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**GEO THERMAL
PROGRAMS**

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Idaho 689
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Volume II

Idaho
Operations
Office

**Low-to-Moderate-Temperature
Hydrothermal Reservoir
Engineering Handbook**

MASTER

**A Joint-Project Report
of Lawrence Berkeley Laboratory and
The Idaho National Engineering Laboratory**

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**LOW-TO-MODERATE-TEMPERATURE HYDROTHERMAL
RESERVOIR ENGINEERING HANDBOOK**

Published June 1982

EG&G Idaho, Inc.
Idaho Falls, Idaho 83415

and

Lawrence Berkeley Laboratory
Berkeley, California 94720

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APPENDIX A
UNITS AND CONVERSIONS

APPENDIX A UNITS AND CONVERSIONS^a

Units

	<u>Metric</u>	<u>English</u>
Pressure	Pa	psia
Temperature	°C	°F
Flow	m ³ /s or l/s	gpm
Compressibility	1/Pa	1/psi
Length	m (Meter)	ft
Permeability	m ²	mD
Static water level	m	ft
Viscosity	Pa*sec	cP

a. Abstracted from the Invitational Well Testing Symposium, Berkeley, California, 1977.

TABLE A-1. Permeability

 $\rho_w = 1$ viscosity = 1 centipoise

	cm^2	m^2	ft^2	Darcy	cm/s	ft/s	ft/year	$\text{L/s}\cdot\text{m}^2$	$\frac{\text{gpd(U.S.)}}{\text{ft}^2}$ (Meinzer)	Ebhlm
cm^2	1	10^{-4}	1.076×10^{-3}	1.014×10^8	9.804×10^4	3.216×10^3	1.015×10^{11}	8.698×10^5	1.845×10^9	0.9
m^2	10^4	1	1.076×10^1	1.014×10^{12}	9.804×10^8	3.216×10^7	1.015×10^{15}	8.697×10^9	1.845×10^{13}	0.8
ft^2	9.294×10^2	9.294×10^{-2}	1	9.417×10^{10}	9.109×10^7	2.988×10^6	9.430×10^{13}	8.080×10^8	1.714×10^{12}	0.7
Darcy	9.862×10^{-9}	9.862×10^{-13}	1.062×10^{-11}	1	9.66×10^{-4}	3.173×10^{-5}	1.001×10^3	8.58×10^{-3}	1.82×10^1	0.6
cm/s	1.020×10^{-5}	1.020×10^{-9}	1.097×10^{-8}	1.035×10^3	1	3.281×10^{-2}	1.035×10^6	9.985×10^0	2.118×10^4	0.5
ft/s	3.109×10^{-4}	3.109×10^{-8}	3.347×10^{-7}	3.152×10^4	3.048×10^1	1	3.156×10^7	2.704×10^2	5.736×10^5	0.4
ft/year	9.852×10^{-12}	9.852×10^{-16}	1.060×10^{-14}	9.990×10^{-4}	9.662×10^{-7}	3.169×10^{-8}	1	8.570×10^{-6}	1.818×10^{-2}	0.3
$\text{L/s}\cdot\text{m}^2$	1.150×10^{-6}	1.150×10^{-10}	1.238×10^{-9}	1.166×10^2	1.001×10^{-1}	3.698×10^{-3}	1.167×10^5	1	2.121×10^3	0.2
$\frac{\text{gpd(U.S.)}}{\text{ft}^2}$ (Meinzer)	5.420×10^{-10}	5.420×10^{-14}	5.834×10^{-13}	5.494×10^{-2}	4.721×10^{-5}	1.743×10^{-6}	5.500×10^1	4.714×10^{-4}	1	0.1
Ebhlm	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	1

TABLE A-2. Compressibility
(Lt^2/M)

	$\frac{\text{m}^2}{\text{N}}$ (Pa) ⁻¹	$\frac{\text{m}^2}{\text{kgf}}$	$\frac{\text{in.}^2 \text{ lbf}}{(\text{psi})^{-1}}$	Bars^{-1}	Atm^{-1}	$(\text{ft of water})^{-1}$ at 68°F	$(\text{m of water})^{-1}$ at 68°F
$\frac{\text{m}^2}{\text{N}}$ (Pa) ⁻¹	1	9.807	6.897×10^3	10^5	1.0133×10^5	2.984×10^3	9.794×10^3
m^2/kgf	1.020×10^{-1}	1	7.031×10^2	1.0197×10^4	1.0332×10^4	3.042×10^2	9.980×10^2
$\frac{\text{in.}^2 \text{ lbf}}{(\text{psi})^{-1}}$	1.450×10^{-4}	1.4223×10^{-3}	1	14.504	14.696	0.4327	1.419
Bars^{-1}	10^{-5}	9.8068×10^{-5}	6.895×10^{-2}	1	1.01325	2.984×10^{-2}	9.790×10^{-2}
Atm^{-1}	9.8692×10^{-6}	9.6787×10^{-5}	6.805×10^{-2}	0.98692	1	2.945×10^{-2}	9.662×10^{-2}
$(\text{ft of water})^{-1}$ at 68°F	3.351×10^{-4}	3.287×10^{-3}	2.311	33.512	33.956	1	3.281
$(\text{m of water})^{-1}$ at 68°F	1.021×10^{-4}	1.002×10^{-3}	0.7044	10.214	10.349	0.3048	1

Table A-3. Temperature °C to °F

°C	°F	°C	°F	°C	°F	°C	°F	°C	°F
0	32	100	212	200	392	300	572	400	752
5	41	105	221	205	401	305	581	405	761
10	50	110	230	210	410	310	590	410	770
15	59	115	239	215	419	315	599	415	779
20	68	120	248	220	428	320	608	420	788
25	77	125	257	225	437	325	617	425	797
30	86	130	266	230	446	330	626	430	806
35	95	135	275	235	455	335	635	435	815
40	104	140	284	240	464	340	644	440	824
45	113	145	293	245	473	345	653	445	833
50	122	150	302	250	482	350	662	450	842
55	131	155	311	255	491	355	671	455	851
60	140	160	320	260	500	360	680	460	860
65	149	165	329	265	509	365	689	465	869
70	158	170	338	270	518	370	698	470	878
75	167	175	347	275	527	375	707	475	887
80	176	180	356	280	536	380	716	480	896
85	185	185	365	285	545	385	725	485	905
90	194	190	374	290	554	390	734	490	914
95	203	195	383	295	563	395	743	495	923

Table A-4. Volume (L³)

	m ³	L	bb1	gal (U.S.)	gal (Imp.)	ft ³
m ³	1	10 ³	6.289	2.642 x 10 ²	2.20 x 10 ²	35.315
L	10 ⁻³	1	6.289 x 10 ⁻³	0.2642	0.220	3.5315 x 10 ⁻²
bb1	0.1590	1.590 x 10 ²	1	42.0	34.97	5.6146
gal (U.S.)	3.7854 x 10 ⁻³	3.7854	2.381 x 10 ⁻²	1	0.8327	0.13368
gal (Imp.)	4.546 x 10 ⁻³	4.546	2.860 x 10 ⁻²	1.2009	1	0.16054
ft ³	2.832 x 10 ⁻²	28.32	0.178	7.481	6.229	1

TABLE A-5. Flow rate
(L³/t or M/t)

	$\frac{m^3}{s}$	$\frac{L}{min}$	$\frac{bbl}{day}$	$\frac{gal}{min}$ (U.S.)	$\frac{gal}{min}$ (Imp.)	$\frac{ft^3}{s}$	$\frac{klb}{h}$ ($\rho_w = 1.0$)	$\frac{klb}{h}$ ($\rho_w = 0.9$)
$\frac{m^3}{s}$	1	6×10^4	5.434×10^5	1.585×10^4	1.320×10^4	35.315	7.94×10^3	7.15×10^3
$\frac{L}{min}$	1.667×10^{-5}	1	9.058	0.2642	0.220	5.885×10^{-4}	1.32×10^{-1}	1.19×10^{-1}
$\frac{bbl}{day}$		1.840×10^{-6}		1.10×10^{-1}	1	2.917×10^{-2}	2.428×10^{-2}	
6.498×10^5		1.46×10^{-2}	1.31×10^{-2}					
$\frac{gal}{min}$ (U.S.)	6.31×10^{-5}	3.785	34.28	1	0.8327	2.2280×10^{-3}	0.50	0.45
$\frac{gal}{min}$ (Imp.)	7.58×10^{-5}	4.546	41.19	1.2009	1	2.676×10^{-3}	0.601	0.541
$\frac{ft^3}{s}$	2.8317×10^{-2}	1.699×10^3	1.539×10^4	4.488×10^2	3.737×10^2	1	2.25×10^2	2.03×10^2
$\frac{klb}{h}$ $\rho_w = 1.0$	1.26×10^{-4}	7.56	68.5	2.00	1.66	4.45×10^{-3}	1	0.900
$\frac{klb}{h}$ $\rho_w = 0.9$	1.40×10^{-4}	8.42	76.2	2.22	1.85	4.93×10^{-3}	1.11	1

TABLE A-6. Pressure
(M/Lt²)

	$\frac{\text{N}}{\text{m}^2}$ (Pa)	$\frac{\text{kgf}}{\text{m}^2}$	$\frac{\text{lbf}}{\text{in}^2}$ (psi)	Bars	Atm	ft of water (at 68°F)	m of water (at 68°F)
$\frac{\text{N}}{\text{m}^2}$ (Pa)	1	1.020×10^{-1}	1.450×10^{-4}	10^{-5}	9.8692×10^{-6}	3.351×10^{-4}	1.021×10^{-4}
$\frac{\text{kgf}}{\text{m}^2}$	9.804	1	1.4223×10^{-3}	9.806×10^{-5}	9.6787×10^{-5}	3.287×10^{-3}	1.002×10^{-3}
$\frac{\text{lbf}}{\text{in}^2}$ (psi)	6.895×10^3	7.031×10^2	1	6.895×10^{-2}	6.805×10^{-2}	2.311	0.7042
Bars	10^5	1.0197×10^4	14.504	1	0.98692	35.512	10.214
Atm	1.0133×10^5	1.0332×10^4	14.696	1.01325	1	33.956	10.349
ft of water (at 68°F)	2.984×10^3	3.042×10^2	0.4328	2.984×10^{-2}	2.945×10^{-2}	1	0.3048
m of water (at 68°F)	9.794×10^3	9.980×10^2	1.419	9.790×10^{-2}	9.662×10^{-2}	3.281	1

TABLE A-7. Viscosity (Dynamic)

$\text{Pa} \cdot \text{s}$	$\frac{\text{lbf} \cdot \text{s}}{\text{in}^2}$	$\frac{\text{lbf} \cdot \text{s}}{\text{ft}^2}$	$\frac{\text{kgf} \cdot \text{s}}{\text{m}^2}$	$\frac{\text{lbm}}{\text{ft} \cdot \text{s}}$	$\frac{\text{dyne} \cdot \text{s}}{\text{cm}^2}$	cP	$\frac{\text{lbm}}{\text{ft} \cdot \text{h}}$
$\text{Pa} \cdot \text{s}$	6.894 757 E+03	4.788 026 E+01	9.806 650 E+00	1.488 164 E+00	1.0 E-01	1.0 E-03	4.133 789 E-04

TABLE A-8. Viscosity (Kinematic)

$\frac{m^2}{s}$	$\frac{ft^2}{s}$	$\frac{in.^2}{s}$	$\frac{m^2}{h}$	$\frac{cm^2}{s}$	$\frac{ft^2}{h}$	cSt
$\frac{m^2}{s}$	9.290 304 E+04	6.451 6 E+02	2.777 778 E+02	1.0 E+02	2.580 64 E+01	1

TABLE A-9. Diffusivity

$\frac{m^2}{s}$	$\frac{ft^2}{s}$	$\frac{cm^2}{s}$	$\frac{ft^2}{h}$
$\frac{m^2}{s}$	9.290 304 E+04	1.0 E+02	2.580 64 E+01

TABLE A-10. Thermal Conductivity

$\frac{W}{m \cdot K}$	$\frac{cal}{s \cdot cm^2 \cdot ^\circ C/cm}$	$\frac{Btu}{h \cdot ft^2 \cdot ^\circ F/ft}$	$\frac{kcal}{h \cdot m^2 \cdot ^\circ C/m}$	$\frac{Btu}{h \cdot ft^2 \cdot ^\circ F/in.}$	$\frac{cal}{h \cdot cm^2 \cdot ^\circ C/cm}$
$\frac{W}{m \cdot K}$	4.184 E+02	1.730 735 E+00	1.162 222 E+00	1.442 279 E-01	1.162 222 E-01

TABLE A-11. Density (Liquids)

$\frac{kg}{m}$	$\frac{lbm}{gal} \text{ (U.K.)}$	$\frac{lbm}{gal} \text{ (Imp.)}$	$\frac{lbm}{ft}$	$\frac{g}{cm}$
$\frac{kg}{m^3}$	1.198 264 E+02	9.977 633 E+01	1.601 846 E+01	1.0 E+03
	1.198 264 E-01	9.977 633 E-02	1.601 846 E-02	1

TABLE A-12. Specific heat capacity (Mass basis)

$\frac{J}{kg \cdot K}$	$\frac{kW \cdot h}{kg \cdot ^\circ C}$	$\frac{Btu}{lbm \cdot ^\circ F}$	$\frac{kcal}{kg \cdot ^\circ C}$
$\frac{J}{Kg \cdot K}$	3.6 E+03	4.186 8 E+00	4.184 E+00

TABLE A-13. Enthalpy calorific value (Mass basis)

$\frac{J}{kg}$	$\frac{Btu}{lbm}$	$\frac{cal}{g}$	$\frac{cal}{lbm}$
$\frac{J}{kg}$	2.326 000 E-03	4.184 E+00	9.224 141 E+00
	2.325 000 E+00		
	6.461 112 E-04		

APPENDIX B
GLOSSARY OF TERMS

APPENDIX B
GLOSSARY OF TERMS^a

ANISOTROPY: Term used to denote the dependence of properties such as permeability on spacial orientation. Anisotropy is usually expressed as a tensor. When the principal axes are perpendicular to each other, the material is said to be orthotropic.

AQUICLUDE (GW)^b: A body of saturated but relatively impermeable material that does not yield appreciable amounts of water to wells. Characterized by very low "leakance" (the ratio of vertical hydraulic conductivity to thickness) and very low rates of yield from compressible storage.

AQUIFER SYSTEM (GW): A heterogeneous body consisting of two or more permeable beds separated at least locally by aquitards that impede groundwater movement but do not greatly affect the regional hydraulic continuity of the system.

AQUITARD (GW): A bed with low permeability that impedes groundwater movement and does not yield water freely to wells, but which may transmit water between aquifers and may constitute an important storage unit. Leakance values vary over a wide range. When low, an aquitard may function as a boundary to an aquifer flow system.

AREA OF INFLUENCE (GW): Defined by Meinzer to be the land area of the same horizontal extent as the portion of the potentiometric surface that is perceptibly lowered due to withdrawal of water by a production well.

a. Adapted from the Invitational Well Testing Symposium, Berkeley, California, 1977.

b. Terms commonly used in hydrogeology.

BANK STORAGE (GW): The change in storage in an aquifer resulting from a change in stage of an adjacent surface water body especially in alluvial deposits adjacent to surface streams.

BAROMETRIC EFFICIENCY OF A WELL: The ratio of water-level changes in the well to the water-level changes in a water barometer.

BOUNDARY PRESSURE (PE)^c: Pressure at boundary of drainage area.

CAPILLARY FRINGE (GW): A zone whose lower part is completely saturated, but with water under less than atmospheric pressure. May range in thickness from a small fraction of an inch in gravel to more than 5 ft in silt.

COEFFICIENT OF PERMEABILITY (GW): See "Hydraulic Conductivity."

COEFFICIENT OF SPECIFIC STORAGE (GW): See "Specific Storage."

COEFFICIENT OF STORAGE (GW): See "Storage Coefficient."

COEFFICIENT OF TRANSMISSIBILITY (GW): See "Transmissivity."

COMMINGLED SYSTEMS (PE): Two-layered or multiple layer reservoirs with communication taking place between layers, either through the wellbore alone or directly across the layer interface.
(cf: multiaquifer well)

COMPACTION (GW): Decrease in volume of sediments, as a result of compressive stress, usually resulting from continued deposition. Also called "one-dimensional consolidation."

c. Terms commonly used in petroleum engineering.

COMPACTION, RESIDUAL (GW): The difference between (a) the amount of compaction that will occur ultimately for a given increase in applied stress, once steady-state pore pressures are achieved, and (b) that which has occurred as of a specified time.

COMPRESSIBILITY, TOTAL SYSTEM (PE): A term representing the combined compressibility of all the elements in an aquifer system. Accounts for the compressibilities of the oil phase, water phase, gas phase, and of the rock formation itself, according to the relative fraction of the total system volume occupied by each.

CONDITION RATIO (PE): Also called flow efficiency, indicates approximate fraction of a well's undamaged producing capacity. Ratio of actual productivity index to the productivity index if there were no skin (ideal conditions).

CONFINING BED (GW): A body of relatively impermeable material stratigraphically adjacent to one or more aquifers. Can be either an "aquitard" or an "aquiclude."

CONSOLIDATION (GW): See "Compaction."

CONSTANT DRAWDOWN TEST (GW): also known as constant pressure test in petroleum engineering. A test in which flow rate is gradually varied in time to maintain a constant drawdown (or constant pressure) in the producing well.

CONSTANT PRESSURE TESTING (PE): Also known as constant drawdown test in groundwater hydrology. Involves recording change in flow rate with time while bottom-hole pressure is held constant.

CRITICAL FLOW (PE): occurs in high-permeability zones; the rate of flow into the drill pipe is independent of drawdown during a drill-stem test.

CRITICAL FLOW PROVER (PE): Device that measures flow rate of a gas through an orifice under critical conditions (velocity is constant at a maximum value despite downstream pressure variations).

DAMAGE FACTOR: A measure of wellbore damage obtained by subtracting the condition ratio from 1.

DAMAGE RATIO (PE): Inverse of condition ratio. Indicates wellbore condition.

DELAYED DRAINAGE (GW): Term used to identify the slow release of water from the unsaturated zone in an unconfined aquifer.

DELIVERABILITY TESTING OF OIL WELLS (PE): Determines capability of a well to deliver against a specific flow bottom-hole pressure. Two main types: (a) flow-after-flow test; flowing pressure is recorded for three or more successive flow rates. Each flow rate is held constant until pressure has stabilized. (b) modified isochronal flow test; used for systems where stabilization time is too long for flow-after-flow test. For each flow rate, the well is shut-in after pressure transience is recorded, but before stabilization occurs. At each step the final flowing pressure and then the final shut-in pressure are observed. At the final flow rate, the well is allowed to produce until the pressure stabilizes, and this pressure is recorded.

DIMENSIONLESS PRESSURE (PE): A dimensionless solution to the diffusivity equation. Directly proportional to physical pressure, where the scaling factor is dependent on flow rate and reservoir properties. Usually denoted by $P_D = \frac{2\pi kH\Delta P}{q\mu}$.

DIMENSIONLESS TIME (PE): A scaled version of real time. Scaling factor depends on reservoir properties and distance to point of observation. $t = \frac{kt}{\phi\mu cr^2}$, where k is intrinsic permeability; t is time; ϕ is porosity; μ is viscosity; c is total compressibility; r is distance to point of observation.

DRAWDOWN (GW): Difference in water level (or pressure) between the static condition and that at any given instant during discharge.

DRAWDOWN TESTING (PE): Involves recording the drop in bottom-hole pressure when a shut-in production well is switched to production at constant flow rate.

DRILL STEM TESTING--DST (PE): Used in testing uncompleted wells. An arrangement of packers seals off the interval to be tested, allowing a pressure to be built up as formation fluid flows into the drill stem and surface-actuated valves are closed. Pressure changes are observed by a pressure gauge located in the test interval. See "Single Packer Test," "Straddle Packer Test."

DYNAMIC PRESSURE (PE): The pressure at a given time and location in a reservoir during a period of transient pressure distribution, such as during a build-up or drawdown test.

EFFECTIVE WELL RADIUS (GW): The radius of an imaginary cylinder centered at the wellbore in which the permeability is much higher than in the reservoir. In a gravel-packed well it often denotes the probable radius of the gravel pack.

EQUIVALENT INJECTION TIME (PE): In a fall-off test on an injection well where the injection rate before shut-in varies, the equivalent injection time is the length of time it would have taken to inject the same volume of fluid at a constant flow rate as was injected at a variable flow rate since the last pressure equalization.

EXCESS PORE PRESSURE (GW): Transient pore pressure at any point in an aquitard or aquiclude in excess of the pressure that would exist under steady-flow condition.

EXPANSION, SPECIFIC (GW): The increase in thickness of deposits per unit decrease in applied stress.

EXPANSION, SPECIFIC UNIT: The expansion (increase in volume) of deposits, per unit thickness, per unit decrease in applied stress.

EXPONENTIAL INTEGRAL (PE): See "Theis Solution."

FALLOFF TESTING (PE): Involves shutting in an injection well and observing the decrease in bottom-hole pressure with time.

FALSE PRESSURE (PE): Obtained by extrapolating the straight-line section of a Horner plot of pressure build-up data to infinite shut-in time. Approximates average reservoir pressure in an infinite system and can be used to estimate average drainage region pressure in a bounded system.

FIVE-SPOT PATTERN (PE): An arrangement of production and injection wells with four production wells at the corners of a square and one injection well in the center.

FLOW-AFTER-FLOW TESTING (PE): See "Deliverability Testing of Oil Wells."

FLOW EFFICIENCY (PE): See "Condition Ratio."

FLUID POTENTIAL (GW): The mechanical energy per unit mass of a fluid at any given point in space and time with respect to an arbitrary state and datum.

FORMATION VOLUME FACTOR (PE): A factor to account for changes in volume in each phase upon transition from reservoir to standard surface conditions. The ratio of the volume at reservoir conditions to the volume at standard surface conditions.

GROUND WATER, PERCHED (GW): Confined ground water separated from an underlying body of ground water by an unsaturated zone. It is held up by a "perching bed" of low permeability, and its water table is a "perched water table."

HEAD, STATIC (GW): The height (above a datum) of a column of water that can be supported by the static pressure at a given point. The sum of the "elevation head" and the "pressure head." See "Head, Total."

HEAD, TOTAL (GW): The sum of three components: (a) "elevation head," which is the elevation of the point above a datum; (b) "pressure head," the height of a column of static water that can be supported by the static pressure at the point; (c) "velocity head," the height the kinetic energy of the liquid is capable of lifting the liquid.

HORNER PLOT (PE): A plot of pressure build-up versus $\log \frac{t + \Delta t}{t}$ where t is time since production and Δt is time since shut-in. A similar plot was proposed in ground water hydrology by Theis to analyze recovery data.

HYDRAULIC CONDUCTIVITY (K) (GW): Has dimensions of length per unit time. A medium has a hydraulic conductivity of unit length per unit time if it will transmit in unit time a unit volume of groundwater at the prevailing viscosity through a cross section of unit area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head through unit length of flow. Replaces the term "coefficient of permeability."

HYDRAULIC CONDUCTIVITY, EFFECTIVE (GW): The rate of flow of water through a porous medium that contains more than one fluid.

HYDRAULIC DIFFUSIVITY (GW): The ratio between hydraulic conductivity and specific storage.

HYDRAULIC GRADIENT (GW): The change in static head per unit of distance in a given direction.

HYDROCOMPACTION (GW): The process of volume decrease and density increase that occurs when moisture-deficient deposits are wetted for the first time.

IMAGE METHOD (METHOD OF IMAGES) (PE): The technique of using image wells to generate no-flow and constant pressure boundaries in an infinite system.

IMAGE WELL (GW): An imaginary well which effectively produces the same drawdown (or recovery) as a linear boundary limiting the aquifer. See "Image Method."

INFLOW PERFORMANCE RELATIONSHIP (PE): Used to predict a well's deliverability when deliverability test data are not available. A relationship between flow rate, bottom-hole pressure, average reservoir pressure, and a productivity index.

INFLUENCE REGION (PE): The region surrounding a well or wells whose properties influence transient tests performed on those wells. (Not to be confused with Meinzer's "area of influence.")

INJECTIVITY TESTING OR INJECTION WELL TESTING (PE): Pressure transient testing during injection into a well. Bottom-hole pressure is recorded while injection rate is held constant.

INTERFERENCE TESTING (PE): A multiple-well transient test which involves the production of an active well (injection) and observing the resulting pressure changes in an observation well.

INTERPOROSITY FLOW PARAMETER (PE): A dimensionless property of a fractured system. Dependent on the well radius, a matrix-to-fracture geometric factor, and the ratio of the formation matrix permeability to the effective fracture permeability.

ISOCHRONAL TESTING (PE): See "Deliverability Testing of Oil Wells."

JACOB'S METHOD (GW): Also known as asymptotic solution. Involves a semi-logarithmic plot of drawdown as a function of the log of time.

LEAKANCE (GW): The ratio of vertical hydraulic conductivity to thickness of the aquiclude.

LEAKY AQUIFER (GW): An aquifer into which overlying and/or underlying aquitards discharge water as the potentiometric head in the aquifer is lowered.

MEINZER UNIT (GW): A unit of hydraulic conductivity defined as the flow of water in gallons per day through a cross-sectional area of 1 ft^2 under a hydraulic gradient of 1 at a temperature of 60°F .

MOBILITY (PE): The ratio of absolute permeability to viscosity.

MOBILITY RATIO: The ratio of the mobility of the injected fluid to that of the in situ fluid.

MULTI-AQUIFER WELL (GW): A well which is screened to produce fluids from multiple aquifers which are separated by zones of low permeability. (cf: "commingled systems")

MULTIFLOW EVALUATOR (PE): A tool used in drill stem testing which allows unlimited sequences of production and shut-in. Includes a fluid chamber to recover an uncontaminated formation-fluid sample under pressure at the end of the flow period.

MULTIPLE RATE TESTING (PE): Tests involving a variable flow-rate. Testing at a series of constant flow rates, or testing at constant bottom-hole pressure with continuously changing flow rate.

ORTHOTROPY (GW): See "anisotropy."

PERMEABILITY, EFFECTIVE (GW): See "Hydraulic Conductivity, Effective."

PERMEABILITY, INTRINSIC: Same as "Permeability." Term adopted by U.S. Geological Survey to indicate a property of the medium alone, independent of the fluid properties. Has dimensions of L^2 . Also called "Absolute Permeability."

PIEZOMETRIC SURFACE (GW): See "Potentiometric Surface."

POROSITY (GW): The property of a rock or soil of containing interstices. Expressed as the ratio of the volume of interstices to the total volume.

POROSITY, DUAL: The porosity of the rock having substantial primary and secondary porosity.

POROSITY, EFFECTIVE (GW): Refers to the amount of interconnected pore space available for fluid transmission. Expressed as the percentage of total volume occupied by interconnecting interstices.

POROSITY, PRIMARY (GW): Refers to the original interstices created when a rock or soil was formed in its present state.

POROSITY, SECONDARY (GW): Refers to the porosity created by fractures, openings along planes of bedding and solution cavities. Occur mostly in consolidated rocks having low primary porosity.

POTENTIOMETRIC SURFACE: A surface which represents the static head. An imaginary surface connecting points to which water would rise in tightly cased wells from a specified surface or stratum in the aquifer.

PRESSURE, AVERAGE RESERVOIR: The pressure a reservoir would attain if all wells were shut in for infinite time, assuming no natural influx of fluid.

PRESSURE BUILDUP TESTING (PE): Involves shutting in a producing well and analyzing the resultant pressure buildup curve for reservoir properties and wellbore condition

PRESSURE, INITIAL RESERVOIR (PE): Stabilized pressure of a shut-in well.

PRESSURE, INTERWELL (PE): The pressure halfway between an injection well and a production well. Sometimes used to approximate average reservoir pressure.

PRODUCTIVITY INDEX (PE): Also known as the specific capacity of a well. Denotes the productivity of a well per unit drawdown.

PSEUDO SKIN FACTOR (PE): The apparent skin factor in a well which has no true physical damage (or improvement) but is not drilled completely through the formation thickness or is only partially completed, thus appearing damaged.

PSEUDO STEADY STATE (PE): A transient flow regime in which the rate of pressure change with time is constant at all points in the reservoir.

PULSE TESTING (PE): A multiple-well transient test, in which flow rate pulses are produced in an active well and the resulting pressure changes are recorded in an observation well. Provides reservoir information for the region around and between the two wells. (Because of the shorter time intervals, the influence region for a pulse test is less than that for an interference test, and thus information is gained about a smaller portion of the reservoir.)

RADIUS OF DRAINAGE (PE): Defines a circular system around a well in which a pseudo steady state pressure distribution exists.

RECOVERY TEST (GW): Also known as build-up test in petroleum engineering. Denotes a test which involves the measurement of recovery in a well after the well is shut in following a known period of production.

RELATIVE PERMEABILITY (PE): Also called effective permeability in ground water hydrology. Denotes the permeability of the porous medium to a particular fluid when more than one fluid is present.

RESIDUAL DRAWDOWN (GW): During recovery, the difference between the static water level and the water level at any instant during recovery.

SAFE YIELD (GW): Given a variety of meanings, but originally defined (by Meinzer) as the rate at which ground water can be withdrawn year after year from a given aquifer system without depleting the supply to the point where withdrawal at this rate is no longer economically feasible.

SEEPAGE FACE (GW): For a well piercing an unconfined aquifer, seepage face denotes that segment of the well screen over which the total head equals elevation above datum and water flows from the aquifer into the well.

SEEPAGE FORCE: See "Stress, Seepage."

SHAPE FACTOR (PE): A geometric factor, characteristic of the reservoir shape and well location.

SLUG METHOD (GW): Used to determine transmissivity of an aquifer. A known volume or "slug" of water is suddenly injected into or removed from a well and the decline or recovery of the water level is measured at closely spaced time intervals during the ensuing minute or two.

SINGLE-PACKER TEST (PE): A drill stem test utilizing one packer in which fluid flows through the perforated anchor pipe into the drill string.

SKIN (PE): A zone of decreased permeability near the wellbore created by drilling and completion practices.

SKIN FACTOR (PE): A constant which relates the pressure drop across the skin to the dimensionless rate of flow. A measure of wellbore damage.

SPECIFIC CAPACITY (GW): The rate of discharge of water from a well divided by the drawdown of water level within the well. Varies slowly with duration of discharge. Also called productivity index in petroleum engineering.

SPECIFIC DISCHARGE or SPECIFIC FLUX (GW): The rate of discharge of ground water per unit area measured at right angles to the direction of flow.

SPECIFIC RETENTION (GW): The ratio of the volume of water a saturated rock or soil will retain against the pull of gravity to its own volume.

SPECIFIC STORAGE (GW): The volume of water released from or taken into storage per unit volume of the porous medium per unit change in head.

SPECIFIC YIELD (GW): The water yielded by water-bearing material by gravity drainage, as occurs when the water table declines. The ratio of the volume of water a saturated rock or soil will yield by gravity to its own volume.

STABILIZATION TIME (PE): The time corresponding to the start of the pseudo steady state period.

STATIC WATER LEVEL (GW): The static position of the potentiometric surface in a well prior to the commencement of discharge. (See also initial reservoir pressure in petroleum engineering.)

STEADY STATE: Pressure is constant at all points in the reservoir.

STEP DRAWDOWN TEST (GW): Also known as productivity index test or step-rate test in petroleum engineering. Involves producing a well at different rates for predetermined periods of time and monitoring drawdown.

STEP-RATE TESTING (PE): A multiple-rate injection well test in which fluid is injected at a series of increasing rates, each rate lasting an equal amount of time. Injection pressure at the end of each rate is plotted versus injection rate.

STORAGE COEFFICIENT: The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

STRADDLE-PACKER TEST (PE): A drill stem test in which the tested interval lies between two packers.

STRESS: APPLIED: The downward stress imposed at the aquifer boundary by (a) the weight (per unit area) of sediments and moisture above the water table, (b) the submerged weight of the saturated sediments overlying the boundary, and (c) the net seepage stress due to flow within the saturated sediments above the boundary.

STRESS, EFFECTIVE: Stress that is borne by and transmitted through the grain to grain contacts of a deposit. The effective stress at a point in an aquifer differs from the applied stress at the aquifer boundary by the submerged weight (per unit area) of the intervening sediments and the net seepage stress due to flow within the intervening sediments.

STRESS, SEEPAGE: Stress created by the seepage force, which is transferred from the water to the porous medium by viscous friction. Seepage force is exerted in direction of flow.

SUBSIDENCE: Sinking or settlement of the land surfaces, due to any of several processes, but most importantly due to artificial withdrawal of subsurface fluids.

TEMPERATURE, PSEUDOCRITICAL (PE): For a mixture of gases, calculated from the relative amounts and critical temperatures of the components.

TEMPERATURE, PSEUDOREDUCED (PE): The ratio of the temperature of interest to the pseudocritical temperature.

THEIM EQUATION (GW): Represents steady-state radial flow solution to a well in the center of a circular, homogeneous, horizontal aquifer with prescribed potential at the circular boundary.

THEIS SOLUTION (GW): Represents the solution to a continuous line source in a homogeneous, horizontal, infinite, isotropic aquifer. (Also known as exponential intergral in petroleum engineering.)

TIDAL EFFICIENCY: A measure of the response of the water level in a well to changes in ocean level. Equal to the barometric efficiency subtracted from 1.

TRANSIENT TESTING: The study of pressure variation with time in an active well (production or injection) under a variety of conditions and possible operating procedures.

TRANSMISSIVITY (T), (GW): The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic grandient.

TWO-RATE TESTING (PE): A multiple-rate test on a production well using only two different flow rates.

TWO-ZONE SYSTEMS: See "Composite Systems."

u (GW): Dimensionless quantity related to the reciprocal of dimensionless time, t_D , used in petroleum engineering.

$$u = \frac{r^2 s}{4Tt} = \frac{1}{4t_D}$$

UNCONFINED AQUIFER (GW): Also called water table aquifer. An aquifer which contains a water table, at which it is in direct contact with the atmosphere.

UNIFORM-FLUX FRACTURE (PE): One in which fluid enters at a uniform flow rate per unit area. A first approximation to the behavior of a vertically fractured well.

VERTICAL PULSE TESTING (PE): Used to determine vertical permeability of a formation. Fluid is injected in pulses above a packer, escapes the wellbore through flow perforations and reenters below the packer through observation perforations where pressure changes are observed with a pressure gauge.

VOID RATIO (GW): The ratio of the volume of the interstices in a rock or soil to the volume of its mineral particles.

WATER DRIVE RESERVOIRS (PE): Reservoirs in direct communication with an active aquifer.

WELLBORE STORAGE (PE): Fluid stored in the wellbore above reservoir level. Usually occurs when a production well is shut-in without packers used to maintain fluid level. Affects pressure build-up data at early time as fluid continues to flow into the wellbore after shut-in.

WELL FUNCTION OF u (GW): Equal to twice the value of P_D , dimensionless pressure, which denotes the value of the exponential integral.

WELL LOSSES (GW): Denotes drawdowns at the well in excess of the theoretical capability of the reservoir. Such well losses may be due to poor development of the well, excessive entrance velocities and casing damages due to skin, scaling, or corrosion.

WIRELINE FORMATION TESTING (PE): A tool is lowered into the well on a logging cable. The mechanism establishes communication with formation fluid and measures pressure response. Slightly more qualitative than a DST.

APPENDIX C
INSTRUMENTATION

APPENDIX C

INSTRUMENTATION

Requirements

Before the appropriate type of instrument can be selected, the developer or consultant must calculate the anticipated pressure changes, flow rates, temperatures, and time resolution requirements. Methods for doing this have been discussed in Volume I. The importance of correctly anticipating these parameters is that the instrument chosen must have accuracy and precision far greater than the expected changes. For instance, when measuring pressure changes in an observation well with an expected 1 psi maximum of pressure change, then the instrument should have a resolution of at least 0.1 psi. On the other hand, in a production well there will be a relatively large pressure change and therefore only require 1 psi resolution. Instruments with a wide range of precision and accuracy are available. In general, the finer the resolution and greater the accuracy, the more expensive the instrument. However, advances in the development and availability of these instruments is lowering the cost of the high precision gauges.

An often overlooked area in test planning is the time element. If pressure changes take place very rapidly the recording equipment and/or personnel may not be suitable to record the data at a sufficiently small time interval. In general, in fractured or highly permeable aquifers the pressure changes will take place very quickly and be of a smaller magnitude than in a moderate or low intergranular permeability system. In almost every case it is valuable to have continuous recording devices with accurately synchronized clocks for measuring and recording each parameter of the test. This minimizes operator error, missed events, ambiguity in the data, and simplifies data analysis and interpretation.

Before any meaningful analysis of the data can be obtained, data of good quality is essential; it can be obtained from careful test planning, control, execution, and adequate instrumentation. Knowing how to use downhole pressure transducers to obtain pressure transient data is important. In principle, downhole data will always provide more reliable data insofar as the effects of temperature changes in the wellbore become unimportant. However, the use of downhole instrumentation may not always be possible or cost effective. For instance, if the production well is being pumped, it may not be possible to use a downhole tool because of the difficulty in setting the tools and the pump. Alternatively, the budget allocation for testing may prohibit the use of downhole tools. In general, the deeper the well or the hotter the well, the more important it is to use downhole instrumentation. If the well is over 100°C and sufficient wellhead pressure cannot be maintained, the water will start to flash (boil) in the wellbore. In this event, wellhead data or water level data will be useless for pressure transient testing and productivity calculations. For this case, downhole data is essential. If good quality production well data cannot be obtained, it is recommended that every effort be made to conduct a simultaneous production and interference test. Instrumentation for interference testing is readily available and, in general, easy to install and maintain.

In the following sections, subdivided by the test parameter to be measured, a variety of instruments will be discussed. Relevant to the discussion is the definition of accuracy and resolution. Accuracy is a measure of how closely a measured parameter compares to the correct value, as determined by the Bureau of Standards. The accuracy of an instrument is a function of its calibration, hysteresis, drift, repeatability and resolution. The resolution of an instrument is a function of sensitivity of the transducer to the parameter being measured, and the smallest quantity that can be observed and measured when using the instrument. For instance, a thermistor may have infinite resolution to temperature changes, but the ohm-meter being used to read the resistance may only have a resolution of five ohms; thus, the meter, not the probe controls the resolution of the instrument. The resolution or accuracy of a measured system is only as good as the worst component. For geothermal applications, the resolution of a pressure

gauge is often the more significant measure of the quality (or suitability) of a gauge. However, for temperature and flow rate measurements, accuracy is a more important requirement.

The following pages list some of the instruments currently available, their assets and drawbacks, and the types of instruments most suitable for a variety of applications. In addition to the detailed discussions, Tables C-1 through C-3 at the end of this subsection, summarize many of the performance characteristics of temperature and pressure sensors as defined in Reference C-1.

Flow Measurement

1. Weirs and flumes

Accuracy: +10%

Range: 1 gpm to any maximum.

Advantages: Very inexpensive, can be home-built. Construction details and formulas are contained in several engineering handbooks.

Disadvantages: Cannot be used if the temperature is greater than 100°C. Also, cannot be installed in a pressurized pipeline and cannot be connected to a continuous recording device very easily.

Suppliers: F. B. Leopold Company and BIF Industries.

2. Known-Volume container or weighing tank and stopwatch

Accuracy: +20%.

Range: Limited only by the scales, container or tank, and the flow control apparatus.

Advantages: Very inexpensive.

Disadvantages: Cannot be connected to a continuous recorder. The person measuring the flow can get burned.

3. Differential pressure meters (orifice meters, nozzles, Pitot tubes, Venturi tubes, and low-pressure loss tubes)

Accuracy: +10%.

Range: Pitot tubes--<1 to >30 ft/sec. Others--0.1 to 30 ft/sec. Depends on orifice and pipeline size.

Advantages: Most pump companies and drillers use these methods and are comfortable and familiar with them. They are most easily connected to continuous recording devices; therefore, these methods are very suitable for most applications.

Disadvantages: Scaling or flashing across the orifice can create undetected inaccuracy in the measurements.

Cost: Costs vary widely with the type of element and also with line size and pressure rating; less than \$100 for an orifice plate to several thousand dollars for a venturi or one of the patented flow tubes. Installed cost also varies greatly with line size and pressure rating except for the pitot tube which is installed in a boss on the pipe wall.

Readout and Recording Equipment: A method must be provided to measure the pressure difference, and if desired, convert that to flow rate. In some cases, ΔP can be measured with a homemade manometer made from clear plastic tubing and a yard

stick, or a commercial manometer. At high line pressures, a ΔP gauge or transmitter with output indicator may be required. In either case the measured ΔP is then used to calculate flow rate. If direct flow reading is required, a pressure gauge scale (nonlinear) can be calibrated in flow units or a transmitter output can be converted electronically to a direct flow indication or output proportional to flow for recording or display. Cost of equipment to provide transmitting, recording, and indication could range from \$2,000 to \$3,000 or more, depending on the grade or quality of equipment.

Partial List of Suppliers:	Pitot Tubes--Foxboro Corp., Meriam Instrument Co., Rosemount Engineering, Deitrich Standard, Taylor Instrument Co. Orifice Plates, Venturi tubes and nozzles--Daniel Industries, Inc., Badger Meter, Meriam Instrument Co., Fischer & Porter Co., Foxboro Corp., Tech Tube Corp.
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4. Turbine Flow Meters

Accuracy:	<u>+5%</u> .
Range:	Depends on impeller and pipe diameter 0.1 to 50 ft/s.
Cost:	Relatively expensive; several hundred dollars to several thousand depending on size and features.
Output:	Output signal of most transmitters is a frequency proportional to volumetric flow rate that can be fed directly to a compatible flow rate indicator meter.
Advantages:	Good accuracy, repeatability, and linearity. Wide ranges. Can be installed in-line or on a probe through the pipe wall.

Disadvantages: Can be degraded by other than clean fluids.
Relatively high cost.

Partial List of Suppliers: Daniel Industries, Flow Technology, Inc., Foxboro Corp., Brooks Instruments, Fischer & Porter, and Electronic Flow-Meters.

5. Others

There are many other types of meters available that could be investigated if those listed above are not suitable. The following types would be in that category:

Acoustic/ultrasonic--no obstruction, thus no pressure loss. The clamp-on Doppler eliminates scaling and corrosion problems.

Magnetic--No obstruction in the line thus no pressure loss. Somewhat pressure and temperature limited by liner material. Relatively insensitive to dirty fluids.

Vortex--Good accuracy--subject to scaling.

Wellhead and Differential Pressure Measurement

1. In addition to the transducers in the preceding table, the following instruments are available:

a. Manometers: Measure pressure or differential pressure.

Accuracy: $\pm 1\%$ of span for most. $\pm 0.1\%$ for precision types.

Range: Minimum span is 0.15" H₂O, maximum span 60 psig.

Design pressure: Up to 6,000 psig.

Design temperature: Function of seal fluid, usually ambient.

Advantages: Relatively low cost. Availability.

Disadvantages: Difficulty connecting to a recording device, not sufficiently rugged for field testing.

Cost: Ranges from a few dollars for the simple units to approximately \$1,000 for the more sophisticated and precise.

Partial List of Suppliers: Meriam Instrument Co., Bailey Meter Co., and Foxboro Corp.

b. Mechanical pressure gauges bourdon tube

Accuracy: Between $\pm 0.1\%$ and $\pm 5\%$ of span.

Range: From 10 in. H_2O to 100,000 psig.

Advantages: Readily available and replaceable. Most drillers and pump operators have them.

Disadvantages: Difficult to connect to recording devices.

Cost: From \$20 to thousands depending on dial size and accuracy.

Partial List of Suppliers: Ashcroft, Foxboro Corp., Robert Shaw Controls, Heise (Dresser) Wallace and Tiernan Inc., ITT Barton.

- c. Electronic pressure and differential pressure transmitters, capacitors, strain gauges, piezoelectric semiconductors (piezoresistive), potentiometers. (Process grade field instrumentation.)

Accuracy: 0.1% to 1% of calibrated span.

Range: A few inches of water to several thousand psig.

Advantages: Easily connected to continuous recording devices. Usually these devices are fairly reliable.

Disadvantages: High cost and lead time for replacement.

Cost: \$750 to \$2,000 depending on accuracy and pressure.

Partial List of Suppliers: ITT Barton, Fisher Controls, Foxboro Corp., Honeywell, Taylor Instrument Co., Rosemount, Bailey Meter Co.

Temperature

Temperature gauges should be placed in thermal wells near the wellhead on the discharge line.

1. Mercury Thermometer

Accuracy: Depends on range 0.1 to 1°C.

Advantages: Readily available. Very accurate if small enough range.

Disadvantages: Cannot be connected to a recording device.

2. Electronic gauges

There are a wide variety of electronic gauges available. Tables C-1 and C-2 summarize the many varieties and manufacturers. Most of the available transducers are suitable for well-head temperature measurements. One advantage of electronic gauges is that they can be easily connected to readout and recording devices. Calibration and recalibration of these gauges will ensure their repeated accuracy.

Downhole Instrumentation

Downhole Temperature Measurement

Tables C-1 through C-3 compare the performance of various sensors. For simple downhole temperature measurement a max-reading thermometer can be lowered into the well on a line. If more than maximum temperature is required, i.e., temperature versus depth or a continuous indication, a thermocouple, RTD or thermistor can be lowered into the well on a conductor line and temperature measured on the surface with a portable bridge, potentiometer or the temperature can be recorded if desired. Small reels or winches with conductor lines are available at reasonable cost. For more precise and detailed temperature logs, it may be more suitable to rent the equipment or hire a well logging service. Downhole tools can be purchased outright but the cost is usually prohibitive. The "Kuster" temperature tool incorporates a downhole recorder and can be run on a wire line. A logging service's charge will include costs/foot of depth, a flat service charge, and other charges depending on well condition, location, etc. The charges to log a 5,000-ft. deep cased hole could be several thousand dollars.

The following companies rent equipment or provide service as noted:

Schlumberger Well Services--Service

Dresser Atlas--Service

Birdwell--Service

Kuster Company--Tool Rental and Sale

Gearhart Owen Industries--Tool rental, sales, and service

Halliburton Services--Service

Sperry-Sun--Tool rental, sales, and service

Downhole Pressure Measurement

1. Bubbler Tube. Perhaps the simplest and least expensive method to measure downhole pressure and water level is the bubbler tube. A crude but sometimes appropriate arrangement consists of a tire pump and a gauge connected to a small pipe or tube suspended in the well. Accuracy of the bubbler tube in well measurement applications can vary widely depending on the equipment, temperature effects, and operating techniques. In ordinary tank level measurement accuracies of $\pm 1\%$ can be achieved.
2. Downhole Capillary Tube. This consists of a small tube suspended in the well with a pressure coupling chamber at the bottom and a precision pressure transducer on the surface. The tube is filled with inert gas or a synthetic fluid. Sperry-Sun Inc., supplies such a system.
3. Electronic Pressure Transducers. Table C-3 compares the performance of several transducers suitable for downhole measurements. As in the case of downhole temperature measurements, the tools can be rented, purchased, or the services can be hired. The table lists suppliers, some of which will rent tools. The same companies listed as renting temperature tools or providing logging service will also provide pressure tools and service at similar costs. In the following section, an instrument incorporating a Paro-scientific digiquartz transducer is discussed.

Downhole Flow Measurement

Most of the downhole flow meters use a variation of the turbine discussed previously. As with downhole pressure and temperature measurement the tools and/or service are available for rent or hire. Most of the companies listed above will provide flow measurement tools or service.

Water Level Measurement

1. Bubbler Tube. The bubbler is usable in subsurface water level or artesian wells. Several companies supply systems and equipment for ordinary tank level measurements which may be suitable for well measurements. Cost would be on the order of several hundred dollars. Some of the companies are: Fisher Governor Co., Meriam Instrument Co., Petrometer Corp., and Uehling Instrument Co.
2. Tape and Float. This method can be used on wells with water levels below the surface. They can be suspended by hand and the distance measured, or wound on a drum with provisions for continuous recording of level. Several companies make the latter unit which is well suited for monitoring well water level at depths up to 300 ft. Cost is approximately \$1,000. Partial list of suppliers: Leopold & Stevens and Keck Instrument Inc.
3. Others. This would include the conductivity probes, which can be fouled by oil, etc., the chalked tape, and other float and changing resistance type systems.

Approximate Cost: \$50 to \$100 for 100 ft of chalk tape.
 \$300 to \$800 for an electric tape.
 \$500 for a conductivity probe and meter.

Partial List of Suppliers:

Lufkin and Roe Instrument: chalk tape.
Sepa-Air Inc.: electric tape.
Springs Instruments: conductivity probe.

TABLE C-1. Manufacturers of temperature sensors reviewed

Manufacturer/Supplier	Electrical Sensing			Passive Indicating	
	Resistance Temperature Detectors (RTDs)	Thermistors	Thermocouples	Maximum Indicating Sensors	Bi-Metallic Stem Thermometers
ARi Industries	X	--	X	--	--
Barber-Coleman Co.	X	X	X	--	--
Big Three Industries	--	--	--	X thermochemical	--
Brooklin Thermometer	--	--	--	X glass/bi-metallic	--
Celestro Transducer Products	X	X	X	--	--
C. S. Gordon Co.	--	--	X	--	--
Fenwal Electronics	--	X	--	--	--
Fischer & Porter Co.	X	--	X	--	--
Foxboro Co.	X	--	X	--	--
Hi-Cal Engineering	X	--	X	--	--
ITT-Barton	X	--	--	--	--
Markal Co.	--	--	--	X thermochemical	--
Matthey Bishop, Inc.	X	--	--	--	--
Minco Products, Inc.	X	--	X	--	--
Rosemont, Inc.	X	--	--	--	--
Semco, Inc.	X	--	X	--	--
Spectro Systems, Inc.	--	--	--	X metal pellets	--
Sybron-Taylor Corp.	X	--	X	X glass	X
Thermometrics, Inc.	--	X	--	--	--
Victory Engineering	--	X	--	--	--
W. Wahl Corp.	X	X	X	X thermochemical and bi-metallic dial	X
Weed Instrument Co.	X	--	--	--	--
W. H. Keseler Co., Inc.	--	--	--	X glass	--
Weston Instruments	--	--	--	--	X
Yellow Springs Instruments	X	X	--	--	--
Omega Engineering	X	X	X	--	--

TABLE C-2.^a Performance comparison of some commercial pressure transducers

No.	Manufacturer and (Model)	Sensor Technique	Accuracy (overall) (% FS)	Resolution (% FS)	Stability and Drift	Max °F	Coefficient	Maximum Pressure Range(s) (psia)	Size	Comments
1.	Hewlett Packard, (2811B)	Diaphragm with oscillating quartz crystal	0.025%	Infinite (0.01 psi typ)	0.01%/yr	300	?	11,000	1-7/16" dia. by 40" long	Accepted standard for precision downhole oil/gas well testing. Temp correction to +1°C recorded.
2.	Mensor, (Digital Quartz manometer)	Fused quartz helical bourdon tube w/optical sensor and electronic nulling	<0.2%	0.0005%	0 @ 3 mos (0.01%/yr)	122	0.0004%/°C	1,000	11" by 10" by 8-1/2"	System temp control/compensation to +2°C to achieve performance quoted. Also makes unit like #3 below.
3.	Heise (Dresser), (Digiquartz)	C bourdon tube and servo force balance	0.05%	0.005%	NA	125	Very small, 0.1% PS over range	10,000	4-3/8" by 6" by 16"	Sperry-Sun sells for use with their 'tube' pressure transmission system.
4.	Paroscientific, (Digiquartz)	Bellows linked to vibrating quartz bar	0.1%	<0.1%	0.1%/yr	225	0.004%/°F	5,000	1.15" dia. by 3-1/4"	Hi temp @ pressure (530°F @ 10,000 psi) unit currently under joint development with Sandia Labs--will have high temp electronics.
5.	Sundstrand Data Controls, Inc., (Developmental)	Bellow linked via quartz structure w/force-balance and capacitor feedback	0.11%	0.004%	0.1%/yr ?	176	NA	500	1-5/8" dia. by 2"	Mfg claims higher pressure (5K-10K) unit is developable, basic sensor capable of higher temperature
6.	Setra Systems, (204/205)	Diaphragm w/capacitor plate displacement	0.11%	<0.01%	0.05%/yr ?	250	0.004%/°F	10,000	1-3/4" dia.	Basic sensor w/o integral electronics capable of much higher temperature.
7A.	Heise (Dresser), (#CMM16)	C bourdon tube linked to dial and potentiometer	0.1%	0.01%	0.02%/yr	125	0	10,000	17-3/8" dia. by 3-1/4"	16" by 660 dial read-out, electrical output also provided.
7B.	Mensor, (2792)			0.01%	0.02%/yr	125	0	10,000	17-3/8" dia. by 3-1/4"	Can operate up to 250°F w/external compensation.
8.	Robinson-Halpern, (144)	Helical bourdon tube linked to differential transformer	0.1%	<0.01%	NA	165	0.1%/°F	10,000	6" by 6" by 4-1/4"	--

TABLE C-2.^a (continued)

No.	Manufacturer and (Model)	Sensor Technique	Accuracy (overall) (% FS)	Resolution (% FS)	Stability and Drift	Max °F	Coefficient	Maximum Pressure Range(s) (psia)	Size	Comments
9.	Bell & Howell, (CEC-1000)	Diaphragm w/thin film strain gage (sputtered)	0.15%	<0.01%	0.1%/yr	600+	0.005%/°F	10,000	1" dia. by 2-1/2"	Mfr claims higher accuracy and temp performance available
10.	Bell & Howell, (CEC-4-361)	Diaphragm w/unbonded wire strain gage	<0.2%	<0.05%	0.5%/yr	700	0.1%/°F	5,000	1-1/4" dia. by 2-1/2"	Fragile and slow temp response time (mfr feels thin film will replace).
11.	Kaman Sciences, (KP-1911)	Diaphragm with eddy current variable impedance coil	0.25%	0.1%	NA	1000	0.1%/°F	5,000	5/8" dia. by 1-1/2"	--
12.	Sparton South-west, (890 HT)	C bourdon tube with wire potentiometer	1%	0.3%	NA	600+	0.1%/°F	10,000	1" dia. by 2-1/2"	--
13.	Celeco, (P2)	Diaphragm w/variable reluctance transducer	1%	0.1%	0.5%/yr	250	0.2%/°F	10,000	1-1/4" dia.	Mfr has built high temp (600°F) unit w/derated accuracy (~1-1/4%).
14.	Data Instruments, (MPA 1000)	Diaphragm w/bonded semiconductor strain gage	0.25%	<0.05%	0.5%/yr	250	0.001%/°F	5,000	1-1/4" dia. by 2-1/2"	--
15.	Vernitech	C bourdon tube with film potentiometer	0.7%	<0.05%	0.5%/yr	185	0.01%/°F	10,000	2-1/2" dia. by 2"	--

a. See Reference C-1.

TABLE C-3. Performance comparison of geothermal process temperature sensors

Performance Parameter	Resistance Temperature Detectors (RTDs)	Thermistors	Thermocouples	Bi-Metallic Thermometer	Thermochemical and Physical Melt Indicators	Bulb-Bourdon Tube (thermal fluid filled)
Temperature range	-260 to 900°C	-100 to 400°C	-270 to 2000°C	-60 to 450°C	38 to 1649°C labels (38 to 600°C)	0 to 340°C
Accuracy	0.01% (<0.1°C)	1%	0.1%	1% (0.5% available)	1% (0.3% available)	1%
Sensitivity (signal level)	Good: +0.5%/°C (<0.1V/°C with bridge)	High: -5%/°C -0.5% linearized (<0.5 V/°C with bridge)	Very low, 1%/°C	Depends on dial size, etc.	NA	0.5% of F.S.
Linearity	Excellent: 1%	Poor: 10-20% Linearized: 2%	Poor: 10-25%	1%	NA	1%
Stability	Excellent	Poor	Excellent	Good	NA	Fair
Interchangeability	Excellent	Good	Poor	NA	NA	NA
Size	Medium: >1/8" diam. by >1/4" long	Very small	Small	1" to 5" dial. stem dia. >1/8"	Typically >1/8"	Very large
Time constant	0.2 to 10 s	0.05 to 10 s	0.1 to 4 s	10 to 30 s	1 s	Long
Cost	\$25 to \$1000	\$2 to \$300	\$1 to \$50		\$0.50 to \$7	High
Comments	Best overall	Narrow span (typically <105°C)	Requires reference temp. junction	Can be configured w/maximum registering dial. Used in Kuster 'bomb' type high temp		Used in GRC 'bomb' type high temp logging tool (span limited ~150°C). Kuster also makes system rated for 260°C.

REFERENCE

- C-1. M. D. Lamers, Measurement Requirements and Methods for Geothermal Reservoir System Parameters (An Appraisal), LBL-9090, GREMP-6, 1979.

APPENDIX D
FABRICATION OF INSTRUMENTS

APPENDIX D

FABRICATION OF INSTRUMENTS

The cost of commercially available downhole instrumentation is often prohibitive. For this reason, and to obtain the highest quality data possible, the Earth Sciences group at Lawrence Berkeley Laboratory has developed a suite of downhole instruments for low-to-moderate temperature geothermal well testing. Three components of a downhole instrument package are described here: a downhole pressure temperature tool, a multiconductor cablehead, and a line driver for transmitting the pressure tool signal. A fourth instrument, a float type water level detector is also discussed. The complete engineering drawings for these instruments are available in Reference D-1.

Downhole Pressure and Temperature Instrument

The Paroscientific 400 psi and 900 psi digiquartz pressure transducers have been used for many years in measuring precise changes in wellhead pressures, pressure differentials across orifice plates and also in conjunction with "Perk" tubes and Sperry Sun downhole pressure chambers. In order to obtain precise pressure data during interference testing and accurate downhole pressure data, the Lawrence Berkeley Laboratory Reservoir Engineering group decided to incorporate the digiquartz pressure transducer in a downhole pressure temperature package which can be used in artesian and non-artesian wells. The maximum operating temperature of the tool is 107°C.

The downhole instrument package incorporates the Paroscientific 400 psi model 2400-A or 900 psi model 2900-A digiquartz pressure transducer (Figures D-1, D-2, and D-3). The transducer is shock-mounted inside the instrument package and connected to the pressure port with a stainless steel capillary tubing filled with Dow Corning f.s. 1265 fluid. The pressure device, when interfaced with the Paroscientific model 600 digiquartz computer and the Hewlett Packard 5150A thermal printer, can record pressure data at intervals of 1 second to 2 hours. The combination pressure-temperature housing is constructed from 316 stainless steel and has an outside diameter of 2.75 in. and a length of 9.5 in.

Figure D-1. Downhole instrument package.

XBL 816-10102

Figure D-2. Downhole pressure and temperature instrument.

REL 816-10101

Figure D-3. Downhole pressure and temperature instrument continued.

The combination pressure-temperature chambers are lowered into the well on armored four-conductor cable. The cable is connected to the tool by a designed cablehead, but can also be run with a conventional multi-conductor cablehead. The temperature sensing element is a YSI 44011 100,000 ohm at 25°C thermistor, isolated from the well fluid by 1/8 in. outside diameter stainless steel tubing with a 0.010 in. wall thickness. The thermistor has a resolution of $\pm 0.2^\circ\text{C}$ (including thermistor interchangeability) and a response time of approximately 1 second in liquids. The resistance of the thermistor, which is temperature dependent, is read at the surface and converted to temperature.

The system has been field tested at Klamath Falls, Oregon; Susanville, California; and Cerro Prieto, Mexico.

Geothermal Multiconductor Cablehead

A cablehead is a connector used to mechanically and electrically attach the armored logging cable to a downhole instrumentation package. Commercially available cableheads perform properly in noncorrosive environments, but when subjected to the corrosive brines and the elevated temperatures found in geothermal wells, the corrosive brine will eventually enter the cablehead. This will short the electrical connectors and cause the armored steel strands to corrode. Loss of data and eventual loss of instrument package downhole can result.

The geothermal group at the Lawrence Berkeley Laboratory has designed an inexpensive multiconductor cablehead (Figure D-4). The body is machined from stainless steel with a length of 9 in. and a 1.5 in. diameter. It has an overshoot provision for retrieval should the instrument package be lost downhole. The cable is mechanically attached within the cablehead by letting a brass cone force the unbraided cable strands against the walls of an internally tapered sleeve. The cablehead incorporates an epoxy pressure seal. The high temperature epoxy used has excellent corrosion, chemical and solvent resistant properties. The epoxy is rated for continuous operation at temperatures up to 600°F. The epoxy seal is formed by pouring the epoxy mix around the electrical conductors inside the specially machined

tapered cablehead cavity. The insulation on the conductors has been previously etched to ensure maximum adhesion of the epoxy. Should it become necessary, the epoxy seal can be easily removed with the aid of an electric drill. The cable can then be reheaded and a new seal poured in place. This can be carried out even under field conditions.

The cablehead also incorporates a grease barrier. A high temperature grease is pumped through a removable zerk fitting and fills void spaces within the cablehead assembly. This procedure keeps the often very corrosive, well bore fluid from entering the cablehead assembly. This eliminates the frequent reheading of the cable due to strand corrosion. The connection of cablehead to instrument package is made with a threaded fastener incorporating an "O" ring seal, and multi-conductor electrical connector.

Line Drivers

When using a Paroscientific pressure transducer it is often desirable to transmit the signal from the measurement location to a central data acquisition location. This allows for accurate clock synchronization and continuous observation of the instrument function. Because the transducer has a limited range in transmitting its frequency output, it is necessary to amplify the signal before it is relayed to the central data acquisition location.

The Field Systems Group at Lawrence Berkeley Laboratory designed an inexpensive line driver that detects, amplifies, and transmits the frequency signal from the transducer. The line driver provides power to the transducer from a 12 V automatic battery and transmits the output signal to a central location on an inexpensive twisted two-conductor wire.

The line driver is housed in a small instrument enclosure. The electronic circuit uses inexpensive commercially available components. A schematic of how the line driver is used in conjunction with the pressure tool is shown in Figure D-5.

INEL-A-19 624

Figure D-5. Schematic of a line driver used in conjunction with the pressure tool.

Water Level Indicator

Description

Fluid level indicators, as used in well testing, are portable instruments used to detect the water level in the wellbore. The most commonly used type of probe is a conductivity-type gauge. The weighted probe attached to a two conductor cable is run down a well. When the probe contacts the water an electrical circuit is completed and the current flow is measured at the surface. When used in cold water wells, such a probe performs adequately; but for hot wells it is often unreliable. Because a conductivity-type gauge relies solely on the conductivity of the downhole fluid to complete the electrical circuit, erroneous readings may result due to heavy steam layers, spill over from pumps, and casing leaks. Non-conductive fluids floating on the water surface, such as liquid paraffin or oil, can also cause erroneous readings.

By replacing a conventional conductivity-type probe with a GEMS model LS-1700 liquid-level switch, these problems can be avoided. In the GEMS unit a magnet-equipped float rises with the fluid level and closes a reed switch encased in the unit's central stem. An electrical circuit is completed and the current is detected at the surface. The assembly drawing for this unit is shown in Figure D-6. It is easily fabricated and the instructions to do so follow.

Fabrication

The assembly and fabrication drawings are as shown. The GEMS liquid-level switch (model LS-1700) is inexpensive and readily available. The parts surrounding the unit, Parts 3 and 4 (see assembly drawing) should be made of a nonmagnetic material to avoid interference with the operation of the probe.

1. Insert the GEMS liquid level switch into the fabricated housing (Items 3 and 4) letting the leads and threaded portion of the GEMS unit protrude through the hole (Item 4). Slip the hose fitting (Item 2) over the leads.
2. Fill the hose fitting with silicon rubber sealant and screw it securely to the GEMS unit.
3. Insert the two-conductor cable with the conductivity type probe removed through a one-foot section of appropriately-sized heat shrink tubing.
4. Solder the leads from the GEMS Unit to the leads of the two-conductor cable approximately two inches beyond the end of the hose fitting. Cover the solder joint, the cable, and the end of the hose fitting with silicon rubber sealant.

XBL 816-10189

Figure D-6. Fluid level indicator.

5. Slip the shrink tubing over the cable solder joint and hose fitting. Heat the shrink tubing until it fits snugly on the cable. Do not use the probe until the silicon rubber sealant has set.
6. Add split-type lead weights to the cable to facilitate running the probe down a well.

Use

The unit described here can be substituted on the end of a conventional conductivity-type water-level indicator. When the fluid level is reached, a current will be detected on the current-detecting instrument at the surface. If an entire water level detector is to be constructed, a suitable substitute for the surface readout is an ohmmeter. When the fluid level is reached by the probe, the ohmmeter will indicate that a circuit has been closed.

REFERENCE

- D-1. Recently Developed Well Test Instrumentation for Low-to-Moderate Temperature Hydrothermal Reservoirs, LBL-13260.

APPENDIX E
VARFLOW PROGRAM USER'S GUIDE

APPENDIX E
VARFLOW PROGRAM USER'S GUIDE

Before a well test is conducted, you should calculate the anticipated drawdown at each of the wells to be monitored during the test. If a single well is being flowed at a constant rate, the drawdown can easily be calculated from the equations in Section 6 of Volume I. However, if two or more wells are flowing and/or you are also reinjecting the produced brine, the calculations are more complicated. Also, if the flow rate from the well is not held at a constant rate, the calculations are more complex. The following computer program can be used to calculate the anticipated pressure response at up to 10 wells, due to the flow rate of up to 10 production and/or injection wells.

Program Description

VARFLOW calculates pressure changes in response to fluid production/injection from/into an idealized reservoir system. The program is set up to calculate pressure changes at up to ten observation wells. These observation wells may be interference monitoring wells or production wells. The reservoir description is as follows:

1. The reservoir is of infinite areal extent, or bounded on one side by a linear constant potential or barrier boundary.
2. The reservoir is completely saturated with a slightly compressible single phase fluid.
3. The reservoir is isothermal.
4. The reservoir is horizontal and has a constant thickness, H .
5. The flow of fluid in the reservoir is described by Darcy's law.

6. The reservoir is homogeneous and bounded above and below by impermeable layers.
7. The reservoir permeability can be anisotropic in a horizontal plane (x-y anisotropy) or isotropic.

The flow into or from a fully penetrating well is uniformly distributed over the length of the well. The well is modeled as a line source. However, a skin effect, indicative of wellbore condition can be included in the analysis.

Flow rates from up to ten wells can vary arbitrarily. Flow rates are modeled by superposition of consecutive "production pulses." Within any "production pulse" the flow rate may be constant or vary linearly. Figure E-1 demonstrates the construction and definition of a "production pulse." With this scheme for modeling flow rates, any variable flow rate history can be represented to the desired accuracy by a series of sequential straight-line segments, each of the appropriate duration and inclination.

Basic Equations

Variable Flow Rate

In an isotropic reservoir, which complies with the description discussed above, pressure changes caused by production/injection from a single well with a variable flow rate can be calculated from Equation (E-1).

$$\Delta P(t) = \frac{\mu}{4\pi kH} \int_{\tau_n}^{\tau_{n+1}} \frac{q(\tau)}{t - \tau} \exp \left[\frac{-r^2}{4\eta(t - \tau)} \right] d\tau \quad (E-1)$$

XBL 815-3075

Figure E-1. Representation of a production pulse.

where

$\Delta P(t)$ = pressure change at time t due to the flow rate $q(\tau)$
for $\tau_n < t < \tau_{n+1}$

μ = dynamic viscosity of the fluid

k = permeability

H = reservoir thickness

τ_n = time at which the flow starts

τ_{n+1} = time at which the flow stops

$q(\tau)$ = volumetric flow rate at time τ

r = distance between the observation well and the production/
injection well

n = the hydraulic diffusivity ($k/\phi\mu c$)

ϕ = storage coefficient = $c_r (1 - \phi) + c_f \phi$.

Then, if $q(\tau)$ expressed as

$$q_n(\tau) = A_n + B (\tau - \tau_n) \quad (E-2)$$

where

$q_n(\tau)$ = the flow rate at time τ which is within production
pulse n

A_n = the flow rate at the beginning of production pulse k

B = the slope of the production pulse

$$= (A_{n+1} - A_n) / (\tau_{n+1} - \tau_n)$$

τ_n = the time at which production pulse n begins

and it:

$$u_n = \frac{\mu\phi cr^2}{4k(t - \tau_n)}$$

$$u_{n+1} = \frac{\mu\phi cr^2}{4k(t - \tau_{n+1})}$$

$$w(u) = \int_u^\infty \frac{\exp(-y)}{y} dy$$

N = the total number of production pulses which begin prior to time τ ,

then, the pressure response is calculated by Equation (E-3).^{E-2, E-3}

$$\Delta P(t) = \frac{\mu}{4\pi kH} \sum_{n=1}^N \left\{ [A_n + B_n (t - \tau_n)(1 + u_n)] [w(u_n) - w(u_{n+1})] - B_n [(t - \tau_n) \exp(-u_n) - (t - \tau_{n+1}) \exp(-u_{n+1})] \right\} . \quad (E-3)$$

The pressure response, caused by production/injection from more than one well is calculated by summing the response due to each production/injection well.

Anisotropy. If the reservoir is anisotropic then the equations are modified in the following manner. If that the principal axes of anisotropy are at 90 degrees to each other and that the x and y axes are chosen to be the principal axes (see Figure E-2) the Equation (E-1) is rewritten as Equation (E-4).^{E-4}

$$\Delta P(t) = \frac{1}{4\pi} \left(\frac{\mu}{kH} \right)_e \int_{\tau_n}^{\tau_{n+1}} \frac{q(\tau)}{t - \tau} \exp \left(\frac{-r^2}{4\eta_\theta(t - \tau)} \right) d\tau \quad (E-4)$$

where

$(kH/\mu)_e$ = effective transmissivity

$$= \sqrt{(kH/\mu)_x \cdot (kH/\mu)_y}$$

and

$$\eta_\theta = \frac{(kH/\mu)_\theta}{\phi cH}$$

Figure E-2. Anisotropy representation.

$$(kH/\mu)_{\theta} = \frac{(kH/\mu)_x}{\cos^2 \theta + \frac{(kH/\mu)_x}{(kH/\mu)_y} \sin^2 \theta} \quad .$$

Theta is defined as the angle between the line adjoining the observation well and the production/injection well as measured counter-clockwise from a line parallel to the x-axis. (See Figure E-2). Since both $(kH/\mu)_e$ and η_{θ} are constants for any single production-observation well pair, the integral in Equation (E-4) may be evaluated analogously to the integral in Equation (E-1). In addition, because the reservoir is still homogeneous, regardless of the anisotropy, superposition of pressure responses, from each production well, is allowable.

Hydrologic Boundaries

A single fully penetrating linear hydrologic boundary can be modeled using the method of images.^{E-5} Briefly stated, a boundary may be modeled as a line of bilateral symmetry about which image wells are arrayed in one-to-one symmetric correspondence with the real production/injection wells. Figure E-3 shows the image well locations for a case with two production wells and a barrier boundary. A barrier boundary is modeled by using image wells which have flow rates which are identical to the production/injection well counterparts. A constant potential boundary (leaky boundary) is modeled using image wells which have flow rates that are identical in magnitude but opposite in sign to the production/injection well counterparts. The image wells contribute an additional pressure response at each observation well.

XBL 815-3073

Figure E-3. Boundary location scheme.

Skin Effect

The calculated pressure response at a production well may also include the effects of a zone of enhancement or damage around a wellbore. The pressure change is calculated using the steady-state pressure change as defined below in Equation (E-5).^{E-6}

$$\Delta P_{\text{skin}}(t) = s \frac{q(t)\mu}{2\pi kH} \quad (\text{E-5})$$

where

$q(t)$ = the instantaneous value of the flowrate at time t .

s = the skin value

$\Delta P(t)_{\text{skin}}$ = the pressure change due to the skin at time t .

A damaged wellbore is indicated by a positive skin value and an enhanced wellbore is indicated by a negative skin value. When the reservoir is anisotropic, kH/μ is replaced by $(kH/\mu)_e$.

Program Input

Input Data Categories

Run Parameters and Problem Description. To run the program, the following information must be specified:

<u>Variable name</u>	<u>Description</u>
IHH	The number of observation wells in this run. (default 0) (maximum 10)

Variable nameDescription

JJ	The number of production wells in this run. (default 0) (maximum 10)
IDIMEN	A flag to indicate that the data are not being input in S.I. units. (0 default--data are input in S.I. units) (1 set flag--data are not in S.I. units) See the following section for a description of the conversion factors.
NTIMES	The number of times at which pressure changes will be calculated. (default 0) (maximum 100)
RKHUX	The transmissivity $(kh/\mu)_x$ in the x-direction. NOTE: The x-axis is always a principal direction of anisotropy, and the second axis is at 90 degree to it, in the y direction. (default value 0.0) (default units $m^3/Pa \cdot s$)
RKHUY	The transmissivity $(kh/\mu)_y$ in the y-direction. (default value 0.0) (default units $m^3/Pa \cdot s$)
PCH	The storativity (ϕch). (default value 0.0) (default units m/Pa)

Variable nameDescription

ANGLE

The azimuth to the boundary (see Figure E-3) measured clockwise from the positive y-axis.

DSTNCE

The perpendicular distance to the boundary from the origin of the coordinate system.

(default value 0.0)

(default units m)

BOUND

If the effects of a boundary are to be included, then the type of boundary, either barrier or constant potential, is input as an alphanumeric variable; either 10HBARRIER, or or 10HLEAKY,, which must be specified

Unit Conversion Factors. All parameter inputs are converted to S.I. units for internal calculation. At the termination of the calculation they are all converted back to the original input units. The conversion factor data required are listed below.

If IDIMEN was set to 1, the following information must be supplied.
If IDIMEN is equal to 0, this data card is eliminated altogether.

Variable nameDescription

PAPRESS

Number of pascals per pressure input unit.

CMSFLOW

Number of m^3/s per flow rate input unit.

SECTIME

Number of seconds per time input unit.

<u>Variable name</u>	<u>Description</u>
MLENGTH	Number of meters per length unit.
PASVISC	Number of pascal*seconds (Pa*s) per viscosity input unit.
SMPERM	Number of m^2 per permeability input unit.

Observation Well Locations and Specifications. The observation wells may be located at any position as specified by a set of x-y coordinates in a cartesian coordinate system. The following is a list of the specifications required for each observation well(I):

<u>Variable</u>	<u>Description</u>
NAME(I)	An alphanumeric name for the well. (default--blank)
OX(I)	The x-coordinate of the well. (default 0.) (default units m)
OY(I)	The y-coordinate of the well. (default 0.) (default units m)
YSTART(I)	The initial pressure at the well prior to any production or injection. (default units Pa)
LOBS(I)	A number (as read) that indicates that this observation well(I) is also production well LOBS(I). (Default 0 indicates the well is an interference monitoring well.)

VariableDescription

SKIN(I)

If the well(I) is also production well LOBS(I) the well may be assigned a non-zero skin value.

(default 0. no skin)

Production Well Specifications and Flow Rate. To input a flow rate schedule, the data must be put in the format of pairs of flow rate points such that the flow rate is specified at the beginning and the end of a production pulse. Then, the flow rate, at all times, between the beginning and end of a production pulse, is known from Equation (E-3). The flow rate record will then consist of consecutive production pulses arranged in chronological order. If there is a step change from one flow rate to another, this is represented by two sequential production pulses, and must be input as such (see Sample Problem 1).

The following is a list of the specifications for each production well(J):

VariableDescription

PNAME(J)

An alphanumeric name for production well (J).

(default value--BLANK)

PX(J)

The x-coordinate, in cartesian coordinates of production well(J).

(default value 0.0)

(default units m)

PY(J)

The y-coordinate, in cartesian coordinates, of production well(J).

(default value 0.0)

(default units m)

VariableDescription

KKJ(J)

The number of flow rate points for
production well (J).

(default value 0)

[TQ(K,J), AQ(K,J)]

The flow rate data points for well(J)
which are of the form (time, flow rate).

Up to 100 points per well are allowed.

(default [0.0, 0.0])

(default units [s, m³/s])

(K = 1, KKJ(J))

Times at Which Pressures Are To Be Calculated. Up to 100 different times
can be specified at which pressure changes will be calculated:

VariableDescription

TIMES (L)

The times at which pressure calculations
will be made up to 100 points.

(default value 0.0) (default
units, s)

INPUT DATA FORMAT

PROBLEM DESCRIPTION AND UNIT CONVERSION FACTORS

1 CARD - Title card (8A10)
- alphanumeric to 80 characters

1 CARD - IHH, II, IDIMEN, NTIMES (4I10)

If IDIMEN Is set equal to 1 on CARD 2

THEN INCLUDE

1 CARD - PAPRESS, CMSFLOW, SECTIME, RLENGTH, PASVISC, SMPERM (6E10.4)

OTHERWISE

1 CARD - RKHUX, RKHUY, PCH, ANGLE, DSTNCE, BOUND (5E10.4, A10)

OBSERVATION WELL DATA

IIH CARDS - NAME(I), OX(I), OY(I), YSTART(I),
 LOBS(I), SKIN(I), etc.
 (I = 1, IIH) (A10, 2F10.2, E10.4, I10, F10.2)

Repeat for each observation well.

PRODUCTION WELL DATA

JJ SETS OF CARDS - PNAME(J), PX(J), PY(J), KKJ(J) (A10, 2F10.2,
I10)

TQ (1, J)	,	AQ (1, J)	(2E10.4)
•		•	
•		•	
•		•	
•		•	
TQ (KKJ(J),J)		AQ (KKJ(J), J)	

Repeat this set of cards for each production well.

TIMES FOR CALCULATIONS OF PRESSURE CHANGES

TIMES(1), TIMES(2), TIMES(3),.....TIMES(8) (8E10.4)

Put eight per card - repeat until amount specified by NTIMES on
CARD 2.

Sample Problems

Four sample problems are discussed in which the various capabilities of the program are demonstrated. Data decks and outputs are provided for each problem.

Sample Problem

No Anisotropy--Variable Flow Rate (Step-Wise)

In this problem a single production well is produced at a step wise variable flow rate and four observation wells monitor the pressure response. The observation wells are located symmetrically around the observation well (Figure E-4). Since there is no x-y reservoir anisotropy, the pressure drop at each of the observation wells should be identical. The flow rate from the production well is shown in Figure E-5. As is shown, there are three consecutive "production" pulses, the first two lasting 1000 minutes each, and the third lasting 2000 minutes.

The data deck for Sample 1 is shown in Figure E-6. The first card (card 1) gives the title information for the problem. The second card indicates that there are four observation wells (column 10, 1 production well (column 20), the IDIMEN flag is set (column 30) and the pressure changes will be calculated at 56 times (columns 30-40). On card three, the unit conversion factors are shown. The following table shows the units used for each quantity and the conversion factor to S.I. units.

XBL 815-3071

Figure E-4. Location scheme, in cartesian coordinates, for the production well and observation wells for Sample Problem 1.

<u>Quantity</u>	<u>Unit</u>	<u>Conversion factor</u>
Pressure	Psia	6895
Flow rate	Gal/min	6.31×10^{-5}
Time	Hours	3600
Length	Feet	0.3048
Viscosity	Centipoise	1×10^{-3}
Permeability	Millidarcies	9.862×10^{-16}

It is important to note that once a time or distance unit is chosen, it must be used consistently throughout the input deck. For instance, when the flow rate is input, the time units must be the same as the time units used for the specification of times at which pressure calculations will be made.

XBL 815-3070

Figure E-5. Variable flow rate schedule for the production well in Sample Problem 1.

Card 4 lists the information about the x and y direction transmissivity and the reservoir storativity. For this problem, since there is no anisotropy, both the x-direction and y-direction transmissivity are equal and set to 150,000 md-ft/cp. The storativity for this problem is set equal to 2×10^{-3} ft/psi.

Cards 5 through 8 list the alphanumeric names for each observation well (columns 1-10), the (x,y) coordinates of each well (columns 11-20 and 21-30 respectively) and the initial reservoir pressure for each well (columns 31-40). The coordinates of each well are shown in Figure E-4.

Cards 9 through 15 contain all of the relevant information about the production well. On card 9, the alphanumeric name of the production well (column 1-10), the coordinates of the production well (columns 11-20, 21-30) and the number of flow rate points (columns 31-40, format I10) are input. For this problem six flow rate points are used to model the step-wise variable flow rate shown in Figure E-5. Note the construction of three "production pulses" to represent the flow rate.

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PROBLEM SAMPLE PROBLEM 1

DATA ENTRY FORMS

PAGE 1

CARD

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	
1	NO ANISOTROPY-VARIABLE RATE																																																																															
2	4 1 1 56																																																																															
3	6.895E+03 6.31E-05 3600. .3048 1.0E-03 9.863E-16																																																																															
4	150000. 150000. .003																																																																															
5	085 1 600. 100. 0.																																																																															
6	085 2 -400. 100. 0.																																																																															
7	085 3 100. 600. 0.																																																																															
8	085 4 100. -400. 0.																																																																															
9	PR00 1 100. 100. 6																																																																															
10	0. 1000.																																																																															
11	1000. 1000.																																																																															
12	1000. 2000.																																																																															
13	2000. 2000.																																																																															
14	2000. 3000.																																																																															
15	4000. 3000.																																																																															
16	1 2. 3. 4. 5. 6. 7. 8.																																																																															
17	10. 20. 30. 40. 50. 60. 70. 80.																																																																															
18	100. 101. 102. 103. 104. 105. 106. 107.																																																																															
19	103. 110. 120. 130. 140. 150. 160. 170.																																																																															
20	180. 200. 200. 202. 203. 204. 205. 206.																																																																															
21	207. 208. 209. 210. 220. 230. 240. 250.																																																																															
22	260. 270. 280. 300. 320. 340. 360. 380.																																																																															

RL-2145-1

Figure E-6. Input deck for Sample Problem 1.

Cards 16 through 22 specify times at which pressure calculations, at each of the four observation wells, will be calculated. For this problem, pressures will be calculated at 1 hour, 2 hours, 3 hours, etc. to 380 hours. The units for the times specified here are input on card 3. If 3.6×10^3 s had not been specified, the default units would have been used, implying that pressures would be calculated at 1 s, 2 s, 3 s, etc., to 380 s.

The output for this problem is shown in Figure E-7. As can be seen, the pressure drop at each well is identical, because each well is equidistant from the production well (500 ft). The next sample problem will show a similar problem but one in which there is extreme x-y anisotropy.

NO ANISOTROPY-VARIABLE FLOWRATE

NUMBER OF OBSERVATION WELLS	4	
NUMBER OF PRODUCTION WELLS	1	
NUMBER OF TIMES AT WHICH PRESSURES WILL BE CALCULATED		56

CONVERSION FACTORS =====

PRESSURE UNIT PER PASCAL	.6895E+04
FLOWRATE UNIT PER CUBIC METER PER SECOND	.6310E-04
TIME UNIT PER SECOND	3600.00
LENGTH PER METER	.30
VISCOSITY PER PASCAL-SECOND	.100E-02
PERMEABILITY PER SQUARE METER	.9862E-15

PARAMETER VALUES =====

X-AXIS TRANSMISSIVITY = .1500E+06
Y-AXIS TRANSMISSIVITY = .1500E+06
STORATIVITY = .2000E-02

OBSERVATION WELL NUMBER 1
WELL OBS 1 COORDINATES (600.00, 100.00)
INITIAL PRESSURE=0.

OBSERVATION WELL NUMBER 2
WELL OBS 2 COORDINATES (-400.00, 100.00)
INITIAL PRESSURE=0.

Figure E-7. Output for Sample Problem 1.

OBSERVATION WELL NUMBER 3
 WELL OBS 3 COORDINATES (100.00, 600.00)
 INITIAL PRESSURE=-.0

OBSERVATION WELL NUMBER 4
 WELL OBS 4 COORDINATES (100.00, -400.00)
 INITIAL PRESSURE=-.0

PRODUCTION WELL NUMBER 1
 PROD 1 COORDINATES (100.00, 100.00)
 NUMBER OF FLOWRATE POINTS= 6

TIME	FLOWRATE
0.	.1000E+04
.1000E+03	.1000E+04
.1000E+03	.2000E+04
.2000E+03	.2000E+04
.2000E+03	.3000E+04
.4000E+03	.3000E+04

DISTANCES BETWEEN OBSERVATION WELLS AND PRODUCTION WELLS

	OBS 1	OBS 2	OBS 3	OBS 4
PROD 1	500.00	500.00	500.00	500.00

TIME	OBS 1	OBS 2	OBS 3	OBS 4
1.00	-.1715E+00	-.1715E+00	-.1715E+00	-.1715E+00
2.00	-.1433E+01	-.1433E+01	-.1433E+01	-.1433E+01
3.00	-.3238E+01	-.3238E+01	-.3238E+01	-.3238E+01
4.00	-.5102E+01	-.5102E+01	-.5102E+01	-.5102E+01
5.00	-.6878E+01	-.6878E+01	-.6878E+01	-.6878E+01
6.00	-.8531E+01	-.8531E+01	-.8531E+01	-.8531E+01
7.00	-.1006E+02	-.1006E+02	-.1006E+02	-.1006E+02
9.00	-.1278E+02	-.1278E+02	-.1278E+02	-.1278E+02
10.00	-.1400E+02	-.1400E+02	-.1400E+02	-.1400E+02
20.00	-.2292E+02	-.2292E+02	-.2292E+02	-.2292E+02
30.00	-.2867E+02	-.2867E+02	-.2867E+02	-.2867E+02
40.00	-.3291E+02	-.3291E+02	-.3291E+02	-.3291E+02
50.00	-.3627E+02	-.3627E+02	-.3627E+02	-.3627E+02
60.00	-.3905E+02	-.3905E+02	-.3905E+02	-.3905E+02
70.00	-.4142E+02	-.4142E+02	-.4142E+02	-.4142E+02

Figure E-7. (continued).

TIME	OBS 1	OBS 2	OBS 3	OBS 4
80.00	-.4349E+02	-.4349E+02	-.4349E+02	-.4349E+02
100.00	-.4697E+02	-.4697E+02	-.4697E+02	-.4697E+02
101.00	-.4729E+02	-.4729E+02	-.4729E+02	-.4729E+02
102.00	-.4871E+02	-.4871E+02	-.4871E+02	-.4871E+02
103.00	-.5067E+02	-.5067E+02	-.5067E+02	-.5067E+02
104.00	-.5268E+02	-.5268E+02	-.5268E+02	-.5268E+02
105.00	-.5461E+02	-.5461E+02	-.5461E+02	-.5461E+02
106.00	-.5641E+02	-.5641E+02	-.5641E+02	-.5641E+02
107.00	-.5809E+02	-.5809E+02	-.5809E+02	-.5809E+02
109.00	-.6110E+02	-.6110E+02	-.6110E+02	-.6110E+02
110.00	-.6246E+02	-.6246E+02	-.6246E+02	-.6246E+02
120.00	-.7275E+02	-.7275E+02	-.7275E+02	-.7275E+02
130.00	-.7976E+02	-.7976E+02	-.7976E+02	-.7976E+02
140.00	-.8517E+02	-.8517E+02	-.8517E+02	-.8517E+02
150.00	-.8962E+02	-.8962E+02	-.8962E+02	-.8962E+02
160.00	-.9342E+02	-.9342E+02	-.9342E+02	-.9342E+02
170.00	-.9675E+02	-.9675E+02	-.9675E+02	-.9675E+02
180.00	-.9973E+02	-.9973E+02	-.9973E+02	-.9973E+02
200.00	-.1049E+03	-.1049E+03	-.1049E+03	-.1049E+03
201.00	-.1053E+03	-.1053E+03	-.1053E+03	-.1053E+03
202.00	-.1068E+03	-.1068E+03	-.1068E+03	-.1068E+03
203.00	-.1088E+03	-.1088E+03	-.1088E+03	-.1088E+03
204.00	-.1109E+03	-.1109E+03	-.1109E+03	-.1109E+03
205.00	-.1129E+03	-.1129E+03	-.1129E+03	-.1129E+03
206.00	-.1148E+03	-.1148E+03	-.1148E+03	-.1148E+03
207.00	-.1165E+03	-.1165E+03	-.1165E+03	-.1165E+03
208.00	-.1182E+03	-.1182E+03	-.1182E+03	-.1182E+03
209.00	-.1197E+03	-.1197E+03	-.1197E+03	-.1197E+03
210.00	-.1211E+03	-.1211E+03	-.1211E+03	-.1211E+03
220.00	-.1322E+03	-.1322E+03	-.1322E+03	-.1322E+03
230.00	-.1399E+03	-.1399E+03	-.1399E+03	-.1399E+03
240.00	-.1460E+03	-.1460E+03	-.1460E+03	-.1460E+03
250.00	-.1511E+03	-.1511E+03	-.1511E+03	-.1511E+03
260.00	-.1555E+03	-.1555E+03	-.1555E+03	-.1555E+03
270.00	-.1594E+03	-.1594E+03	-.1594E+03	-.1594E+03
280.00	-.1630E+03	-.1630E+03	-.1630E+03	-.1630E+03
300.00	-.1693E+03	-.1693E+03	-.1693E+03	-.1693E+03
320.00	-.1747E+03	-.1747E+03	-.1747E+03	-.1747E+03
340.00	-.1794E+03	-.1794E+03	-.1794E+03	-.1794E+03
360.00	-.1838E+03	-.1838E+03	-.1838E+03	-.1838E+03
380.00	-.1877E+03	-.1877E+03	-.1877E+03	-.1877E+03

Figure E-7. (continued).

Sample Problem 2

Verification of Anisotropy. In Sample Problem 2 a well in an anisotropic reservoir is produced at a constant flow rate of 1000 GPM for a period of 5000 hours. Four observation wells, located symmetrically about the production well, along the major axes of anisotropy, are used to observe the pressure changes. For this problem, the x-axis permeability was chosen to be 150 times larger than the permeability in the y-direction. Thus, transmissivity values of 150,000 md·ft/cp and 1000 md·ft/cp were used.

Figure E-8 shows the well location scheme and the representation of the reservoir anisotropy.

The data deck for Sample Problem 2 is shown in Figure E-9. The first three cards are the same as they are in Sample Problem 1. On card 4 the x-direction transmissivity (column 1-10) is set to 150,000 md·ft/cp, and

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Figure E-8. Well location scheme for Sample Problems 2 and 3.

VERIFICATION OF ANISOTROPY							
	04	1	1	56			
6.895 E+03	6.310E-05	3.5E+03	.3048	1.0	E-03	9.862E-16	
150000.	1000.	.002	00.	0000.			
OBS 1	500.	0.	0.		0	0.	
OBS 2	-500.	0.	0.				
OBS 3	000.	500.					
OBS 4	000.	-500.					
PROD 1	0.	0.		2			
0.	1000.						
5000.	1000.						
1.	2.	3.	4.	5.	6.	7.	9.
10.	20.	30.	40.	50.	60.	70.	80.
100.	101.	102.	103.	104.	105.	106.	107.
109.	110.	120.	130.	140.	150.	160.	170.
180.	200.	201.	202.	203.	204.	205.	206.
207.	208.	209.	210.	220.	230.	240.	250.
260.	270.	280.	300.	320.	340.	360.	380.

Figure E-9. Input deck for Sample Problem 2.

the y-direction transmissivity is set to 1000 md*ft/cp. As in Problem 1, the storativity, ϕch , is set to 0.002 ft/psi. The remaining part of the data deck is similar to that in Problem 1, except that only one production pulse or two flow rate points are required to model the flow rate.

The output for Sample Problem 2 is shown in Figure E-10. Note the effect of the extreme anisotropy on the reservoir pressure response.

Sample Problem 3

Verification of Anisotropy--Boundary Problem. Sample Problem 3 is identical to Problem 2 except that there is a barrier boundary in the reservoir 1000 ft from the production well, in a direction perpendicular to the x-axis. Figure E-11 shows the well locations and the boundary location scheme. Note that the alpha is measured clockwise from the positive y-axis.

The data deck (Figure E-12) for this problem is identical to the data deck in Problem 2 except for card 4. Columns 1-10 and 11-20 contain the reservoir transmissivity information and columns 21-30 contain the storativity data. Alpha, the angle seen in Figure E-11, is input in columns 31-40 and DSTNCE, the distance from the origin to the perpendicular of the boundary, is input in columns 41-50. The type of boundary is indicated alphanumerically in columns 51-60. Note that the type, either BARRIER or LEAKY must begin in column 51.

VERIFICATION OF ANISOTROPY

NUMBER OF OBSERVATION WELLS 4
 NUMBER OF PRODUCTION WELLS 1
 NUMBER OF TIMES AT WHICH PRESSURES WILL BE CALCULATED 56

CONVERSION FACTORS

PRESSURE UNIT PER PASCAL .6895E+04
 FLOWRATE UNIT PER CUBIC METER PER SECOND .6310E-04
 TIME UNIT PER SECOND 3600.00
 LENGTH PER METER .30
 VISCOSITY PER PASCAL-SECOND .100E-02
 PERMEABILITY PER SQUARE METER .9862E-15

PARAMETER VALUES

X-AXIS TRANSMISSIVITY = .1500E+06
 Y-AXIS TRANSMISSIVITY = .1000E+04
 STORATIVITY = .2000E-02

OBSERVATION WELL NUMBER 1
 WELL OBS 1 COORDINATES (500.00, 0.)
 INITIAL PRESSURE=0.

OBSERVATION WELL NUMBER 2
 WELL OBS 2 COORDINATES (-500.00, 0.)
 INITIAL PRESSURE=0.

OBSERVATION WELL NUMBER 3
 WELL OBS 3 COORDINATES (0. , 500.00)
 INITIAL PRESSURE=-.0

OBSERVATION WELL NUMBER 4
 WELL OBS 4 COORDINATES (0. , -500.00)
 INITIAL PRESSURE=-.0

PRODUCTION WELL NUMBER 1
 PROD 1 COORDINATES (0. , 0.)
 NUMBER OF FLOWRATE POINTS= 2

TIME FLOWRATE

0. .1000E+04
 .5000E+04 .1000E+04

DISTANCES BETWEEN OBSERVATION WELLS AND PRODUCTION WELLS

	OBS 1	OBS 2	OBS 3	OBS 4
PROD 1	500.00	500.00	500.00	500.00

Figure E-10. Output for Sample Problem 2.

TIME	OBS 1	OBS 2	OBS 3	OBS 4
1.00	-.2101E+01	-.2101E+01	-.3917-206	-.3917-206
2.00	-.1755E+02	-.1755E+02	-.8058-103	-.8058-103
3.00	-.3966E+02	-.3966E+02	-.2625E-68	-.2625E-68
4.00	-.6251E+02	-.6249E+02	-.5152E-51	-.5152E-51
5.00	-.8435E+02	-.8424E+02	-.1286E-40	-.1286E-40
6.00	-.1048E+03	-.1045E+03	-.1136E-33	-.1136E-33
7.00	-.1239E+03	-.1232E+03	-.1064E-28	-.1064E-28
9.00	-.1587E+03	-.1566E+03	-.4742E-22	-.4742E-22
10.00	-.1745E+03	-.1715E+03	-.1026E-19	-.1026E-19
20.00	-.3029E+03	-.2915E+03	-.4294E-09	-.4294E-09
30.00	-.3935E+03	-.3553E+03	-.1870E-05	-.1870E-05
40.00	-.4754E+03	-.4131E+03	-.1373E-03	-.1373E-03
50.00	-.5399E+03	-.4618E+03	-.1916E-02	-.1916E-02
60.00	-.5954E+03	-.5043E+03	-.1151E-01	-.1151E-01
70.00	-.6441E+03	-.5424E+03	-.4241E-01	-.4241E-01
80.00	-.6875E+03	-.5769E+03	-.1147E+00	-.1147E+00
100.00	-.7522E+03	-.6377E+03	-.4767E+00	-.4767E+00
101.00	-.7655E+03	-.6405E+03	-.5048E+00	-.5048E+00
102.00	-.7639E+03	-.6433E+03	-.5341E+00	-.5341E+00
103.00	-.7722E+03	-.6461E+03	-.5644E+00	-.5644E+00
104.00	-.7755E+03	-.6488E+03	-.5959E+00	-.5959E+00
105.00	-.7789E+03	-.6515E+03	-.6286E+00	-.6286E+00
106.00	-.7821E+03	-.6542E+03	-.6624E+00	-.6624E+00
107.00	-.7853E+03	-.6569E+03	-.6975E+00	-.6975E+00
109.00	-.7917E+03	-.6623E+03	-.7712E+00	-.7712E+00
110.00	-.7943E+03	-.6649E+03	-.8098E+00	-.8098E+00
120.00	-.8250E+03	-.6903E+03	-.1267E+01	-.1267E+01
130.00	-.8530E+03	-.7141E+03	-.1861E+01	-.1861E+01
140.00	-.8792E+03	-.7366E+03	-.2597E+01	-.2597E+01
150.00	-.9039E+03	-.7579E+03	-.3480E+01	-.3480E+01
160.00	-.9269E+03	-.7780E+03	-.4509E+01	-.4509E+01
170.00	-.9483E+03	-.7972E+03	-.5683E+01	-.5683E+01
180.00	-.9695E+03	-.8155E+03	-.6997E+01	-.6997E+01
200.00	-.1008E+04	-.8498E+03	-.1002E+02	-.1002E+02
201.00	-.1010E+04	-.8514E+03	-.1019E+02	-.1019E+02
202.00	-.1012E+04	-.8530E+03	-.1035E+02	-.1035E+02
203.00	-.1013E+04	-.8546E+03	-.1052E+02	-.1052E+02
204.00	-.1015E+04	-.8563E+03	-.1069E+02	-.1069E+02
205.00	-.1017E+04	-.8579E+03	-.1086E+02	-.1086E+02
206.00	-.1019E+04	-.8595E+03	-.1103E+02	-.1103E+02

Figure E-10. (continued)..

TIME	OBS 1	OBS 2	OBS 3	OBS 4
207.00	-.7160E+03	-.7160E+03	-.6501E+01	-.6501E+01
208.00	-.7169E+03	-.7169E+03	-.6598E+01	-.6598E+01
209.00	-.7178E+03	-.7178E+03	-.6695E+01	-.6695E+01
210.00	-.7188E+03	-.7188E+03	-.6793E+01	-.6793E+01
220.00	-.7278E+03	-.7278E+03	-.7806E+01	-.7806E+01
230.00	-.7365E+03	-.7365E+03	-.8874E+01	-.8874E+01
240.00	-.7448E+03	-.7448E+03	-.9992E+01	-.9992E+01
250.00	-.7528E+03	-.7528E+03	-.1116E+02	-.1116E+02
260.00	-.7604E+03	-.7604E+03	-.1236E+02	-.1236E+02
270.00	-.7678E+03	-.7678E+03	-.1361E+02	-.1361E+02
280.00	-.7749E+03	-.7749E+03	-.1489E+02	-.1489E+02
300.00	-.7884E+03	-.7884E+03	-.1755E+02	-.1755E+02
320.00	-.8011E+03	-.8011E+03	-.2031E+02	-.2031E+02
340.00	-.8129E+03	-.8129E+03	-.2316E+02	-.2316E+02
360.00	-.8241E+03	-.8241E+03	-.2607E+02	-.2607E+02
380.00	-.8348E+03	-.8348E+03	-.2904E+02	-.2904E+02

Figure E-10. (continued).

XBL 815-3076

Figure E-11. Boundary location scheme for Sample Problem 3.

VERIFICATION OF ANISOTROPY--RUN TO COMPARE WITH BOUNDARY							
04	1	1	56				
6.895 E+03	6.310E-05	3.6E+03	.3048	1.0 E-03	9.862E-16		
150000.	1000.	.002	90.	1000.	BARRIER		
OBS 1	500.	0.	0.	0	0.		
OBS 2	-500.	0.	0.				
OBS 3	000.	500.					
OBS 4	000.	-500.					
PROD 1	0.	0.	2				
0.	1000.						
5000.	1000.						
1.	2.	3.	4.	5.	6.	7.	9.
10.	20.	30.	40.	50.	60.	70.	80.
100.	101.	102.	103.	104.	105.	106.	107.
109.	110.	120.	130.	140.	150.	160.	170.
180.	200.	201.	202.	203.	204.	205.	206.
207.	208.	209.	210.	220.	230.	240.	250.
260.	270.	280.	300.	320.	340.	360.	380.

Figure E-12. Input deck for Sample Problem 3.

The output for the Sample Problem 3 is shown in Figure E-13.

Sample Problem 4

Verification of Anisotropy--Run to Compare with Boundary. Sample Problem 4 demonstrates how the algorithm in VARFLOW accounts for the effects of a barrier or constant potential boundary in the pressure calculations. In this calculation the existence of a boundary is not specified, however, a well which would be the image well for the calculation in Sample Problem 3 is explicitly included in the calculation. The well locations for the observation wells, the production well and the "image" production well are shown in Figure E-14.

The input deck (Figure E-15) for the problem is similar to the data decks in problems 2 and 3. Note that on Card 2, Column 20, it is specified that there are two production wells for this problem. The production data and production well specifications for the second production well, PROD2, are on Cards 12-14. Note that the production rate for PROD2 is identical to that of PROD1.

The output for this problem is shown in Figure E-16. Note that the pressure response is identical to the pressure response in Problem 3.

--- VERIFICATION OF ANISOTROPY--RUN TO COMPARE WITH BOUNDARY

NUMBER OF OBSERVATION WELLS 4
 NUMBER OF PRODUCTION WELLS 1
 NUMBER OF TIMES AT WHICH PRESSURES WILL BE CALCULATED 56

----- CONVERSION FACTORS -----

 PRESSURE UNIT PER PASCAL .6895E+04
 FLOWRATE UNIT PER CUBIC METER PER SECOND .6310E-04
 TIME UNIT PER SECOND 3600.00
 LENGTH PER METER .30
 VISCOSITY PER PASCAL-SECOND .100E-02
 PERMEABILITY PER SQUARE METER .9862E-15

----- PARAMETER VALUES -----

 X-AXIS TRANSMISSIVITY = .1500E+06
 Y-AXIS TRANSMISSIVITY = .1000E+04
 STORATIVITY = .2000E-02

THERE IS A BARRIER BOUNDARY AT AN ANGLE OF 90.00 DEGREES AND A DISTANCE OF 1000.00

OBSERVATION WELL NUMBER 1
 WELL OBS 1 COORDINATES (500.00, 0.)
 INITIAL PRESSURE=0.

OBSERVATION WELL NUMBER 2
 WELL OBS 2 COORDINATES (-500.00, 0.)
 INITIAL PRESSURE=0.

OBSERVATION WELL NUMBER 3
 WELL OBS 3 COORDINATES (0. , 500.00)
 INITIAL PRESSURE=-.0

OBSERVATION WELL NUMBER 4
 WELL OBS 4 COORDINATES (0. , -500.00)
 INITIAL PRESSURE=-.0

PRODUCTION WELL NUMBER 1
 PROD 1 COORDINATES (0. , 0.)
 NUMBER OF FLOWRATE POINTS= 2

----- TIME FLOWRATE -----
 0. .1000E+04
 .5000E+04 .1000E+04

----- DISTANCES BETWEEN OBSERVATION WELLS AND PRODUCTION WELLS -----

PROD 1 OBS 1 500.00 OBS 2 500.00 OBS 3 500.00 OBS 4 500.00

Figure E-13. Output for Sample Problem 3.

TIME	OBS 1	OBS 2	OBS 3	OBS 4
1.00	-.2101E+01	-.2101E+01	-.3917-206	-.3917-206
2.00	-.1755E+02	-.1755E+02	-.8058-103	-.8058-103
3.00	-.3966E+02	-.3966E+02	-.2625E-68	-.2625E-68
4.00	-.6251E+02	-.6249E+02	-.5152E-51	-.5152E-51
5.00	-.8435E+02	-.8424E+02	-.1286E-40	-.1286E-40
6.00	-.1048E+03	-.1045E+03	-.1136E-33	-.1136E-33
7.00	-.1239E+03	-.1232E+03	-.1064E-28	-.1064E-28
9.00	-.1587E+03	-.1566E+03	-.4742E-22	-.4742E-22
10.00	-.1745E+03	-.1715E+03	-.1026E-19	-.1026E-19
20.00	-.3029E+03	-.2915E+03	-.4294E-09	-.4294E-09
30.00	-.3935E+03	-.3553E+03	-.1870E-05	-.1870E-05
40.00	-.4754E+03	-.4131E+03	-.1373E-03	-.1373E-03
50.00	-.5399E+03	-.4618E+03	-.1916E-02	-.1916E-02
60.00	-.5954E+03	-.5043E+03	-.1151E-01	-.1151E-01
70.00	-.6441E+03	-.5424E+03	-.4241E-01	-.4241E-01
80.00	-.6875E+03	-.5769E+03	-.1147E+00	-.1147E+00
100.00	-.7522E+03	-.5377E+03	-.4767E+00	-.4767E+00
101.00	-.7555E+03	-.5405E+03	-.5048E+00	-.5048E+00
102.00	-.7539E+03	-.5433E+03	-.5341E+00	-.5341E+00
103.00	-.7722E+03	-.5461E+03	-.5644E+00	-.5644E+00
104.00	-.7755E+03	-.5488E+03	-.5959E+00	-.5959E+00
105.00	-.7788E+03	-.5515E+03	-.6286E+00	-.6286E+00
106.00	-.7821E+03	-.5542E+03	-.6624E+00	-.6624E+00
107.00	-.7853E+03	-.5569E+03	-.6975E+00	-.6975E+00
109.00	-.7917E+03	-.5623E+03	-.7712E+00	-.7712E+00
110.00	-.7943E+03	-.5649E+03	-.8098E+00	-.8098E+00
120.00	-.8250E+03	-.5903E+03	-.1267E+01	-.1267E+01
130.00	-.8530E+03	-.7141E+03	-.1861E+01	-.1861E+01
140.00	-.8792E+03	-.7366E+03	-.2597E+01	-.2597E+01
150.00	-.9039E+03	-.7579E+03	-.3480E+01	-.3480E+01
160.00	-.9269E+03	-.7780E+03	-.4509E+01	-.4509E+01
170.00	-.9483E+03	-.7972E+03	-.5683E+01	-.5683E+01
180.00	-.9695E+03	-.8155E+03	-.6997E+01	-.6997E+01
200.00	-.1008E+04	-.8498E+03	-.1002E+02	-.1002E+02
201.00	-.1010E+04	-.8514E+03	-.1019E+02	-.1019E+02
202.00	-.1012E+04	-.8530E+03	-.1035E+02	-.1035E+02
203.00	-.1013E+04	-.8546E+03	-.1052E+02	-.1052E+02
204.00	-.1015E+04	-.8563E+03	-.1069E+02	-.1069E+02
205.00	-.1017E+04	-.8579E+03	-.1086E+02	-.1086E+02
206.00	-.1019E+04	-.8595E+03	-.1103E+02	-.1103E+02

Figure E-13. (continued).

TIME	OBS 1	OBS 2	OBS 3	OBS 4
207.00	-.1021E+04	-.8611E+03	-.1120E+02	-.1120E+02
208.00	-.1022E+04	-.8627E+03	-.1137E+02	-.1137E+02
209.00	-.1024E+04	-.8642E+03	-.1155E+02	-.1155E+02
210.00	-.1026E+04	-.8658E+03	-.1172E+02	-.1172E+02
220.00	-.1043E+04	-.8813E+03	-.1354E+02	-.1354E+02
230.00	-.1059E+04	-.8961E+03	-.1546E+02	-.1546E+02
240.00	-.1075E+04	-.9104E+03	-.1747E+02	-.1747E+02
250.00	-.1090E+04	-.9243E+03	-.1959E+02	-.1959E+02
260.00	-.1105E+04	-.9376E+03	-.2178E+02	-.2178E+02
270.00	-.1119E+04	-.9505E+03	-.2406E+02	-.2406E+02
280.00	-.1133E+04	-.9630E+03	-.2641E+02	-.2641E+02
300.00	-.1158E+04	-.9869E+03	-.3129E+02	-.3129E+02
320.00	-.1183E+04	-.1009E+04	-.3640E+02	-.3640E+02
340.00	-.1206E+04	-.1031E+04	-.4169E+02	-.4169E+02
360.00	-.1227E+04	-.1051E+04	-.4712E+02	-.4712E+02
390.00	-.1243E+04	-.1070E+04	-.5268E+02	-.5268E+02

Figure E-13. (continued).

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Figure E-14. Observation well locations, production well location, and "image" well location for Sample Problem 4.

VERIFICATION OF ANISOTROPY-RUN TO COMPARE WITH BOUNDARY							
6.895 E+03	6.310E-05	3.6E+03	.3048	1.0	E-03	9.862E-16	
150000.	1000.	.002	0.	0.	0.	0.	
OBS 1	500.	0.	0.	0	0.		
OBS 2	-500.	0.	0.				
OBS 3	000.	500.					
OBS 4	000.	-500.					
PROD 1	0.	0.		2			
0.	1000.						
5000.	1000.						
PROD 2	2000.	0.		2			
0.	1000.						
5000.	1000.						
1.	2.	3.	4.	5.	6.	7.	9.
10.	20.	30.	40.	50.	60.	70.	80.
100.	101.	102.	103.	104.	105.	106.	107.
109.	110.	120.	130.	140.	150.	160.	170.
180.	200.	201.	202.	203.	204.	205.	206.
207.	208.	209.	210.	220.	230.	240.	250.
260.	270.	280.	300.	320.	340.	360.	380.

Figure E-15. Input deck for Sample Problem 4.

VERIFICATION OF ANISOTROPY-RUN TO COMPARE WITH BOUNDARY

NUMBER OF OBSERVATION WELLS 4
NUMBER OF PRODUCTION WELLS 2
NUMBER OF TIMES AT WHICH PRESSURES WILL BE CALCULATED 56

CONVERSION FACTORS =====

PRESSURE UNIT PER PASCAL .6895E+04
FLOWRATE UNIT PER CUBIC METER PER SECOND .6310E-04
TIME UNIT PER SECOND 3600.00
LENGTH PER METER .30
VISCOSITY PER PASCAL-SECOND .100E-02
PERMEABILITY PER SQUARE METER .9862E-15

PARAMETER VALUES =====

X-AXIS TRANSMISSIVITY = .1500E+06
Y-AXIS TRANSMISSIVITY = .1000E+04
STORATIVITY = .2000E-02

OBSERVATION WELL NUMBER 1
WELL OBS 1 COORDINATES (500.00, 0.)
INITIAL PRESSURE=0.

Figure E-16. Output for Sample Problem 4.

OBSERVATION WELL NUMBER 2
 WELL OBS 2 COORDINATES (-500.00, 0.)
 INITIAL PRESSURE=0.

OBSERVATION WELL NUMBER 3
 WELL OBS 3 COORDINATES (0. , 500.00)
 INITIAL PRESSURE=-.0

OBSERVATION WELL NUMBER 4
 WELL OBS 4 COORDINATES (0. , -500.00)
 INITIAL PRESSURE=-.0

PRODUCTION WELL NUMBER 1
 PROD 1 COORDINATES (0. , 0.)
 NUMBER OF FLOWRATE POINTS= 2

TIME	FLOWRATE
0.	.1000E+04
.5000E+04	.1000E+04

PRODUCTION WELL NUMBER 2
 PROD 2 COORDINATES (2000.00, 0.)
 NUMBER OF FLOWRATE POINTS= 2

TIME	FLOWRATE
0.	.1000E+04
.5000E+04	.1000E+04

DISTANCES BETWEEN OBSERVATION WELLS AND PRODUCTION WELLS

	OBS 1	OBS 2	OBS 3	OBS 4
PROD 1	500.00	500.00	500.00	500.00
PROD 2	1500.00	2500.00	2061.55	2061.55

Figure E-16. (continued).

TIME	OBS 1	OBS 2	OBS 3	OBS 4
1.00	-.2101E+01	-.2101E+01	-.3917-206	-.3917-206
2.00	-.1755E+02	-.1755E+02	-.8058-103	-.8058-103
3.00	-.3966E+02	-.3966E+02	-.2625E-68	-.2625E-68
4.00	-.6249E+02	-.6249E+02	-.5152E-51	-.5152E-51
5.00	-.8424E+02	-.8424E+02	-.1286E-40	-.1286E-40
6.00	-.1045E+03	-.1045E+03	-.1135E-33	-.1135E-33
7.00	-.1232E+03	-.1232E+03	-.1063E-28	-.1063E-28
9.00	-.1566E+03	-.1566E+03	-.4727E-22	-.4727E-22
10.00	-.1715E+03	-.1715E+03	-.1020E-19	-.1020E-19
20.00	-.2807E+03	-.2807E+03	-.4004E-09	-.4004E-09
30.00	-.3512E+03	-.3512E+03	-.1601E-05	-.1601E-05
40.00	-.4031E+03	-.4031E+03	-.1092E-03	-.1092E-03
50.00	-.4442E+03	-.4442E+03	-.1440E-02	-.1440E-02
60.00	-.4783E+03	-.4783E+03	-.8268E-02	-.8268E-02
70.00	-.5073E+03	-.5073E+03	-.2939E-01	-.2939E-01
80.00	-.5326E+03	-.5326E+03	-.7720E-01	-.7720E-01
100.00	-.5752E+03	-.5752E+03	-.3071E+00	-.3071E+00
101.00	-.5771E+03	-.5771E+03	-.3246E+00	-.3246E+00
102.00	-.5790E+03	-.5790E+03	-.3428E+00	-.3428E+00
103.00	-.5809E+03	-.5809E+03	-.3617E+00	-.3617E+00
104.00	-.5828E+03	-.5828E+03	-.3812E+00	-.3812E+00
105.00	-.5846E+03	-.5846E+03	-.4014E+00	-.4014E+00
106.00	-.5864E+03	-.5864E+03	-.4223E+00	-.4223E+00
107.00	-.5882E+03	-.5882E+03	-.4439E+00	-.4439E+00
109.00	-.5918E+03	-.5918E+03	-.4893E+00	-.4893E+00
110.00	-.5935E+03	-.5935E+03	-.5130E+00	-.5130E+00
120.00	-.6103E+03	-.6103E+03	-.7912E+00	-.7912E+00
130.00	-.6257E+03	-.6257E+03	-.1147E+01	-.1147E+01
140.00	-.6400E+03	-.6400E+03	-.1583E+01	-.1583E+01
150.00	-.6534E+03	-.6534E+03	-.2101E+01	-.2101E+01
160.00	-.6659E+03	-.6659E+03	-.2699E+01	-.2699E+01
170.00	-.6777E+03	-.6777E+03	-.3375E+01	-.3375E+01
180.00	-.6888E+03	-.6888E+03	-.4126E+01	-.4126E+01
200.00	-.7093E+03	-.7093E+03	-.5840E+01	-.5840E+01
201.00	-.7102E+03	-.7102E+03	-.5932E+01	-.5932E+01
202.00	-.7112E+03	-.7112E+03	-.6026E+01	-.6026E+01
203.00	-.7122E+03	-.7122E+03	-.6119E+01	-.6119E+01
204.00	-.7131E+03	-.7131E+03	-.6214E+01	-.6214E+01
205.00	-.7141E+03	-.7141E+03	-.6309E+01	-.6309E+01
206.00	-.7150E+03	-.7150E+03	-.6405E+01	-.6405E+01

Figure E-16. (continued).

TIME	OBS 1	OBS 2	OBS 3	OBS 4
207.00	-.1021E+04	-.8611E+03	-.1120E+02	-.1120E+02
208.00	-.1022E+04	-.8627E+03	-.1137E+02	-.1137E+02
209.00	-.1024E+04	-.8642E+03	-.1155E+02	-.1155E+02
210.00	-.1026E+04	-.8658E+03	-.1172E+02	-.1172E+02
220.00	-.1043E+04	-.8813E+03	-.1354E+02	-.1354E+02
230.00	-.1059E+04	-.8961E+03	-.1546E+02	-.1546E+02
240.00	-.1075E+04	-.9104E+03	-.1747E+02	-.1747E+02
250.00	-.1090E+04	-.9243E+03	-.1959E+02	-.1959E+02
260.00	-.1105E+04	-.9376E+03	-.2178E+02	-.2178E+02
270.00	-.1119E+04	-.9505E+03	-.2406E+02	-.2406E+02
280.00	-.1133E+04	-.9630E+03	-.2641E+02	-.2641E+02
300.00	-.1158E+04	-.9869E+03	-.3129E+02	-.3129E+02
320.00	-.1183E+04	-.1009E+04	-.3640E+02	-.3640E+02
340.00	-.1206E+04	-.1031E+04	-.4169E+02	-.4169E+02
360.00	-.1227E+04	-.1051E+04	-.4712E+02	-.4712E+02
380.00	-.1248E+04	-.1070E+04	-.5268E+02	-.5268E+02

Figure E-16. (continued).

```

**PROGRAM VARFLOW(INPUT,OUTPUT,TAPE1,TAPE2)**
1. 0000008 PROGRAM VARFLOW(INPUT,OUTPUT,TAPE1,TAPE2)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C THIS PROGRAM CALCULATES DRAWDOWN IN AN ANISOTROPIC,HOMOGENEOUS,
C CONSTANT THICKNESS POROUS MEDIUM. THERE CAN BE UP TO 10
C PRODUCTION WELLS AND TEN OBSERVATION WELLS. FLOWRATES
C CAN BE VARIABLE. THE PROGRAM CAN ALSO INCLUDE DRAWDOWN DUE TO
C SKIN EFFECTS AND A SINGLE LINEAR RESERVOIR BOUNDARY (BARRIER
C OR CONSTANT POTENTIAL).
C
2. 0022058 DIMENSION X(3),TITLE(8),YSTART(10),LOBS(10),KKJ(10),ROY(10),
SSKIN(10),KT(10,10),TIMEST(100),RIZT(10,10),UX(10),UYT(10),ROXT(10),
SPX(10),PY(10),AQ(100,10),TQ(100,10),BQ(100,10),YCALC(100,10)
S,NAME(10),PRNAME(10),RFX(10),RPV(10),RFX(10),RPV(10)
3. 0022058 COMMON /SUB/ PI
4. 0022058 DATA ((KKJ(J),J=1,10),L)/11*0/
5. 0022058 DATA (PI,PAPRESS,CMSFLOW,SECTIME,RLENGTH,SMPERM,PASVISC)
173.141592654,6*1.0/
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C READ IN ALL OF THE PROBLEM PARAMETERS AND FLOW RATE DATA
C PRINT OUT ALL OF THE ABOVE
6. 0022058
7. 0022058 READ 100,(TITLE(I),I=1,8)
8. 0130128 100 FORMAT(8A10)
9. 0130128 PRINT 200,(TITLE(I),I=1,8)
10. 0130218 200 FORMAT(1H1,2X,8A10)
11. 0130218 READ 101,INH,JJ,IOIMEN,NTIMES
12. 0130308 101 FORMAT(4I10)
13. 0130308 PRINT 201,INH,JJ,NTIMES
14. 0130368 201 FORMAT(//,* NUMBER OF OBSERVATION WELLS*,I10,
$/,* NUMBER OF PRODUCTION WELLS *,I10,
$/,* NUMBER OF TIMES AT WHICH PRESSURES WILL BE CALCULATED*,I10)
15. 0130368 IF(IOIMEN .EQ. 0)GO TO 10
16. 0130378 READ 102,PAPRESS,CMSFLOW,SECTIME,RLENGTH,PASVISC,SMPERM
17. 0130508 102 FORMAT(6E10.4)
18. 0130508 10 PRINT 202,PAPRESS,CMSFLOW,SECTIME,RLENGTH,PASVISC,SMPERM
19. 0130618 202 FORMAT(//,20X,*CONVERSION FACTORS*,/,20X,18(1H=),/,
$/,*PRESSURE UNIT PER PASCAL*,Z1X,E10.4,/,10X,
$/,*FLOWRATE UNIT PER CUBIC METER PER SECOND*,5XE10.4,/,10X,
$/,*TIME UNIT PER SECOND*,25XF10.2,/,10X,*LENGTH PER METER*,29XF10.2,
$/,*VISCOSITY PER PASCAL-SECOND*,18XE10.3,/,10X,
$/,*PERMEABILITY PER SQUARE METER*,16XE10.4)

```

Figure E-17. VARFLOW Program sample.

Figure E-17. (continued).

```

VARFLOW      **PROGRAM VARFLOW(INPUT,OUTPUT,TAPE1,TAPE2)**

71. 0134608 CALL RKHUNF(RKHUX,RKHUY,OX(IH),OY(IH),PX(J),PY(J),RKHUN)
72. 0134678 RKHUN=X(1)*RKHUE/RKHUN
73. 0134718 X(2)=RT(IH,J)*XT(IH,J)*(LENGTH**3.)*PI*PCH*RKHUN/CMSFLOW/SECTIME
74. 0135028 IF( BOUND .EQ. 10H )GO TO 50
75. 0135058 RPX(J)=PX(J)*SIN(ALPHA)+PY(J)*COS(ALPHA)
76. 0135158 RPY(J)=PY(J)*SIN(ALPHA)-PX(J)*COS(ALPHA)
77. 0135258 RIPY(J)=RPY(J)
78. 0135268 RIPX(J)=2.*DISTNCE-RPX(J)

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C CALCULATE THE DISTANCE BETWEEN THE IMAGE WELLS AND THE OBSERVATION
C WELLS
79. 0135308 RIZ(IH,J)=(ROX(IH)-RIPX(J))**2. + (ROY(IH)-RIPY(J))**2.
80. 0135368 CALL COURT(RIPXT(J),RIPYT(J),XI,YI,ANGLE)
81. 0135448 CALL RKHUNF(RKHUX,RKHUY,OX(IH),OY(IH),XI,YI,RKHUN)
82. 0135508 RKHUN=X(1)*RKHUE/RKHUN
83. 0135528 X(3)=RIZ(IH,J)*(LENGTH**3.)*PI*PCH*RKHUN/CMSFLOW/SECTIME
84. 0135618 NNW=3
85. 0135628 50 IF(BOUND .EQ. 10H )NNW=2

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C MAIN CALCULATION LOOP
86. 0135668 TR=TIMES(N)
87. 0135678 FII=0.
88. 0135708 DO 1100 I=2,NNW
89. 0135728 FI=0.0
90. 0135728 DO 1110 KJ=1,KKJ(J)-1
91. 0135778 IF(ABSTTQ(KJ+1,J)-TQ(KJ,J)).LT.T.E-5) GO TO 1110
92. 0136068 TN=TR-TQ(KJ,J)
93. 0136138 TNI=TR-TQ(KJ+1,J)
94. 0136168 IF(TNI.LE.0.) GO TO 1100
95. 0136218 IF(TNI.LE.0.0) GO TO 80
96. 0136238 FI=(AO(KJ,J)+BO(KJ,J)*(TN+X(1)))*(EI(-X(1),TNI)-EI(-X(1),TN))
S=BO(KJ,J)*TN*EXP(-X(1)/TNI)-TNI*EXP(-X(1)/TNI)*FI
97. 0136648 1110 CONTINUE
98. 0136678 GO TO 90
99. 0136708 80 FI=(AO(KJ,J)+BO(KJ,J)*(TN+X(1)))*(EI(-X(1),TN)
A=BO(KJ,J)*TN*EXP(-X(1)/TNI)*FI
IF(L.EQ.1.AND.I.GT.2)FI=-FI
100. 0137148 90 FI=FI+FI
101. 0137238 1100 FI=FI+FI
102. 0137278 IF(L085(IH).NE.J) GO TO 70
103. 0137318 FI=FI+2.*SKIN(IH)*(AO(KJ,J)+BO(KJ,J)*TNI)
104. 0137428 70 F=FI*X(1)
105. 0137448 2000 YCALC(IH)=YCALC(IH)+F
106. 0137528 2002 CONTINUE
107. 0137548 2001 CONTINUE

C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C PRINT OUT RESULTS OF THE CALCULATION
108. 0137578 PRINT 118,(NAME(I),I=1,IHH)
109. 0137708 N=0
110. 0137708 IN=0
111. 0137708 DO 1120 I=1,NTIMES
112. 0137738 PRINT 119,TIMES(I),(YCALC(I,IH),IH=1,IHH)
113. 0140128 N=N+1
114. 0140138 IF(N .NE. 5)GO TO 1120
115. 0140148 PRINT 120
116. 0140208 IN=IN+1
117. 0140218 N=0
118. 0140218 IF(IN .NE. 8)GO TO 1120
119. 0140238 PRINT 118,(NAME(M),M=1,IHH)
120. 0140348 IN=0
121. 0140348 1120 CONTINUE
122. 0140378 118 FORMAT(1H1,/,5X,* TIME *,10(A10,2X),/,5X,130(1H=),/)
123. 0140378 119 FORMAT(3X,F10.2,2X,10(E10.4,2X))
124. 0140378 120 FORMAT(/)
125. 0140378 STOP
126. 0140408 END

EI          **FUNCTION EI(X,T)**

1. 0000008 FUNCTION EI(X,T)
2. 0000008 A=-X/T

```

Figure E-17. (continued).


```

VARFLOW      **PROGRAM VARFLOW(INPUT,OUTPUT,TAPE1,TAPE2)**
3.  0000028      IF(A.GT.10.0) GO TO 20
4.  0000058      ET=-ALOG(A)-.5772156649
5.  0000108      TERM=1.0
6.  0000118      DO 10 J=1,100
7.  0000148      TERM=-TERM*A/J
8.  0000168      ET=ET-TERM/J
9.  0000218      IF(ABS(TERM/J/ET).LT.1.E-8) GO TO 12
10. 0000218      10 CONTINUE
11. 0000308      12 ET=-ET
12. 0000328      RETURN
13. 0000348      20 ET=-EXP(-A)/A*(1.0-1.0/A+2.0/A**2-6.0/A**3)
14. 0000468      RETURN
15. 0000518      END

RKHUNF      **SUBROUTINE RKHUNF(RKHUX,RKHUY,OXD,OYD,PXD,PYD,RKHUN)**
1.  0000008      SUBROUTINE RKHUNF(RKHUX,RKHUY,OXD,OYD,PXD,PYD,RKHUN)
2.  0000008      COMMON /SUB/ PI
3.  0000008      YD=OYD-PYD
4.  0000018      XD=OXD-PXD
5.  0000038      THETA=ATAN2(YD,XD)
6.  0000068      PRINT 99,THETA
7.  0000138      99 FORMAT(5X,*THETA=*,F10.2)
8.  0000138      RKHUN=RKHUX/((COS(THETA)**2.) + RKHUX*(SIN(THETA)**2.)/RKHUY)
9.  0000248      PRINT 100,RKHUN
10. 0000318      100 FORMAT(5X,*RKHUN=*,F10.2)
11. 0000318      RETURN
12. 0000338      END

COORD      **SUBROUTINE COORD(RIPXD,RIPYD,XI,YI,ANGLE)**
1.  0000008      SUBROUTINE COORD(RIPXD,RIPYD,XI,YI,ANGLE)
2.  0000008      COMMON /SUB/ PI
3.  0000008      ANG=90.-ANGLE
4.  0000018      ANG=ANG*PI/180.
5.  0000038      XI=RIPXD*COS(ANG)+RIPYD*SIN(ANG)
6.  0000128      YI=RIPYD*COS(ANG)-RIPXD*SIN(ANG)
7.  0000218      RETURN
8.  0000248      END

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Figure E-17. (continued).

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REFERENCES

- E-1. H. S. Carslaw, and J. C. Jaeger, Conduction of Heat in Solids, Oxford: Clarendon Press, pp. 258-262, 1959.
- E-2. D. G. McEdwards, Variable Rate Well Test Analysis (Ph.D Dissertation) Berkeley: University of California, 1979.
- E-3. D. G. McEdwards, and C. F. Tsang, "Variable Rate Well Testing Analysis," in Proceedings of the Invitational Well-Testing Symposium, LBL-7027, 1977.
- E-4. G. P. Kruseman and N. A. De Ridder, Analysis and Evaluation of Pumping Test Data, Ulageningen, The Netherlands: International Institute for Land Reclamation and Improvement, 1976.
- E-5. M. S. Hantush, "Drawdown Around Wells of Variable Discharge" Journal of Geophysical Research, 69, 29, 1964, pp. 4221-4235.
- E-6. R. C. Earlougher, Advances in Well Test Analysis, Society of Petroleum Engineers Monographs, 1977.

APPENDIX F
REFERENCE BIBLIOGRAPHY

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- D. W. Allman, D. Goldman, and W. L. Niemi, "Evaluation of Testing and Reservoir Parameters in Geothermal Wells at Raft River and Boise, Idaho," Geothermal Resources Council Annual Meeting, Reno, NV, September 24, 1979, p. 4.
- C. B. Ammann, "Case Histories of Analysis of Characteristics of Reservoir Rock from Drill-Stem Tests," Journal of Petroleum Technology, 12, 5, 1960, p. 27.
- K. E. Anderson, Water Well Handbook, St. Louis: Scholin Brothers Printing Corp., 1967.
- J. K. Applegate, P. R. Donaldson, D. L. Hinkley, and T. L. Wallace, "Borehole Geophysics Evaluation of the Raft River Geothermal Reservoir, Idaho," Geophysics, 42, 1, 1977, pp. 138-139.
- S. Arnorsson, "Application of the Silica Geothermometer in Low Temperature Hydrothermal Areas in Iceland," American Journal of Science 275, 1975, pp. 763-784.
- S. R. Aydelotte, Transient Well Testing in Two-Phase Geothermal Reservoirs, LBL NTIS PCA07/MFA01, March 1980, p. 148.
- R. Bentall, "Methods of Collecting and Interpreting Ground-Water Data," U.S. Geologic Survey Water Supply Paper, 1544-H, 1963, pp. 1-97.
- R. Bentall, "Shortcuts and Special Problems in Aquifer Tests," U.S. Geological Survey Water-Supply Paper 1545-C, 1963, p. C1-C117.
- H. C. Bixel, B. K. Larkin, and H. K. Van Poolen, "Effect of Linear Discontinuities, or Pressure Build-up and Drawdown Behavior," Journal of Petroleum Technology, August 1963, pp. 885-895.
- G. Bodvarsson, "Capacitative Perturbations in Well Interference Testing," Proceedings of the Fifth Workshop on Geothermal Reservoir Engineering, Stanford, California, December 12, 1979, pp. 85-90.
- G. Bodvarsson, "Mechanism of Reservoir Testing," Proceedings Fourth Workshop Geothermal Reservoir Engineering, Stanford, California, December 13, 1978, pp. 146-152.
- N. S. Boulton, "Analysis Data from Non-Equilibrium Pumping Tests Allowing for Delayed Yield from Storage," Proceedings of the Institution of Civil Engineers, London, Paper No. 6693, 26, 1963, pp. 469-478.
- C. A. Brook et al., "Hydrothermal Convection Systems with Reservoir Temperatures 90°C," U.S. Geological Survey Circular 790, 1978, pp. 18-85.

- D. H. Brownell et al., "Governing Equation for Geothermal Reservoirs," Water Resources, 13, 6, 1977, pp. 929-934.
- D. A. Campbell, "Hot Water vs. Dry Steam Reservoir Assessment," Geothermal Environment Seminar, 1978, Sacramento, California, May 9, 1978, pp. 118-138.
- H. S. Carslaw and J. C. Jaeger, Conduction of Heat in Solids, Oxford: Oxford at the Clarendon Press, 1959.
- B. Chen, Geothermal Reservoir and Well Test Analysis: A Literature Survey, University of Hawaii, NTIS PCA031 MFA01, 1974, p. 38.
- P. Cheng and K. H. Lau, The Effects of Steady State Withdrawal of Fluid in Geothermal Reservoirs, University of Hawaii, NTIS PCA03/MFA01, 1975, p. 31.
- C. Y. Chiang and C. R. Y. Chang, "Application of the Horner Method to the Estimation of Static Reservoir Temperature During Drilling Operations," Proceedings of Fifth Workshop on Geothermal Reservoir Engineering, Stanford, CA, December 12, 1979, pp. 367-372.
- R. N. Clayton and A. Steiner, "Oxygen Isotope Studies of the Geothermal System at Wairakei, New Zealand," Geochemica Cosmochimica Acta, 39, 1975, pp. 1179-1186.
- G. Cortecchi, "Oxygen Isotopic Ratios of Sulfate Ions-Water Pairs as a Possible Geothermometer," Geothermics 3, 1974, pp. 60-64.
- A. Desplan, J. Deschamps and M. Leleu, "Chemical Reactions Occurring During the Exploitation of Geothermal Well Doublet: Thermodynamic and Experimental Approach for the Case of the Dogger Reservoir in the Pairs Basin," First Seminar on Geothermal Energy, Brussels, Belgium, December 6, 1977, pp. 529-547.
- R. J. M. De Wiest, "On the Storage Coefficient and the Equations of Ground-Water Flow," Journal of Geophysical Research, 71, 4, 1966.
- A. Domenico, Concepts and Models in Groundwater Hydrology, New York: McGraw-Hill Book Company, Inc., 1972, p. 405.
- I. G. Donaldson, "Geothermal Reservoir Engineering Research in New Zealand," Proceedings Fourth Workshop Geothermal Reservoir Engineering, Stanford, California, December 13, 1978, pp. 36-41.
- M. H. Dorfman and R. W. Deller, "Well Design and Reservoir Research and Technology," Proceedings of Second Geopressured Geothermal Energy Conference, Volume I, Austin, Texas, February 23, 1976, pp. 19-23.
- R. C. Earllougher, Jr., K. M. Kersch, and H. J. Ramey, "Wellbore Effects in Injection Well Testing," Journal of Petroleum Technology, November 1973, pp. 1244-1250.

R. C. Earllougher, Jr. and K. M. Kersch, "Analysis of Short-time Transient Test Data by Type Curve Matching," Journal of Petroleum Technology, July 1974, pp. 793-800, Transactions, AIME, p. 257.

R. C. Earllougher, "Advances in Well Test Analysis," SPE Monograph Series, 5, 1977.

C. Economides, "Recent Development in Well Test Analysis in the Stanford Geothermal Program," Proceedings Fourth Workshop Geothermal Reservoir Engineering, Stanford, California, December 18, 1978, pp. 188-200.

M. J. Economides, "Shut-in and Flowing Button Hole Pressure Calculation for Geothermal Steam Wells," Proceedings of the Fifth Workshop on Geothermal Reservoir Engineering, Stanford, California, December 12, 1979, pp. 139-151.

R. O. Elemo, "Estimation of Stress-Sensitive Reservoirs' Initial Parameters by Use of the Conventional Well Test Methods," Fourth United States Gulf Coast Geopressured-Geothermal Energy Conference: Research and Development, Austin, Texas, October 29, 1979, pp. 960-971.

A. J. Ellis and N. A. J. Mahon, "National Hydrothermal Systems and Experimental Hot-Water/Rock Interactions," Geochemica et Cosmochimica Acta, 28, 1964, pp. 1323-1357.

G. Endo, "Numerical Model for Steam-Dominated Type Geothermal Reservoir," Third Meeting of the Japan Geothermal Energy Association, Tokyo, Japan, December 9, 1976, p. 2

Energy Research and Development Administration, "Geothermal Resource Assessment and Reservoir Engineering," DOE Workshop on Geothermal Resources Assessment and Reservoir Engineering, Larderello, Italy, September 12, 1977, p. 442.

J. G. Ferris, D. B. Knowles, R. H. Brown, and R. H. Stallman, "Theory of Aquifer Tests," U.S. Geological Survey Water-Supply Paper 1536-E, 1962, pp. 69-174.

R. O. Fournier, D. E. White, and A. H. Truesdell, "Geochemical Indicators of Subsurface Temperature-1, Basic Assumptions," U.S. Geological Survey Journal of Research, 2, 1974, pp. 259-262.

R. O. Fournier and A. H. Truesdell, "Geochemical Indicators of Subsurface Temperature-2. Estimation of Temperature and Fraction of Hot Water Mixed with Cold Water," U.S. Geological Survey Journal of Research, 2, 1974, pp. 263-269.

R. O. Fournier and A. H. Truesdell, "Geochemical Indicators of Subsurface Temperature Applied to Hot Spring Waters of Yellowstone National Park, Wyoming, U.S.A.," Geothermics 2, 1970, pp. 529-535.

R. O. Fournier and R. W. Potter II, "Magnesium Correction to the Na-K-Ca Chemical Geothermometer," Geochemica Cosmochimica Acta, 43, pp. 1543-1550.

- R. O. Fournier and J. J. Rowe, "Estimation of Underground Temperatures from the Silica Content of Water from Hot Springs and Wet-Steam Wells," American Journal of Science, 264, 1966, pp. 685-697.
- R. O. Fournier and A. H. Truesdell, "An Empirical Na-K-Ca Geothermometer for Natural Waters," Geochemica et Cosmochimica Acta, 37, 1973, pp. 1255-1275.
- R. O. Fournier, "Chemical Geothermometers and Mixing Models for Geothermal Systems," Geothermics, 5, 1977, pp. 41-50.
- S. K. Garg, "Pressure Transient Analysis for Two-Phase Geothermal Reservoirs," Geothermal Resources Council Meeting, Hilo, Hawaii, July 25, 1978, pp. 203-206.
- R. E. Glover, "Studies of Ground Water Movement," Bureau of Reclamation Technical Memorandum 657, Bureau of Reclamation, Denver, 1960.
- C. B. Goranson and R. C. Schroeder, "Site-Specific Geothermal Reservoir Engineering Activities," LBL Earth Sciences Division Annual Report 1978, NTIS PCAS12/MFA01, pp. 97-106.
- K. P. Goyal and D. R. Kassdy, "Fault Zone Controlled Charging of a Liquid-Dominated Geothermal Reservoir," Journal of Geophysics, 85, 84, pp. 1867-1875.
- "Geophysics and Ground Water, An Introduction--Part I; Applied Use of Geophysics--Part II," Water Well Journal, 25, 7,; 25, 8, 1971.
- K. E. Gray, "Approximating Well to Fault Distance From Pressure Build-up Tests," Journal of Petroleum Technology, July 1965, pp. 761-767.
- B. D. Gunter and B. C. Musgrave, "New Evidence on the Origin of Methane in Hydrothermal Gases," Geochemica Cosmochimica Acta, 35, 1971, pp. 113-118.
- M. S. Hantush, "Analysis of Data from Pumping Tests in Anisotropic Aquifers," Journal of Geophysical Research, 71, 2, January 15, 1966, pp. 421-425.
- M. S. Hantush, "Analysis of Data from Pumping Tests in Leaky Aquifers," Transactions of the American Geophysical Union, 37, December 1956, pp. 702-714.
- M. S. Hantush, "Hydraulics of Wells," Advances in Hydrosience, 1, 1964.
- S. Hirakawa, Y. Mizuishi, Y. Fujinaga, and K. Hida, "Geothermal Reservoir Modeling," Meeting of the Mining and Metallurgical Institute, Tokyo, Japan, March 30, 1976, p. 2.
- S. Hirakawa, "System Approach to Geothermal Field Development," Proceedings Fourth Workshop Geothermal Reservoir Engineering, Stanford, California, December 13, 1978, pp. 234-238.

J. R. Hoagland, "Applications of Solute Equilibrium Models to the Study of Geothermal Reservoirs," Geothermal Resources Council, San Diego, California, May 9, 1977, pp. 143-145.

W. A. Hobba, D. W. Fisher, F. J. Pearson Jr. and J. C. Chemerys, "Hydrology and Geochemistry of Thermal Springs of the Appalachians, II. Geochemistry," U.S. Geological Survey Paper, 1044-E, 1978.

R. N. Horne, D. O. Ogbe, K. Temeng and H. J. Ramey Jr., Geothermal Reservoir Engineering Computer Code Comparison and Validation Using the GEONZ Simulator Program, NTIS PCA04/MF A01, November 1980, p. 67.

D. R. Horner, "Pressure Build-up in Wells," Proceedings of the Third World Petroleum Congress, Leiden: E. J. Brill, 1951.

J. H. Howard, Geothermal Reservoir Engineering Management Program: Developmental in Fiscal 1979, NTIS PCA07/MFA01, August 1980, pp. 66-69.

M. K. Hubbert, The Theory of Ground-Water Motion and Related Papers, Hafner Publishing Co., 1969.

A. Hunsbedt, et al., "Laboratory Studies of Non-Isothermal Fluid Production from Fractured Geothermal Reservoirs," American Society Mechanical Engineering Paper No. 77-HT-53, 1977, pp. 1-8.

C. E. Jacob, "Drawdown Test to Determine the Effective Radius of an Artesian Well," Transactions of the ASCE, 112, 1947, pp. 1047-1070.

C. E. Jacob, "Flow of Groundwater: Engineering Hydraulics, New York: John Wiley and Sons, 1950, pp. 321-386.

C. E. Jacob, "Full Utilization of Groundwater Reservoirs," Transactions of the American Geophysical Union, 38, June 1957, p. 417.

C. E. Jacob and S. W. Lohman, "Nonsteady Flow to a Well of Constant Drawdown in an Extensive Aquifer," Transactions of the American Geophysical Union, 33, 4, August 1952, pp. 559-569.

C. E. Jacob, "On the Flow of Water in an Elastic Artesian Aquifer," Transactions of the American Geophysical Union, 21, part II, pp. 574-596.

W. C. Kettenacker, Two-Dimensional Simulation of the Raft River Geothermal Reservoir and Wells, INEL, NTIS PCA06/MFA01, 1977, p. 107.

W. S. Keys and L. M. MacCary, "Application of Borehole Geophysics to Water-Resources Investigations," U.S. Geological Survey Technical Water Resources Investigations, Book 2, Chapt. E1, 1971.

L. E. Klyen, "A Vessel for Collecting Subsurface Water Samples from Geothermal Drillholes," Geothermics, 2, 1973, pp. 57-60.

P. Kruger and H. J. Ramey, Jr., Geothermal Reservoir Engineering, Second Workshop Summaries, December 1-3, 1976, Stanford University, NTIS PCA16/MFA01, 1976, p. 352.

P. Kruger and H. J. Ramey, Jr. (eds), Proceedings Fourth Workshop Geothermal Reservoir Engineering, NTIS PCA15/MFA01, December 1978, p. 336.

P. Kruger and H. J. Ramey, Jr., Stimulation and Reservoir Engineering of Geothermal Resources First Annual Report, June 1, 1977-March 31, 1978, Stanford University, NTIS PCA04/MFA01, April 1978, p. 68.

J. F. Kunze and P. A. Witherspoon, "Energy Extraction and Reservoir Management of a Moderate Temperature Hydrothermal System," American Nuclear Society Topical Meeting on Energy and Mineral Recovery Research, Golden, CO, April 12, 1977, pp. 68-76.

R. B. Leonard, T. M. Brosten, and N. A. Midtlyng, "Selected Data from Thermal Springs Areas, Southwestern Montana," U.S. Geological Survey Open-File Report 78-438, 1978.

W. H. Li, "Interaction Between Well and Aquifer," Proceedings of the ASCE, 80, Separate No. 578, December 1954.

T. M. C. Li, J. W. Mercer, C. R. Faust, and R. J. Greenfield, "Simulation of Geothermal Reservoirs Including Changes in Porosity and Permeability Due to Silica-Water Reactions," Proceedings Fourth Workshop Geothermal Reservoir Engineering, Stanford, December 13, 1978, pp. 275-279.

M. J. Lippmann, C. F. Tsang, and P. A. Witherspoon, "Analysis of the Response of Geothermal Reservoirs Under Injection and Production Procedures," 47 Annual California Regional Meeting of the Society of Petroleum Engineers of AIME, Bakersfield, CA, April 13, 1977, p. 15.

R. M. Lloyd, "Oxygen Isotope Behavior in the Sulfate-Water System," Journal of Geophysical Research, 73, 1968, pp. 6099-6110.

R. Marconcini et al, "Modeling Vapor Dominated Geothermal Reservoirs," DOE Workshop on Geothermal Resources Assessment and Reservoir Engineering, Larderello, Italy, September 12, 1977, pp. 256-298.

R. H. Mariner, T. S. Presser, and W. C. Evans, "Chemical Characteristics of the Major Thermal Springs of Montana," U.S. Geological Survey Open-File Report 76-480, 1976, 31 pp.

R. H. Mariner and L. M. Willey, "Geochemistry of Thermal Waters in Long Valley, Mono County, California," Journal of Geophysical Research, 81, 1976, pp. 792-800.

R. H. Mariner, C. A. Brook, J. R. Swanson, and D. R. Mabey, "Selected Data for Hydrothermal Convection Systems in the United States with Estimated Temperatures 90°C," U.S. Geological Survey Open File Report 78-858, 1978.

C. S. Matthews and D. G. Russell, "Pressure Buildup and Flow Test in Wells," SPE Monograph Series, 1, 1967.

W. F. McKenzie and A. H. Truesdell, "Geothermal Reservoir Temperatures Estimated from the Oxygen Isotope Compositions of Dissolved Sulfate and Water from Hot Springs and Shallow Drillholes," Geothermics, 5, 1977, pp. 51-62.

T. Meider, "Geophysical Methods in Reservoir Engineering and Reservoir Management," Proceedings of the Third Annual Geothermal Conference and Workshop, Monterey, California, June 26, 1979, pp. 2.31-2.37.

D. E. Meinzer, "Large Springs in the United States," U.S. Geological Survey Water Supply Paper 557, 1927.

D. E. Meinzer, "Outline of Groundwater Hydrology," U.S. Geological Survey Water Supply Paper 494, 1923.

S. Mercado, "High Activity Hydrothermal Zones Detected by Nalk, Cerro Prieto, Mexico," Geothermics 2, 1970, pp. 1367-1376.

J. W. Mercer and C. R. Faust, Reservoir Engineering and Evaluation, USGS, NTIS PCA06/MFA01, April 1979, pp. 37-42.

"Methods and Techniques of Ground Water Investigations and Developments," UNESCO Water Resources Series, 33, 1967.

C. C. Miller, A. B. Dyes, and C. A. Hutchison, "The Estimation of Permeability and Reservoir Pressure from Bottomhole Pressure Build-up Characteristics," Transactions, AIME, 1950 pp. 91-105, 189.

F. G. Miller, H. Cinco, H. J. Ramey, Jr., F. Kucuk, "Reservoir Engineering Aspects of Fluid Recharge and Heat Transfer in Geothermal Reservoirs," Geothermal Resources Council Meeting, Hilo, Hawaii, July 25, 1978, pp. 449-452.

A. F. Moench, "Effect of Thermal Conduction Upon Pressure Drawdown and Buildup in Fissured, Vapor Dominated Geothermal Reservoirs," Proceedings Fourth Workshop Geothermal Reservoir Engineering, Stanford, December 13, 1978, pp. 112-117.

A. F. Moench and P. G. Atkinson, "Transient-Pressure Analysis in Geothermal Steam Reservoirs with an Immobile Vaporizing Liquid Phase," Geothermics, 7, 2-4, pp. 253-264.

W. G. Mook, J. C. Bommerson, and W. H. Staverman, "Carbon Isotope Fractionation Between Dissolved Bicarbonate and Gaseous Carbon Dioxide," Earth Planetary Science Letter, 22, 1974, pp. 169-176.

J. G. Morse, "Reservoir Engineering Study of a Portion of the Salton Sea Geothermal Field," Geothermal Resources Council Meeting, Hilo, Hawaii, July 25, 1978, pp. 471-474.

- T. D. Mueller and P. A. Witherspoon, "Pressure Interference Effects Within Reservoirs and Aquifers," Journal of Petroleum Technology, April 1975, pp. 471-474, AIME p. 234.
- M. Muskat, The Flow of Homogeneous Fluids Through Porous Media, New York: McGraw-Hill Book Company, 1937.
- M. Muskat, "Use of Data on the Build-up of Bottomhole Pressures," Transactions of AIME, 1937, pp. 123, 44-88.
- T. N. Narasimhan and P. A. Witherspoon, Reservoir Evaluation Tests on RRGE1 and RRGE2, Raft River Geothermal Project, Idaho, LBL NTIS PCA04/MFA01, 1977, p. 53.
- M. Nathenson, T. C. Urban, and W. H. Diment, "Approximate Solution for the Temperature Distribution Caused by Flow up a Fault and its Application to Temperatures Measured in a Drillhole at Raft River Geothermal Area, Cassia County, Idaho," Geothermal Resources Council Transactions, V. 3, 1979, pp. 477-480.
- M. Nathenson, "Summary of Section VII: Production Technology, Reservoir Engineering, and Field Management," Proceedings of the Second United Nations Symposium the Development and Use of Geothermal Resources, San Francisco, May 20, 1975, pp. XCVII-CI.
- A. S. Odeh and L. G. Jones, "Pressure Drawdown Analysis Variable Rate Case," Journal of Petroleum Technology, August 1965, pp. 960-964.
- T. Paces, "A Systematic Deviation from Na-K-Ca Geothermometer Below 75°C and above 10^{-4} ATM P_{CO_2} ," Geochemica et Cosmochimica Acta 39, 1975.
- F. J. Pearson Jr. and A. H. Truesdell, "Tritium in the Waters of Yellowstone National Park (Wyoming)," Short Papers of the Fourth International Conference of Geochronology, Cosmochronology, and Isotope Geology, Open-File Report 78-701, 1978, pp. 327-329.
- J. D. Pendergrass and V. J. Berry, Jr., "Pressure Transient Performance in a Multi-layered Reservoir with Cross-flow," Society of Petroleum Engineers Journal, December 1962, pp. 347-354.
- G. F. Pinder, State-of-the-Art Review of Geothermal Reservoir Modelling, LBL, NTIS, PCA08/MFA01, March 1979, p. 151.
- P. Polubarinova-Kochina, Theory of Groundwater Movement, Princeton: Princeton University Press, 1972.
- T. A. Prickett and C. G. Lonnquist, "Selected Digital Computer Techniques for Groundwater Resource Evaluation," Illinois State Water Survey, Urbana, Bulletin 55, 1971, p. 62.

K. Pruess and R. C. Schroeder, "Basic Theory and Equations Used in the Two Phase Multi-Dimensional Geothermal Reservoir Simulator, Geothermal Resources Council Annual Meeting, Reno, Nevada, September 24, 1979, p. 5.

R. Raghavan, G. V. Cady, and H. J. Ramey, Jr., "Well Test Analysis for Vertically Fractured Wells," Journal of Petroleum Technology, August 1972, pp. 1014-1020; Transactions, AIME, p. 253.

H. J. Ramey, Jr., "Interference Analysis for Anisotropic Formations--A Case History" Journal of Petroleum Technology, October 1975, pp. 1290-1298, Transactions AIME, p. 259.

H. J. Ramey, Jr., "Short-Time Well Test Data Interpretation in Presence of Skin Effect and Wellbore Storage" Journal of Petroleum Technology, January 1970, Transactions AIME, p. 249.

H. J. Ramey, Jr., "Commercialization of Geothermal Resources," Conference on Commercialization of Geothermal Resources, San Diego, California, November 28, 1978, pp. 15-17.

H. J. Ramey Jr. and P. Kruger (eds), Proceedings of Fifth Workshop on Geothermal Reservoir Engineering, December 12-14, 1979, NTIS PCA17/MFA01, December 1979, pp. 261-267.

H. J. Ramey Jr., and A. L. London, Stimulation and Reservoir Engineering of Geothermal Resources, Stanford University Geothermal Program Report No. 4, NTIS PCA05/MFA01, August 1975, p. 78.

G. S. Randall and R. F. Harrison, "Annotated Research Bibliography for Geothermal Reservoir Engineering," Proceedings Fourth Workshop Geothermal Reservoir Engineering, Stanford, California, December 13, 1978, pp. 272-274.

R. C. Reda, "Influence of Steam/Water Relative Permeability Models on Predicted Geothermal Reservoir Performance: A Sensitivity Study," Sixth Annual Workshop on Geothermal Reservoir Engineering, Stanford, California December 16, 1980, p. 7.

Republic Geothermal et al., Raft River Well Stimulation Experiments: Geothermal Reservoir Well Stimulation Program, NTIS PCA08/MFA01, August 1980, p. 158.

L. F. Rice, Pressure Drawdown and Buildup Analyses in Geothermal Reservoirs, Science and Software Systems, 1976, p. 24.

C. T. Rightmire, H. W. Young, and R. L. Whitehead, "Geothermal Investigations in Idaho, IV. Isotropic and Geochemical Analyses of Water from the Bruneau-Grand View and Weiser Areas, Southwest Idaho," Idaho Dep. Water Admin., Water Information Bulletin, 30, 1976.

R. J. Rivera, "Decline Curve Analysis--A Useful Reservoir Engineering Tool for Predicting the Performance of Geothermal Wells," Geothermal Resources Council, San Diego, California, May 9, 1977, pp. 257-259.

- M. I. Rorabaugh, "Graphic and Theoretical Analysis of Step-Drawdown Tests of Artesian Wells," Proceedings of the ASCE, 79, 362, September 1953.
- D. G. Russell and N. E. Truitt, "Transient Pressure Behavior in Vertically Fractured Reservoirs," Journal of Petroleum Technology, October 1964, pp. 1159-1170.
- H. Sakai, "Sulfate-Water Isotope Thermometry Applied to Geothermal Systems," Geothermics, 5, 1977, pp. 67-74.
- M. Saltuklaroglu, "Interference Effect of Producing Wells on Observation Wells in a Geothermal Field," Proceedings of the Fifth Workshop on Geothermal Reservoir Engineering Stanford, California, December 12, 1979, pp. 49-59.
- G. Sandquist, S. Swanson, R. Stoker, and J. Kunze, "Evaluating the Energy Capacity and Lifetime of Fracture Dominated Geothermal Reservoirs," 12th Intersociety Energy Conversion Engineering Conference, Washington, D.C., August 28, 1977, pp. 804-809.
- S. K. Sanyal, H. J. Ramey Jr., and H. T. Meidav, "Geothermal Reservoir Assessment Techniques Manual," EPRI Annual Geothermal Program, January 1978, pp. 2.85-2.90.
- C. R. Scherer, Geothermal Reservoir Management, University of California, Berkeley, NTIS PCA10/MFA01, 1978, p. 203.
- R. Schneider, "An Application of Thermometry to the Study of Ground Water," U.S. Geological Survey Water Supply Paper 1544-B, 1962.
- R. J. Schicht, "Selected Methods of Aquifer Test Analysis," Water Resources Bulletin, 8, 1, February 1972, pp. 175-187.
- C. S. Slichter, "Field Measurements of Rate of Movement of Underground Water," U.S. Geological Survey Water Supply Paper 140, 1905.
- C. S. Slichter, "Theoretical Investigation of the Motion of Ground Waters: Washington, D.C.," U.S. Geological Survey Nineteenth Annual Report, Part 2, 1899, pp. 295-384.
- G. A. Sudol, R. F. Harrison, and H. J. Ramey Jr., "Annotated Research Bibliography for Geothermal Reservoir Engineering," NTIS PCA08/MFA01, August 1979, p. 155.
- W. K. Summers, The Annotated Indexed Bibliography of Geothermal Phenomena, Socorro: New Mexico Institute of Mining and Technology, 1971.
- P. K. Takahashi, B. H. Chen, K. I. Mashima, and A. S. Seki, "State-of-the-Art of Geothermal Reservoir Engineering," Proceedings of American Society of Civil Engineers, 101, 1, July 1975, pp. 11-126.

C. V. Theis, "Relation Between the Lowering of the Piezometer Surface on the Rate and Duration of Discharge of a Well Using Ground Water Storage," Transactions of the American Geophysical Union, 16, 1935, pp. 519-524.

D. K. Todd, Ground Water Hydrology, New York: John Wiley and Sons, 1960.

C. F. Tolman, Ground Water, New York: McGraw-Hill Book Company, Inc., 1957 pp. 341-346.

C. F. Tsang, M. J. Lippman and P. A. Witherspoon, "Production and ReInjection in Geothermal Reservoirs," Geothermal: State of the Art, 1977, pp. 301-303.

F. VanderLeeden, Ground Water, A Selected Bibliography, New York: Water Information Center, 1971.

A. F. van Everdingen, "The Skin Effect and its Influence on the Productive Capacity of a Well," Transactions of AIME, 1953.

A. F. van Everdingen and W. Hurst, "The Application of the Laplace Transformation to Flow Problems in Reservoirs," Transactions of AIME, 1949, pp. 186, 305-324.

D. J. Vetter, "Tritium Tracer as a Means for Reservoir Verification in Geothermal Reservoirs," EPRI Annual Geothermal Program, California, January 1978, pp. 4.17-4.23.

W. C. Walton, Groundwater Resource Evaluation, New York: McGraw-Hill Book Company, Inc., 1970, p. 194.

W. C. Walton, "Selected Analytical Methods for Well and Aquifer Evaluation," Illinois State Water Survey, Department of Regulation and Education Bulletin No. 49, Urbana, 1962.

S. H. Ward, Program Review: Resource Evaluation, Reservoir Confirmation, and Exploration Technology, NTIS PCA09/MFA01, May 1978, p. 182.

J. E. Warren and P. J. Root, "The Behavior of Naturally Fractured Reservoirs" Society of Petroleum Engineers Journal, September 1963, pp. 245-255.

"Well Logging in Ground Water Hydrology," Ground Water, 6, 1, 1968, pp. 10-18.

D. Weres, "Dynamics of Steam Producing Geothermal Reservoirs," Geothermal Environmental Seminar, 1978, Sacramento, California, May 9, 1978, pp. 189-195.

P. W. Werner, "Notes on Flow-Time Effects in the Great Artesian Aquifers of the Earth;" Transactions of the American Geophysical Union, 27, October 1946.

N. D. White, "Annual Report on Ground Water in Arizona," Water Resources Report, 24, 1964-1965.

P. A. Witherspoon, T. N. Narasimhan, and D. G. McEdwards, "Results of Interference Tests from Two Geothermal Reservoirs," Journal of Petroleum Engineering, 30, January 1978, pp. 10-16.