIPE DIAMETER (FT) = 0.583
ABSOLUTE ROUGHNESS (FT) = 0.006

TOTAL LENGTH DIVIDED IN 43 INTERVALS

DOWNHOLE SHUT-IN TEMPERATURE AS FOLLOW

DEPTH, FT	TEMP, F
0.	100.00
4000.00	400.00

* TWO-PHASE FLOW *

DEPTH, FT	PRES, PSIA	TEMP, F	EN, BTU/LB	FRICTION Psi/100ft	C EL / O	POTENTIAL Psi/100ft	STM FRAC	REGIME	qw/A ft/s	qs/A ft/s
0.	590.00	484.30	577.44				0.1464			
99.09	601.79	486.62	577.44	6.5223	0	5.[illegible]809	0.1433	SLUG	6.3051	41.9538
198.17	613.56	488.70	577.44	6.3030	0	5.[illegible]699	0.1405	SLUG	6.3367	40.2866
297.26	625.31	490.77	577.44	6.0966	0	5.[illegible]603	0.1377	SLUG	6.3676	38.7157
396.34	637.05	492.78	577.44	5.8990	0	5.[illegible]552	0.1349	SLUG	6.3983	37.2111
495.43	648.81	494.80	577.44	5.7069	0	6.[illegible]576	0.1321	SLUG	6.4292	35.7475
594.52	660.59	496.76	577.44	5.5251	0	6.[illegible]623	0.1293	SLUG	6.4597	34.3612
693.60	672.40	498.73	577.44	5.3474	0	6.[illegible]752	0.1266	SLUG	6.4904	33.0078
792.69	684.26	500.65	577.44	5.1793	0	6.[illegible]909	0.1238	SLUG	6.5207	31.7238
891.77	696.18	502.58	577.44	5.0128	0	7.[illegible]159	0.1210	SLUG	6.5515	30.4514
990.86	708.18	504.47	577.44	4.8539	0	7.[illegible]513	0.1183	SLUG	6.5819	29.2357
1089.95	720.26	506.38	577.44	4.6975	0	7.[illegible]956	0.1155	SLUG	6.6128	28.0325
1189.03	732.44	508.25	577.44	4.5458	0	7.[illegible]486	0.1127	SLUG	6.6439	26.8765

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1288.12	744.74	510.14	577.44	4.4007	0.	8.0065	0 1099	SLUG	6.6746	25.7652
1387.20	757.16	512.03	577.44	4.2576	0.	8 2791	0 1070	SLUG	6.7060	24.6668
1486.29	769.72	513.88	577.44	4.1205	0.	8.5579	0 1042	SLUG	6.7372	23.6140
1585.38	782.44	515.77	577.44	3 9849	0.	8 8530	0 1013	SLUG	6 7691	22.5710
1684.46	795.34	517.62	577.44	3.8527	0.	9 1609	0 0984	SLUG	6 8013	21.5532
1783.55	808.42	519.51	577.44	3.7254	0.	9 4784	0 0955	SLUG	6 8333	20.5719
1882.63	821.71	521.41	577.44	3.5978	0.	9 8184	0 0925	SLUG	6.8663	19.5893
1981.72	835.24	523.31	577.44	3.4731	0.	10.1764	0 0894	SLUG	6 8998	18.6256
2080.81	849.01	525.19	577.44	3.3526	0.	10.5476	0 0864	SLUG	6.9332	17.6943
2179.89	863.06	527.12	577.44	3.2324	0.	10 9458	0 0832	SLUG	6.9677	16.7643
2278.98	877.41	529.07	577.44	3.1144	0.	11 3674	0 0800	SLUG	7 0028	15.8493
2378.07	892.09	531.00	577.44	2.9981	0.	11.8148	0 0768	SLUG	7.0387	14.9479
2477.15	907.12	532.99	577.44	2.8855	0	12 2839	0 0735	SLUG	7 0748	14.0725
2576.24	922.54	535.00	577.44	2.7727	0.	12.7924	0 0700	SLUG	7 1122	13.1947
2675.32	938.39	537.03	577.44	2.6614	0.	13 2375	0 0665	SLUG	7.1506	12.3267
2774.41	954.72	539.11	577.44	2.5503	0.	13 9284	0 0629	SLUG	7.1901	11.4606
2873.50	971.57	541.19	577.44	2.4419	0.	14 5589	0 0592	SLUG	7 2302	10.6131
2972.58	988.99	543 34	577.44	2 3327	0.	15 2542	0 0553	SLUG	7 2722	9.7581
3071.67	1007.06	545.54	577.44	2.2242	0.	16 0144	0 0513	SLUG	7.3157	8.9064
3170.75	1025.86	547.80	577.44	2.1161	0.	16.8502	0 0471	SLUG	7.3608	8.0565
3269.84	1045.46	550.12	577.44	2.0092	0.	17.7762	0 0428	SLUG	7.4078	7.2067
3368.93	1065.98	552.51	577.44	1.9002	0.	18 8102	0 0382	SLUG	7.4569	6.3541
3468.01	1087.55	554.99	577.44	1.7920	0.	19 9743	0 0334	SLUG	7.5083	5.4981
3567.10	1110.33	557.56	577.44	1 6627	0.	21 2061	0 0284	SLUG	7.5627	4.6307
3666.18	1134.50	560.22	577.44	1.5735	0.	22 8258	0 0230	SLUG	7 6197	3.7620
3765.27	1160.35	563 05	577.44	1 4614	0.	24 6266	0 0172	SLUG	7 6811	2.8684
3864.36	1188.22	566.04	577.44	1.3472	0.	26 7782	0 0109	SLUG	7.7473	1.9546
3963.44	1218.99	569.28	577.44	1.3531	0.	29 7004	0 0040	BBLE	7.8196	1.0072

FLASH POINT

4011.40	1234.84	570 82	576.70	1 1760	0.	31 8634

* LIQUID FLOW *

DEPTH,FT	PRES,PSIA	TEMP,F	EN,BTU/LB	FRICTION Psi/100ft	ACCE Psi/10	POTENTIAL Psi/100ft	qw/A ft/s
4136 05	1277 21	570 82	576 54	1.1040	0	32 6925	7 8939
4260.70	1319.59	570.82	576 39	1.1039	0.	32 8960	7 8981

** PRESSURE ANALYSIS **

TOTAL FRICTION, LIQUID = 2 7521 PS
TOTAL POTENTIAL, LIQUID = 82.0037 PS

TOTAL FRICTION, TWO-PHASE = 142 1608 PS
TOTAL POTENTIAL, TWO-PHASE = 502 6773 PS
TOTAL ACCELE , TWO-PHASE = 0 PS

APPENDJX C: Measured Pressure and Temperature Data

All measured pressure and temperature data for the ten wells are presented in the form of tables. Reference at the end of each table indicates the source of the data.

TABLE C-1
Measured flowing pressure and temperature data for Ngawha 11

Depth, meter	Pressure, bar-g	Temperature, Deg C
0	19	206
100	22.5	211.5
201	26.5	215
301	31	218.5
351	33.9	
401	37	220
451	40.6	
501		222.5
502	43.8	
552	48	
602	51.9	223.5
702	60.1	224
802	69.2	224.5
902	78.4	224.5
952		222.5
1002	86.3	222.5

Data obtained from Bixley (1984).

TABLE C-2
Measured flowing pressure and temperature data for Los Azufres 18

Depth, meter	Pressure, bar-g	Temperature, Deg C
0	30	238
100	31.2	242.5
200	32.2	244
300	33.1	246
400	34.2	248
500	35.2	249
600	36.2	251
700	37.4	253
800	38.4	254
900	39.5	256
1000	40.8	257.5
1050	41.9	258.8
1100	42.9	260.2
1150	43.8	261.5
1200	45	263
1250	46.5	267
1300	50.1	271
1324	52.1	272

Data obtained from Molinar (1985).

TABLE C-3
Measured flowing pressure and temperature data for Cerro-Prieto 90

Depth, meter	Pressure, bar-g	Temperature, Deg C
25	40.9	249
100	42.5	250.5
200	45.3	254
300	48.1	257.5
400	51	261
500	54	264.5
600	57.4	269
700	60.5	272
800	64.3	275.5
900	68.3	279
1000	72.2	283
1100	76.8	287
1200	82	290.5
1225	83.6	291.5
1250	85	292
1299	88.5	292

Data obtained from Ortiz-R. (1983).

TABLE C-4
Measured flowing pressure and temperature data for Okoy 7

Depth, meter	Pressure, bar-g	Temperature, Deg C
0	41.7	261
200	45.8	267
400	49.8	272
600	54.1	277
800	59.1	282
1000	64.9	288
1200	71.8	294
1400	81.4	300
1600	93	305
1800	106.3	314
2000	120.3	317
2200	134.7	318
2400	149	319
2600	162.9	319

Data obtained from Catigtig (1983).

TABLE C-5
Measured flowing pressure and temperature data for Cerro-Prieto 91

Depth, meter	Pressure, bar-g	Temperature, Deg C
0	56.5	
150	62.5	
200		288
250	66	
350	70	
400		294.5
450	74	
540	78	
600		301
640	82	
750	87	
800		308
850	92	
950	98	
1000		315.5
1050	104.	
1140	111.5	
1200		322
1220	117	

Data obtained from Goyal et *al.* (1980).

Depth, meter	Pressure, bar-g	Temperature, Deg C
0	3.5	157
304	5.2	171
607	7.4	182
902	9.2	189.5
1978	21.5	223

Data obtained from Chierici et *al.* (1981).

TABLE C-7
Measured flowing pressure and temperature data for East Mesa 6

Depth, meter	Pressure, bar-g	Temperature, Deg C
0	2.3	
152	2.7	125.5
305	3.1	134
457	3.7	139.5
610	4.3	145
762	5.2	153
915	6.4	161
1067	7.9	170
1219	13.2	192
1234	14.3	196
1372	26.3	196.7
1524	39.6	197.2
1676	52.9	197.8
1829	66.3	198.3
2134	93	198.5

Data obtained from Lundberg (1973).

TABLE C-8
Measured flowing pressure and temperature data for Krafla 9

Depth, meter	Pressure, bar-g	Temperature, Deg C
0	16.3	199
100	17.5	205.5
200	20	212
300	22.8	219.5
400	25.8	227.5
500	30	235.5
600	34.3	243.5

Data obtained from Ryley and Parker (1982).

TABLE C-9
Measured flowing pressure data for Utah State 14

Depth, meter	Pressure, bar-g
10	27
41	27.8
85	29.4
169	31.2
233	32.8
296	34.5
359	36.1
388	37
420	37.9
445	38.7
469	39.5
495	40.3
516	41.2
539	42
573	43.2
616	45
645	46.2
675	47.4
701	48.7
725	49.9
747	51.2
772	52.5
786	53.3
807	54.5
828	55.8
846	57
863	58.3
884	59.6
901	60.8
913	61.6

Data obtained from Butz and Plooster (1979).

TABLE C-10
Measured flowing pressure and temperature data for HGP A well (70 klb/hr)

Depth, meter	Pressure, bar-g	Temperature, Deg C
0	3.2	146
160	4	152.7
305	4.6	158.4
401	4.9	160
465	5.2	162.4
642	5.9	166.2
770	7.2	174.3
914	8.6	181.3
1067	9.8	186.5
1219	11.5	192.4
1316	12.2	196.2
1380	12.6	196.2
1524	14.1	200
1684	15.5	202.7
1765	16.1	205.4
1829	16.7	207
1925	16.7	207

Data obtained from Kihara *et al.* (1977).

TABLE C-11
Measured flowing pressure and temperature data for HGP A well (66 klb/hr)

Depth, meter	Pressure, bar-g	Temperature, Deg C
0	6	166
127	6.3	170.3
305	6.6	175
401	6.9	176
465	7	178.4
642	7.9	181.9
770	8.6	181.9
914	10.6	191.1
1067	12.5	197.8
1219	14.1	204
1316	15.2	208.1
1380	15.4	208.6
1524	16.3	212.4
1684	17.8	212.2
1765	18.4	213.8
1829	19.4	216.8
1925	20.1	219.2

Data obtained from Kihara er *al.* (1977).

TABLE C-12
Measured flowing pressure and temperature data for HGP A well (58 klb/hr)

Depth, meter	Pressure, bar-g	Temperature, Deg C
0	15	201
160	16.1	203.2
305	17.2	206.8
401	17.5	208.1
465	17.7	208.6
642	18.8	213
770	20.1	216.8
914	21.6	219.2
1067	23.3	221.8
1219	24.7	223
1316	25.9	225.7
1380	26.5	227.8
1524	28.8	232.4
1684	31	237.8
1765	31.6	238.5
1829	32.9	240.5
1925	34	243.2

Data obtained from Kihara *et al.* (1977).

TABLE C-13
Measured flowing pressure and temperature data for HGP A well (50 klb/hr)

Depth, meter	Pressure. bar-g	Temperature, Deg C
0	25.2	226
160	**26.5**	231
305	27.9	233
401	28.8	233.5
465	29.5	236.8
642	30.9	239.5
770	32.8	243.2
914	34.8	248.6
1067	37.9	251
1219	39.7	252.7
1316	41.4	255.2
1380	42.5	256.7
1524	44.8	258.2
1684	47.7	264.9
1765	49.4	266
1829	**50.5**	268.9
1925	52.6	271

Data obtained from Kihara *et al.* (1977).

APPENDIX D: Papers Presented at 11th Stanford Geothermal Workshop

These papers describe the Orkiszewski **(1967)** correlations and present analysis of pressure profiles for the **ten** geothermal wells used in our study.

PROCEEDINGS, Eleventh Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 21-23, 1986
SGP-TR-93

GEOTHERMAL TWO-PHASE WELLBORE FLOW: PRESSURE DROP CORRELATIONS AND FLOW PATTERN TRANSITIONS

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ABSTRACT

In this paper we present some basic concepts of two-phase flow and review the Orkiszewski (1967) correlations which have been suggested by various investigators to perform well for geothermal wellbore flow situations. We also present a flow regime map based on the transition criteria used by Orkiszewski (1967) and show that most geothermal wells flow under slug flow regime. We have rearranged bubble- to slug- flow transition criterion used by Orkiszewski (1967) to show that the transition depends on the dimensionless pipe diameter number in addition to dimensionless liquid and gas velocity numbers. Our aim is also to identify what research may lead to improvements in two-phase pressure drop calculations for geothermal wellbore flow.

INTRODUCTION

The Orkiszewski (1967) two-phase vertical upward flow correlations have been used by several investigators to model steam/water wellbore flow. In a companion paper we use a geothermal wellbore simulator based on the Orkiszewski (1967) correlations to calculate the flowing pressure and temperature profiles in several wells (Ambastha and Gudmundsson, 1986). There we study under what flowing conditions the measured and calculated profiles match. Our study differs from others because we use data sets from several geothermal wells, but only one set of two-phase flow correlations.

In addition to identifying the conditions when measured and calculated wellbore data match, we want to identify what research may lead to improvements of geothermal wellbore simulators. For this we need to know the details of the wellbore simulator used, flow regime transitions, and pressure drop calculations. We also need to know how the correlations relate to two-phase flow studies in general. The purpose of this paper is to present the details of the Orkiszewski (1967) two-phase vertical flow correlations used in a geothermal wellbore simulator, described by Ortiz-R. (1983). We also present a flow regime map based on the transition criteria used by Orkiszewski (1967) as applied to geothermal wells.

PREVIOUS WORK

Early studies of two-phase flow in geothermal wells are those of Gould (1974) and Nathenson (1974). The Gould (1974) study is based on flow pattern specific correlations; the applications considered were wellbore deposition and deliverability. The Nathenson (1974) study considered no-slip (homogeneous) wellbore flow, coupled to porous media flow in the reservoir. The problems considered by Nathenson (1974) were the same.

Geothermal wellbore flow simulators have been developed by universities, national laboratories, industry, and consultants. However, progress has been slow since the initial Gould (1974) and Nathenson (1974) studies. Updhyay *et al.* (1977) compared calculated and observed pressure drops in geothermal wells producing steam/water mixtures. They compared flowing pressure profiles to several two-phase flow comlations and concluded that the Orkiszewski (1967) correlations are satisfactory - the Hagedorn and Brown (1965) correlations came second. Fandriana *et al.* (1981) developed the first version of the wellbore simulator used by Ortiz-R. (1983) and us. They compared four correlations and found that the Orkiszewski (1967) method was the best - the Hagedorn and Brown (1965) and Duns and Ros (1963) methods were found to give reasonable results also. Miller (1979) and Mitchell (1982) wrote geothermal wellbore simulators based on the Orkiszewski (1967) correlations. The above authors agreed on the general applicability of the Orkiszewski (1967) correlations to geothermal wellbore flow. Therefore, we think they form the best basis to compare predicted and measured pressure/temperature profiles in geothermal wells.

TWO-PHASE FLOW

The total pressure drop in wellbores consists of three components: frictional, accelerational, and gravitational. In typical two-phase wells the gravitational component dominates; the frictional component contributes only at high flow rates; and the accelerational component is usually insignificant. In *homogeneous* steady-state flow the total pressure drop in a constant cross-section duct is given by

$$-\frac{dp}{dz} = \frac{\tau S}{A} + \frac{d(G_M^2/\rho_M)}{dz} + g\,\rho_M \sin\theta \qquad (1)$$

In terms of pressure drop components the equation takes the form

$$\frac{dp}{dz} = \frac{dp_f}{dz} + \frac{dp_a}{dz} + \frac{dp_g}{dz} \qquad (2)$$

In separated steady-state flow the total pressure drop in a constant cross-section duct is given by

$$-\frac{dp}{dz} = \frac{\tau S}{A} + G_M \frac{d}{dz}\left[\frac{x^2}{\rho_G \alpha} + \frac{(1-x)^2}{\rho_L(1-\alpha)}\right] \tag{3}$$

where a is the void fraction given by

$$\alpha = \frac{A_G}{A} \tag{4}$$

An examination of Equations 1 and 3 shows that in homogeneous flow the wall shear stress τ is the unknown, while in separated flow both the wall shear stress and void fraction a arc unknown. The wall shear stress is used to calculate the frictional component in both homogeneous and separated flow. The void fraction is used to calculate the gravitational component in both models, and the accelerational component in separated flow.

Two kinds of correlations have been developed for frictional pressure drop in two-phase flow; called generalized and specific correlations. The generalized correlations are empirical and make no reference to the flow pattern and physical nature of two-phase flow phenomena. Nevertheless, many engineering calculations arc carried out using generalized methods; f a example that of Hagedorn and Brown (1965). The specific correlations me specific to the flow pattern (bubbly, slug, chum, annular) and flow situation (vertical. inclined, horizontal).

The Orkiszewski (1967) correlations are the specific kind. They are specific to vertical upward flow in oil and gas wells and can also be used f a geothermal wells. In addition to prescribing what correlation to use for pressure drop in different flow regimes, it is necessary to prescribe the criteria for transition between flow regimes. Small discontinuities in pressure drop can occur at transitions between flow patterns.

FLOW PATTERN TRANSITIONS

Our presentation follows that of Orkiszewski (1967), Brill and Beggs (1977), and Upadhyay a al. (1977). The flow regime transition criteria are essentially those of Ros (1961), and Duns and Ros (1963). They defined the following limits for the transition between flow regimes:

Bubble Flow $L_{bs} > v_{SG}/v_{ST}$

Slug Flow $L_{bs} < v_{SG}/v_{ST}$, $L_{st} > N_{GV}$

Transition Flow $L_{st} < N_{GV} < L_{tm}$

Mist Row $L_{tm} < N_{GV}$

The definition of these terms arc given in the nomenclature. The N r are dimensionless expressions of superficial velocities, the v's are superficial velocities, and the L'r arc flow regime boundary terms. They arc given by the expressions:

$$L_{bs} = 1.071 - 0.2218\,\frac{v_{ST}^2}{d} \geq 0.13 \tag{5}$$

$$L_{st} = 50 + 36\,N_{LV} \tag{6}$$

$$L_{tm} = 75 + 84\,(N_{LV})^{0.75} \tag{7}$$

$$N_{LV} = 1.938\,v_{SL}\left[\frac{\rho_L}{\sigma}\right]^{0.25} \tag{8}$$

$$N_{GV} = 1.938\,v_{SG}\left[\frac{\rho_L}{\sigma}\right]^{0.25} \tag{9}$$

$$v_{SL} = \frac{q_L}{A} \tag{10}$$

$$v_{SG} = \frac{q_G}{A} \tag{11}$$

$$v_{ST} = v_{SG} + v_{SL} \tag{12}$$

Note that the constant 1.938 in Equations 8 and 9 arises when engineering units are used. If we use the following definition of dimensionless pipe diameter number

$$N_D = 120.872\,d\sqrt{\frac{\rho_L}{\sigma}} \tag{13}$$

the criterion for bubble-to-slug flow can be rewritten as

$$\frac{N_{GV}}{N_{LV}+N_{GV}} < 1.071 - 13.8335\,\frac{\left[N_{LV}+N_{GV}\right]^2}{N_D} \tag{14}$$

Thus, the transition from bubble to slug flow involves a nonlinear relationship between liquid and gas velocity numbers for a particular value of pipe diameter number. We prepared a flow pattern map using the above flow regim transition criteria. In our companion paper (Ambastha and Gudmundsson, 1986), the pipe diameter number varied in the range of 60 to 100. Therefore, the boundary between bubble and slug flow regime was evaluated for a representative pipe diameter number of 80. Figure 1 presents the flow pattern map on log-log coordinates. Figure 2 provides the same information on cartesian coordinates. Chierici a al. (1974) also present this flow pattern map on log-log coordinates. They note that the boundary between bubbk and slug flow regimes results in a family of curves, corresponding to different sets of ρ_L, a rad d. We observe that the three parameters can be combined into a dimensionless pipe diameter number rad that the boundary between bubble and slug flow regimes can be represented by Equation 14.

In a companion paper (Ambastha and Gudmundsson, 1986), we present flowing data for 10 two-phase geothermal wells. The flowrate ranges from 12.9 kg/s to 68.6 kg/s; the enthalpy from 965 kJ/kg to 1966 kJ/kg; wellhead pressure from 245 kPa to 6027 kPa; well depth from 913 m to 2600 m; wellbore diameter from about 7-5/8" to 9-5/8". We used our Orkiszewski-based geothermal wellbore simulator to calculate the flowing pressure and temperature profiles in the 10 wells. The two-phase flow patterns encountered in these calculations arc shown in Figure 3. The

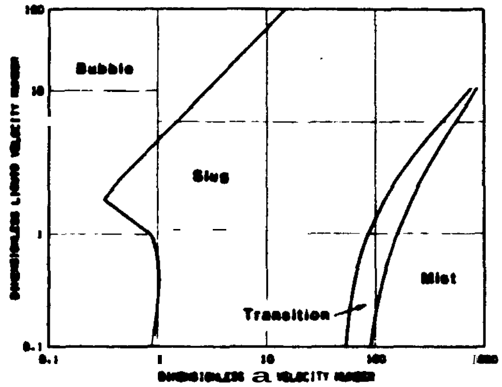

Figure 1. Orkiszewski flow pattern map (log-log coordinates).

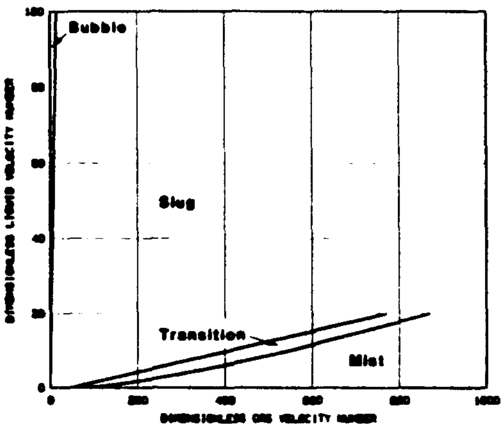

Figure 2. Orkiszewski flow pattern map (cartesian coordinates).

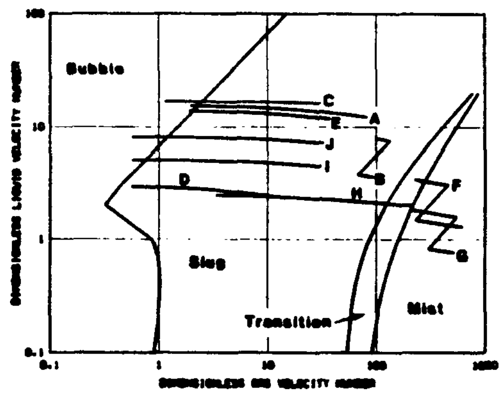

Figure 3. Flow regimes fa geothermal wells.

figure gives the dimensionless superficial velocity of liquid water against steam vapor, so the flow lines for individual wells go from left to right. Low enthalpy wells tend to be in the upper left hand part of Figure 3, and high enthalpy wells in the lower right hand part. The steps in the lines result from wellbore diameter changes; increased flow area reduces the superficial velocity of both phases. Figure 3 shows that slug flow is the dominant flow regime in the 10 wells.

PRESSURE DROP CORRELATIONS

The Orkiszewski (1967) correlations for pressure drop calculations are based on several works: Griffith and Wallis (1961) for bubble flow regime, and Duns and Ros (1963) for transition and mist flow regimes. Orkiszewski (1967) developed a new correlation for slug flow based upon the experimental data of Hagedorn and Brown (1965). The pressure drop correlations for different flow regimes are presented below.

Bubble Row (Criffith and Wallis, 1961)

Liquid holdup in this flow regime is given by the equation

$$H_L = 1 - 0.5\left[1 + \frac{v_{ST}}{v_s} - \sqrt{(1+v_{ST}/v_s)^2 - 4v_{SG}/v_s}\right] \quad (15)$$

The bubble velocity, v_s (also called the slip velocity) is assumed to have a constant value of 0.8 ft/sec. Once the liquid holdup is obtained, the mixture density can be determined from

$$\rho_M = \rho_L H_L + \rho_G (1 - H_L) \quad (16)$$

The holdup is related to void fraction by

$$H_L = 1 - \alpha \quad (17)$$

The pressure drop due to friction is given by

$$\frac{dp_f}{dz} = \frac{f\rho_L\left[\frac{v_{SL}}{H_L}\right]^2}{2g_c d} \quad (18)$$

The friction factor f is obtained from the Moody diagram. The Reynolds number for this purpose is given by

$$N_{Re} = \frac{1488\ \rho_L\ v_{SL}\ d}{H_L\ \mu_L} \quad (19)$$

Note that the constant 1488 in Equations 19.22 and 23, arises when engineering units are used. In this flow regime, pressure drop due to acceleration is considered negligible.

Slug Flow (Orkiszewski, 1967)

The mixture density in this flow regime is calculated by

$$\rho_M = \frac{\rho_L(v_{SL} + v_s) + \rho_G\ v_{SG}}{v_{ST} + v_s} + \rho_L\delta \quad (20)$$

where v_B is bubble rise velocity and is given by

$$v_B = C_1 C_2 \sqrt{gd} \qquad (21)$$

C_1 is a function of N_{ReB} and C_2 is a function of both N_{ReB} and N_{ReL}, defined as

$$N_{ReB} = \frac{1488\, \rho_L\, v_B\, d}{\mu_L} \qquad (22)$$

$$N_{ReL} = \frac{1488\, \rho_L\, v_{ST}\, d}{\mu_L} \qquad (23)$$

The Griffith and Wallis (1961) coefficients, C_1 and C_2, were presented by Orkiszewski (1967) in the form of figures. Because of the interrelationship of v_B and N_{ReB}, the calculation of v_B requires an iterative procedure. v_B can also be calculated using Equations 24 through 27.

When $N_{ReB} \leq 3000$,

$$v_B = (0.546 + 8.74 \times 10^{-6} N_{ReL})\sqrt{gd} \qquad (24)$$

When $N_{ReB} \geq 8000$,

$$v_B = (0.35 + 8.74 \times 10^{-6} N_{ReL})\sqrt{gd} \qquad (25)$$

When $3000 < N_{ReB} < 8000$,

$$v_B = 0.5 \left[\psi + \sqrt{\psi^2 + \frac{13.59\mu_L}{\rho_L \sqrt{d}}}\right] \qquad (26)$$

$$\psi = (0.251 + 8.74 \times 10^{-6} N_{ReL})\sqrt{gd} \qquad (27)$$

where ψ is an arbitrarily defined parameter.

The Orkiszewski (1967) liquid distribution coefficient δ, which is an empirical coefficient relating theory to reality, is given by the expressions:

For $v_{ST}<10$,

$$\delta = (0.013 \log \mu_L)/d^{1.38} - 0.681 + 0.232 \log v_{ST} - 0.428 \log d \qquad (28)$$

with the limit $\delta \geq -0.065\, v_{ST}$

For $v_{ST}>10$,

$$\delta = (0.045 \log \mu_L)/d^{0.799} - 0.709 + 0.162 \log v_{ST} - 0.888 \log d \qquad (29)$$

with the limit

$$\delta \geq -\frac{v_B}{v_{ST} + v_B}\left[1 - \frac{\rho_M}{\rho_L}\right]$$

Pressure drop due to friction is given by

$$\frac{dp_f}{dz} = \frac{f \rho_L v_{ST}^2}{2 g_c d}\left[\left(\frac{v_{SL} + v_B}{v_{ST} + v_B}\right) + \delta\right] \qquad (30)$$

The friction factor f is obtained from the Moody diagram using the Reynolds number given by Equation 23. The pressure drop due to acceleration in the slug flow regime is neglected.

Transition Flow (Duns and Ros, 1963)

In the transition flow regime, the total pressure gradient is obtained by linear interpolation between the slug and mist flow boundaries. The pressure gradient in the transition flow regime is then

$$\frac{dp}{dz} = M\left[\frac{dp}{dz}\right]_{slug} + (1-M)\left[\frac{dp}{dz}\right]_{mist} \qquad (31)$$

where

$$M = \frac{L_{sm} - N_{GV}}{L_{sm} - L_{st}} \qquad (32)$$

Mist Flow (Duns and Ros, 1963)

The gas phase is continuous in this flow regime. The slip velocity is assumed to be zero; that is, homogeneous flow. The mixture density is given by

$$\rho_M = \rho_L\, v_{SL}/v_{ST} + \rho_G\, v_{SG}/v_{ST} \qquad (33)$$

The frictional pressure drop is calculated as:

$$\frac{dp_f}{dz} = \frac{f \rho_G v_{SG}^2}{2 g_c d} \qquad (34)$$

The friction factor f is obtained from the Moody diagram and the Reynolds number defined by

$$N_{Re} = \frac{1488\, \rho_G\, v_{SG}\, d}{\mu_G} \qquad (35)$$

A modified relative roughness factor (e/d) is calculated to be used with the Moody diagram. This is done to take into account the effect of the liquid film on the pipe.

Pressure drop due to acceleration is given by

$$\frac{dp_a}{dz} = \frac{v_{ST}\, v_{SG}\, \rho_M}{g_c P}\left[\frac{dp}{dz}\right] \qquad (36)$$

WELLBORE SIMULATOR

The wellbore simulator used in our work is that of Fandriana *et al.* (1981) and Ortiz-R. (1983). It is based on the Orkiszewski (1967) recommended flow regimes and pressure drop correlations. The computer code is written such that we can start the calculations from the wellhead or wellbottom. We divide the wellbore into segments and calculate the pressure drop due to friction, gravity, and acceleration. To calculate the frictional pressure drop, the casing roughness needs to be specified. The heat transfer to/from the wellbore can also be calculated. We specify the geothermal gradient and the overall heat transfer coefficient, which are then used to calculate the heat loss/gain between each wellbore segment and surrounding formation. Thermodynamic properties used in the computer code are from steam tables. However, when calculating the density of liquid water, its salinity is included. The effect of non-condensible gases is not included in our simulator.

SUMMARY

Most of the geothermal wells tested in our companion paper (Ambastha and Gudmundsson, 1986), flowed in the slug flow regime, as shown in Figure 3. As reported in the companion paper (Ambastha and Gudmundsson, 1986). we obtained not-—good matches for some of the wells, and those wells also fall in the slug flow regime. Therefore, further research for geothermal two-phase flow applications should be directed towards the slug flow regime.

ACKNOWLEDGMENTS

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NOMENCLATURE

A	Pipe inside area, sq. ft.
A_G	Pipe area occupied by gas. sq. A.
C_1–C_2	Parameters to calculate bubble rise velocity
d	Pipe inside diameter, ft
e	Absolute pip roughness, ft
f	Moody friction factor
G_M	Total mass flux. lbm/sec·ft^2
g	Acceleration due to gravity, 32.2 ft/sec^2
g_c	Conversion constant, 32.2 lbm·ft/lbf·sec^2
H_L	Liquid holdup, fraction
L_{bs}	Bubble-slug boundary term
L_{st}	Slug-transition boundary term
L_{tm}	Transition-mist boundary term
M	Parameter defined by Eq. 32
N_D	Pipe diameter number
N_{GV}	Gas velocity number
N_{LV}	Liquid velocity number
N_{Re}	Reynolds number
N_{ReB}	Bubble Reynolds number
N_{ReL}	Liquid Reynolds number
P	Pressure, psf
dp_a/dz	Acceleration pressure gradient, psf/ft
dp_f/dz	Frictional pressure gradient, psf/ft
dp_g/dz	Gravitational pressure gradient, psf/ft
S	Wetted Perimeter, ft
v_B	Bubble rise velocity. ft/sec
v_{ST}	Total superficial velocity, ft/sec
v_{SG}	superficial gas velocity. ft/sec
v_{SL}	Superficial liquid velocity, ft/sec
z	Vertical length, ft

Greek symbols

α	Void fraction
δ	Liquid distribution coefficient
μ_G	Gas viscosity
μ_L	Liquid viscosity
μ_M	Mixture viscosity
ψ	Parameter defined by Eq.27
ρ_G	Gas density, lbm/ft^3
ρ_L	Liquid density, lbm/ft^3
ρ_M	Mixture density, lbm/ft^3
σ	Interfacial tension, dynes/cm
τ	Wall shear stress, dynes/cm^2
θ	Inclination angle, radian

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PRESSURE PROFILES IN TWO-PHASE GEOTHERMAL WELLS: COMPARISON OF FIELD DATA AND MODEL CALCULATIONS

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Abstract

Increased confidence in the predictive power of two-phase correlations is a vital part of wellbore deliverability and deposition studies for geothermal wells. Previously, the Orkiszewski (1967) set of correlations has been recommended by many investigators to analyze geothermal wellbore performance. In this study, we use measured flowing pressure profile data from ten geothermal wells pound the world, covering a wide range of flowrate, fluid enthalpy, wellhead pressure and well depth. We compare measured and calculated pressure profiles using the Orkiszewski (1967) correlations.

Introduction

Two-phase steam/water flow occurs in geothermal reservoirs, wellbores, *rad* surface pipelines. The production of steam/water mixtures depends on how the reservoir, wellbore, and surface facilities operate in series. It means that the overall performance of the system can be dominated by poor performance by any of its components. Improved understanding of the system components, therefore, may lead to better production methods for geothermal resources of the liquid- and boiling-dominated type. In this paper we consider the wellbore part of the system.

A feature common to previous studies of geothermal wellbore flow, is that several two-phase flow correlations *arc* compared to a single or few data sets, and the best-fit correlation identified. A limitation of this approach is that a particular correlation can be matched to a single set of flowing data by adjusting a number of parameters. This leaves open the question of generalizability; that is, the application of the best-fit wellbore model to other geothermal wells. It may also not be dear what wellbore correlations to use for predictive purposes. Furthermore, the several-models and single-data-set approach may hide what aspects of modeling *rad* measurements would benefit from research and development. In this paper we address the issue of generalizability by adopting an approach of a single-model and several-data-sets.

The Orkiszewski (1967) wellbore correlations *rad* simulator used in *our* work *me* discussed in a companion paper (Ambastha and Gudmundsson, 1986). A related papa ir that of Gudmundsson ct *d*. (1984).

Field Data

Flowing pressure *rad* temperature profiles from 10 geothermal wells were collected for the purpose of our study. The wells *me* in 6 countries: the United States, Mexico. New Zealand, the Philippines, Iceland, and Italy. The discharge data for these wells are shown in Table I. The total flowrate ranges from 12.9 kg/s to 68.6 kg/s; the mixture enthalpy from 965 kJ/kg to 1966 kJ/kg (corresponding to liquid water at 225°C and up); wellhead pressure from 23 bar-g to *56.5* bar-g (245 kPa to 6027 kPa); well depth from 913 m to 2600 m. The wellbore diameter is also given in Table 1, the nominal using size near the surface ranging from 7-5/8" to 9-5/8". We were not able to compile the chemical data (dissolved solids and non-condensible gas content) for the wells.

Flowing data for wells Cerro Prieto 90, East Mesa 6-1, and Utah State 14-2 are given by Ortiz-R. (1983). who in turn obtained the data from Castaneda (1983), Fandriana *et al.* (1981). *rad* Butz *rad* Plooster (1979). respectively. The different sources of the same data sets are listed here to assist investigators in further studies. The data for wall East Mesa 6-1 has ken used in several studies; for example. Gould (1974). Nathenson (1974), and Juprasert and Sanyal (1977). The original East Mesa reference is that of Lundberg (1973). A reference for the Roosevelt Hot Springs well Utah State 14-2 data is that of Butz and Mickley (1982). Flowing data for well Cerro Prieto 91 was obtained from Ryley and Parker (1982). who in turn used a paper by Goyal *et al.* (1980). The Ryley and Parker (1982) paper was also the source for the data for Krafla 9 in Iceland. The data for well Okoy 7 in the Philippines were taken from a report by Catigtig (1983). A papr authored by Chierici *et al.* (1981) provided the data for the Italian well Mofete *2* Information on well HGP-A in Hawaii was taken from Kihara *et al.* (1977) and Yuen *et al.* (1978). The New Zealand data on well Ngawha 11 was provided by Bixley (1984); the Mexican data on well Los Azufres 18 was provided by Molinar (1985). More wellbore profile data are found in Upadhyay *a al* (1977), Barelli *et al.* (1982). Butz and Mickley (1982). *rad* Wilson (1984).

Wellbore Simulation

The pressure *rad* temperature profiles for the 10 wells, respectively, are shown in Figure 1 and Figure 2. However. well Utah State 14-2 had no temperature profile data. Using the data in Table 1, we used the Orkiszewski-based simulator discussed in the companion paper (Ambastha *rad* Gudmundsson, 1986), to calculate the flowing profiles. All calculations were done from the surface to well bottom. The matches we obtained with the measured profiles ranged from good to not-so-good. It is not possible to show all the matches in this paper. Instead, we determined the average pressure gradient in the first 500 m

Table 1. Data used to calculate pressure and temperature profiles from wellhead to bottom

Well	Total Flowrate kg/s	Mixture Enthalpy kJ/kg	Wellhead Pressure bar-g	Wellbore Suing Design	Total Depth m
A-- Cerro Prieto 90	45	1343	40.7	0.5808 ft from 0-bottom	1299
B--Los Azufres 18	26.7	1607	30.0	0.7296 ft from 0-959 m 0.5153 ft from 959 m-bottom	1324
C--Ngawha 11	68.6	965	19.8	0.652 ft from 0-673.5 m 0.4934 ft from 673.5 m-boaom	950
D--Okoy 7	132	1403	465	0.7251 ft from 0-1308 m 0523 fi from 1308 m-boaom	2600
E--Cerro Prieto 91	342	1372	565	0.5361 ft from 0-1942 m 0.3370 ft from 1942 m-boaom	2294
F--Mofete 2	16.4	1834	35	0.7283 ft from 0.1272 m 0.5118 ft from 1272 m-bottom	1989
G--HGP-A	13.9	1966	3 2	0.802 fi from 0-680 m 0.5833 ft from 680 m-boaom	1966
H--East Mesa 6-1	12.9	1197'	2.3	0.7267 ft from 0-bottom	2134
I--Krafla 9	25	1532'	16.3	0.7297 ft from 0-1053 m 0.5856 ft from 1053 m-bottom	1251
J--Utah State 14-2	40.9	1648*	26.7	0.7433 ft from 0-bottom	913

* --- Based on measured bottom-hole temperature

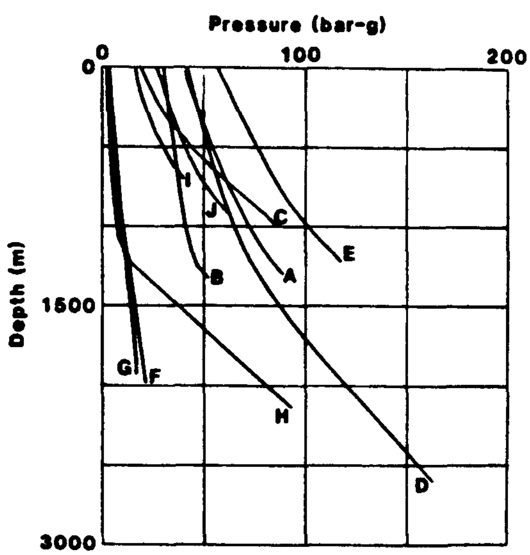

Figure 1. Measured pressure profiles.

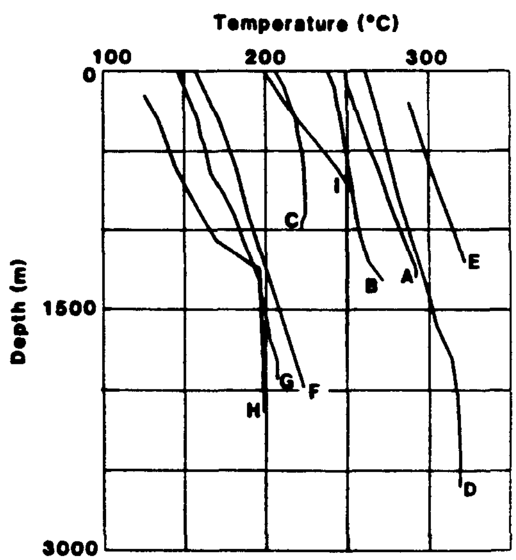

Figure 2. Measured temperature profiles.

Table 2. Values representing two-phase nature of flow at/near wellhead

Well	Total Mass Flux kg/s-m²	Quality at Wellhead	Steam Mass Flux kg/s-m²	Wellhead Pressure bar-g	Measured Pressure Gradient bar/m	Calculated Pressure Gradient bar/m	Ratio
A--Cerro Prieto 90	1830	0.15	275	40.7	0.0275	0.0275	1.00
B--Los Azufres 18	687	0.33	227	30.0	0.0104	0.0088	0.85
C--Ngawha 11	2211	0.025	55	19.0	0.0494	0.0770	1.56
D--Okoy 7	344	0.16	55	46.5	0.0207	0.0220	1.06
E--Cerro Prieto 91	1630	0.11	179	56.5	0.0398	0.0333	0.84
F--Mofete 2	424	0.57	242	3.5	0.0064	0.0071	1.11
G--HGP-A	296	0.63	187	3.2	0.0042	0.0049	1.17
H--East Mesa 6-1	335	0.14	47	1.5	0.0030	0.0060	2.00
I--Krafla 9	644	0.08	52	20.9	0.0274	0.0117	0.42
J--Utah State 14-2	1015	0.08	83	30.6	0.0275	0.0192	0.70

of each well (from the wellhead and 500 m down) and compared the measured and calculated values. These values are shown in Table 2 for the 10 wells. Also given is the ratio of the calculated and measured pressure gradients. A pressure gradient ratio of unity indicates a good match; a gradient ratio less than unity means that the measured is greater than the calculated; a gradient ratio greater than unity means that the calculated pressure gradient is greater. Our visual inspection of the measured and calculated profiles suggested that the matches were reasonable when the calculated pressure gradient was within about 20 percent of the measured gradient. This means *that* not-so-good matches were obtained for wells Ngawha 11, East Mesa 6-1, Utah State 14-2 and Krafla 9. Well Cerro Prieto 90 gave a good match, and other wells reasonable matches. Well Okoy 7 was a special case. The calculated and measured pressure gradients near the wellhead were similar, but diverged with depth.

We looked at the quality of matches by estimating mean and standard deviation of error and percent error, as follows:

$$e_i = p_{calc} - p_{meas} \qquad (1)$$

$$d_i = \frac{p_{calc} - p_{meas}}{p_{meas}} \times 100 \qquad (2)$$

where p_{calc} and p_{meas} are calculated and measured pressures at any point respectively.

$$\bar{e} = \frac{\sum_{i=1}^{n} e_i}{n} \qquad (3)$$

$$\sigma_e = \left[\frac{\sum_{i=1}^{n}(e_i - \bar{e})^2}{n-1}\right]^{1/2} \qquad (4)$$

$$\bar{d} = \frac{\sum_{i=1}^{n} d_i}{n} \qquad (5)$$

$$\sigma_d = \left[\frac{\sum_{i=1}^{n}(d_i - \bar{d})^2}{n-1}\right]^{1/2} \qquad (6)$$

where e_i is the error, $\bar{e}$ is arithmetic mean error, σ_e is the standard deviation about $\bar{e}$, and n is the number of data points. Similarly, d_i is the percent error, d is mean percent error, and σ_d is the standard deviation about $\bar{d}$. Such statistical parameters have been used before to evaluate the accuracies of two-phase correlations (Vohra *et al.*, 1975). Results of our calculations are summarized in Table 3. For a good match, we should have a low mean and standard deviation. Looking at the mean and standard deviation of error, we find that Ngawha 11, Okoy 7, East Mesa 6-1, Krafla 9 and Utah State 14-2 fall in the category of not-so-good matches. Similar conclusion is drawn by looking at the columns of mean percent error and standard deviation of percent error, except that now it seems that Mofete 2 and HGP-A are also not-so-good matches. But these two wells are low pressure wells and hence small deviation in calculated pressure gets magnified when we calculate percent error. So mean and standard deviation of percent error is not necessarily a good way to determine the quality of matches in low pressure cases. Thus three different criteria to determine the quality of matches suggest that we have not-so-good matches for 5 wells.

The Cerro Prieto 90, Ngawha 11 (ratio greater than unity), and Krafla 9 (ratio less than unity) pressure profiles are shown in Figures 3, 4, and 5, respectively. They demonstrate the range of results obtained in our work. All the wellbore calculations reported here were done assuming no heat transfer to/from the formation; the absolute casing

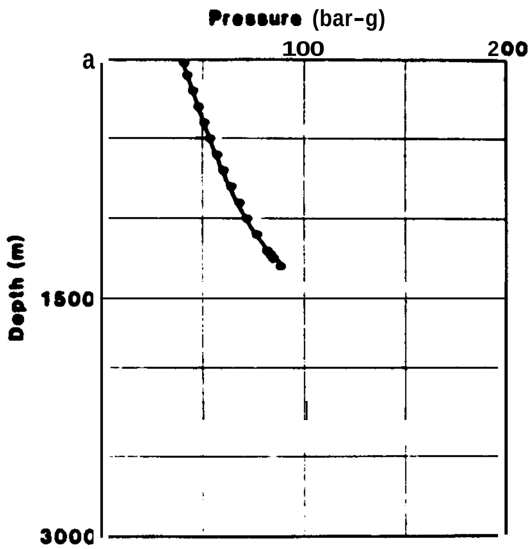

Figure 3. Pressure profile match for well Cerro Prieto 90.

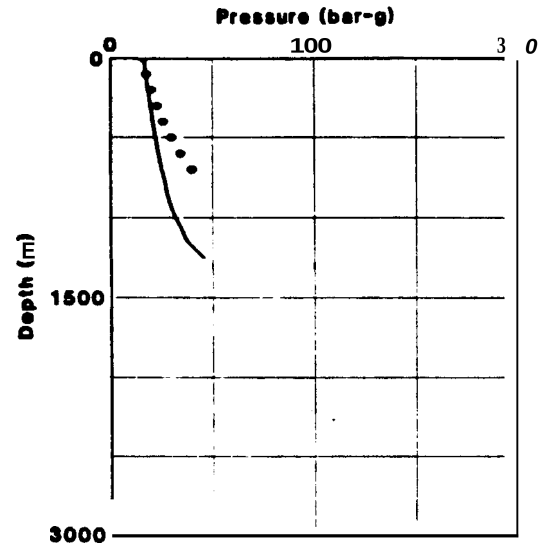

Figure 5. Pressure profile match for Krafla 9.

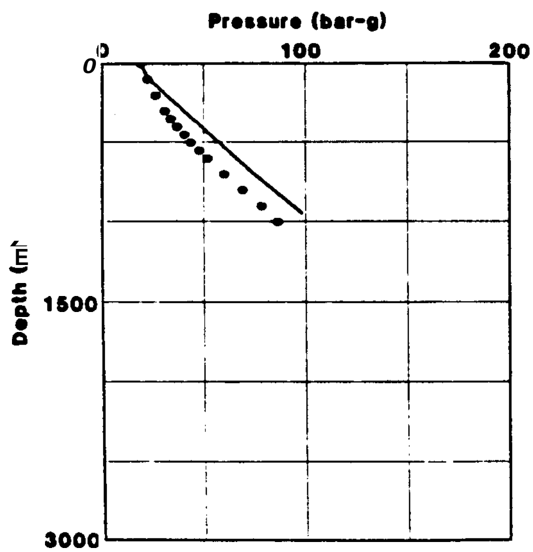

Figure 4. Pressure profile match for well Ngawha 11.

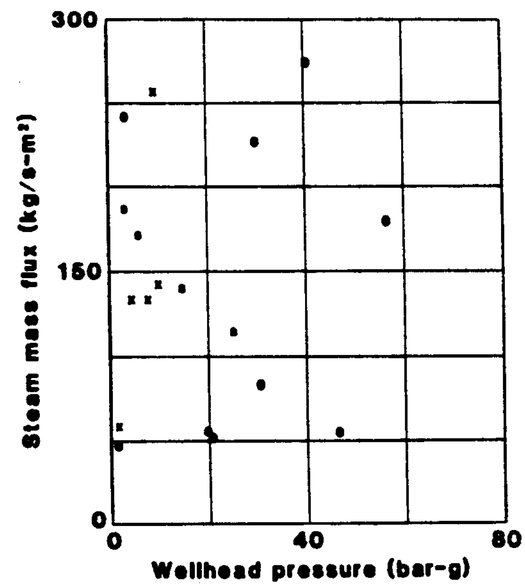

Figure 6. Steam mass dux vs. wellhead pressure

roughness used throughout was 0.0006 feet; the wellbore was divided into about 50 segments in most cases. The effects of noncondensible gases and dissolved solids were not considered.

We think that the Orkiszewski (1967) method performs as well as any other method for geothermal wellbore flow; that is, the method seems to have general applicability. What we would like to know also, is under what conditions it performs best, and under what conditions it should not be expected to give good results. We looked at the 10 matches of calculated and measured profiles, and tried to group the good and not-so-good wells using two-phase flow related criteria such as mass flux, void fraction, and pressure. We found that by plotting the "steam mass flux at the wellhead" against "wellhead pressure," the wells exhibiting not-so-good matches formed a group away from the better matched wells. This result is shown in Figure 6. The values used to draw this figure are given in Table 2. The rationale for Figure 6 are these: (1) the steam mass flux represents the dryness or void fraction of the flow, arbitrarily taken at the wellhead; (2) the wellhead pressure correlates the physical properties of steam and water.

There are more points in Figure 6 than are given *in* Table 2. Nine of the wells in Table 2 are represented by circles in Figure *6*. The well not shown by a circle is HGP-A in Hawaii; it is represented by stars. There are four stars in Figure 6. The highest flowrate one is that given in Table 2 The other three are lower flowrate pnfiks that we also matched using the wellbore simulator The five crosses in Figure 6 are data points from a paper by Upadhyay *et al.* (1977), from wells in the Philippines

Table 3. Comparison of measured and calculated pressure profiles

Well	Data Points	Measured Pressure Range, bar-g	Mean Error bar-g	Standard Deviation of Error, bar-g	Mean Percent Error	Standard Deviation of Percent Error
A--Cerro Prieto 90	16	40.9-88.5	-0.3	0.8	-0.6	1.1
B--Los Azufres 18	18	30.0-52.1	-1.1	1.2	-2.65	2.2
C--Ngawha 11	14	19.0-86.3	10.8	5.1	22.8	10.4
D--Okoy 7	14	41.7-162.9	5.3	4.1	5.1	3.9
E--Cerro Prieto 91	13	56.5-117.0	-0.15	2.6	-0.66	2.9
F--Mofete 2	5	3.5-21.5	0.4	0.4	4.9	5.1
G--HGP-A	17	3.2-16.7	0.6	0.4	6.1	2.7
H--East Mesa 6-1	15	2.3-92.9	11.0	9.4	5995	532
I--Krafla 9	8	16.3-40.0	-5.5	5.4	-17.5	13.8
J--Utah State 14-2	30	27.0-61.6	-6.7	4.6	-13.6	6.9

and the United States. Upadhyay *et al.* (1977) stated that reasonable matches were obtained when comparing measured profiles to calculated profiles *using* a wellbore simulator based on Orkiszewski's (1967) correlations. The total flowrate of these two-phase wells ranged from 3 kg/s to 11 kg/s. It appears from Figure 6 that the Orkiszewski (1967) correlations do not work as well when the steam mass flux is below 100 kg/s-m^2.

Discussion

In general, the Orkiszewski (1967) correlations work well for different geothermal wellbore flow situations. The mean percent errors for Ngawha 11, East Mesa 6-1, Krafla 9 and Utah State 14-2, however, were larger than 10%. Ngawha 11 has 1.4% of noncondensible gas in the total uow. This may be the reason for the bad match, because the wellbore simulator does not *consider* the effect of noncondensible gases.

Krafla 9 is said to have wellbore deposition problems which reduces the effective area open to flow in the wellbore and this could be the reason for the bad match. If we reduce the wellbore string diameter, we will h v e larger pressure drop and can match the measured pressure profile. We are not aware of any problems with well Utah State 14-2, so we can not propose / reason for the not-so-good match in this case.

East Mesa 6-1 is a special case. The mean percent error and standard deviation about mean percent error for East Mesa 6-1 were unusually large. This match is shown in Figure 7. We see that calculated pressure profile is displaced away from the measured pressure profile by a constant positive pressure in single-phase section of the wellbore. This means that the predicted depth of flashing is higher up io the wellbore than the actual depth of flashing. The calculated depth of flashing is highly dependent on the fluid enthalpy value used. Thus fluid enthalpy is an important parameter which determines the depth of flaslung and hence the quality of match.

Conclusions

The Orkiszewski (1967) correlations have been used to compare the measured and calculated pressure profiles from ten wells that cover a wide range of flowrate, fluid enthalpy, wellhead pressure and well depth. We conclude

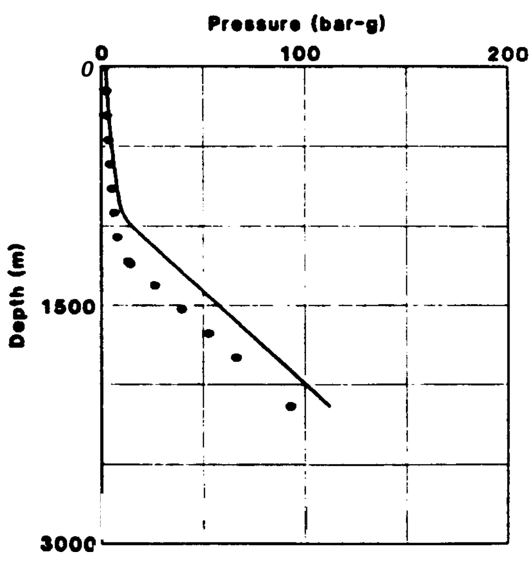

Figure 7. Pressure profile match for well East Mesa 6-1.

the following:

1. The Orkiszewski (1967) correlations seem to have general applicability for geothermal wellbore flow, and work well under a variety of situations.
2. Good matches between the calculated and measured pressure profiles were obtained using the correlations if the steam mass flux is larger than 100 kg/s·m².
3. Gas content and fluid enthalpy are important parameters in determining the depth of flashing and hence the agreement between calculated and measured pressure profiles.

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