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GEOTHERMAL RESERVOIR ENGINEERING COMPUTER CODE COMPARISON
AND VALIDATION USING THE GEONZ SIMULATOR PROGRAM

by

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1.0 INTRODUCTION AND SUMMARY

The Stanford approach to the geothermal simulator code comparison project was that of a user working with a program authored by another group. It was originally proposed to use the Zyvoloski and O'Sullivan GEOTHERM geothermal simulator program to prepare solutions to the first five of the six Department of Energy computer code comparison sets. Valid solutions were anticipated in all of the five problems attempted, but it was expected that problems 3 and 4 might present some difficulties--problem 3 because it might produce superheated conditions beyond the range of the program's thermodynamics subroutines, and problem 4 because it might produce counterflows of steam and water which would be problematical in view of the program's method of assigning an "upstream" node.

In fact, a more recent version of the program, called GEONZ (by Zyvoloski, Blakely, and O'Sullivan), became available to us during the contract period, and was used successfully on problems 3 and 4. The new program, GEONZ, had additional capabilities that enabled it to handle both superheated steam and counterflows of steam and water.

Some delays had been anticipated in the installation of the program, and in familiarization of the contractors with its use. In the actual event, installation was accomplished in a very short period of time, but familiarization took somewhat longer. There was some additional delay with the arrival of the updated program GEONZ; however, the familiarization difficulties were finally overcome either by in-depth examination of the source code or, in many cases, consultation with its authors.

In general, the GEONZ should be classified as a laboratory code, although it lacks only a very few conveniences to align it with commercial simulators. The necessity of entering the code to program each of the problems was a time-consuming task, and the major source of errors during the contract. There were also some additional pitfalls of data entry that could be avoided with some data checking by the program or possibly by some more extensive output stating more clearly the implications of some of the "flags" which had been set or unset. In spite of these vagaries, the GEONZ code was impressively rapid in its operation, and the high efficiency of its computation algorithms reduced the actual computer costs to one-third of those budgeted. Unfortunately, this saving in cost was absorbed by the additional human labor costs necessary to overcome the programming difficulties within the contract period. In brief, it cost us very much more in human cost than in computer cost to solve the problem set. With commercialization of the program, we anticipate that the two costs would become about equal.

In the following sections, the choice of the GEONZ code is discussed, followed by an in-depth description of the solutions obtained for problems 1 through 5. The problem statements are included as Appendix A of this report.

2.0 SELECTION OF THE GEONZ COMPUTER CODE

As a program user, the criteria for selection of a computer code were necessarily different from those of a program author making a choice between codes of his own authorship. The primary criteria were the same--that the program should be capable of performing the required tasks accurately and efficiently. However, equally important to the user, he must be able to

make the program perform those tasks. The program therefore had to be readily installed, well documented, and well supported.

Considering first the primary criteria of accuracy, applicability, and efficiency, it was determined that the major source of inaccuracy in geothermal reservoir simulators arose during calculations involving a change of phase. The difficulty here is that some properties of the reservoir fluid (for example, compressibility, density, viscosity) go through order-of-magnitude changes from one phase to the other. Since the basis of numerical methods is usually to consider finite changes in a difference approximation to the rate of change of these properties, the discontinuity of derivatives at the phase boundary is the major source of difficulty. Much of this difficulty may be overcome in the careful selection of the dependent variables. In the absence of noncondensable gases, the dependent variables may usually be reduced to two.

The two dependent variables used in the GEONZ program based on the work described by Zyvoloski, O'Sullivan, and Krol (1979), are mixture enthalpy and pressure. The advantage of the choice of these two dependent variables is that neither of them undergoes order-of-magnitude changes in gradient through phase changes. The pressure is in fact constant throughout a phase change. This choice of dependent variables was therefore considered to have advantages over alternatives used by other codes; for example, density and internal energy used in the S^3 model (Pritchett, Garg, Brownell, and Levine, 1975), and also in LBL's SHAFT (Pruess, 1978). The reservoir simulator of Faust and Mercer (1979) also uses the desirable combination of pressure and enthalpy, and could therefore be considered a candidate program, along with GEONZ, on the basis of expected success in two-phase calculations. Moving on to consideration of efficiency, it was determined that

the GEONZ code is computationally more streamlined than the Faust-Mercer program. Both use the Newton-Raphson method (see Zyvoloski, O'Sullivan, and Krol, 1979) to solve implicit nonlinear finite difference approximations to the governing equations. However, the computational procedures used in GEONZ are more compact since they involve the solution of small and sparse matrix equations. The use of the ADI method in GEONZ reduces the number of iterations in any particular area to that necessary to achieve local accuracy of the solution. The procedure used by Faust and Mercer (1979) requires global iteration. This is particularly important since typically local convergence is extremely fast except at a few points in the vicinity of a phase change. Since a substantial portion of the computation time is involved in function evaluation, the added computational overhead of the ADI scheme in reducing the number of function evaluations is extremely worthwhile. The GEONZ program was therefore found to be most acceptable under the primary criteria.

The secondary criteria of availability and ease of installation, use, and support highlighted two programs: GEONZ and SHAFT. Both were already implemented on facilities geographically close to the investigators, as were their support teams. Both had the added advantage that authors of the programs were readily accessible to the investigators. SHAFT has a greater degree of user orientation and support. On the other hand, one of the investigators in this project had a greater familiarity with GEONZ, having been associated with the research effort under which it was written (although not involved in the program itself).

A final consideration in the selection of GEONZ was specific to DOE's objective of ascertaining the validity of geothermal reservoir simulators. Although preferable under our technical criteria, GEONZ was probably not

as well known to the U.S. geothermal community, having been written overseas. It was funded by the New Zealand government under a contract through the New Zealand Energy Research and Development Committee, and is public property. Although newer on the scene and not as user oriented as some other codes, the more recent preparation of GEONZ permitted the avoidance of many of the disadvantages of codes produced somewhat earlier. The innovative and compact GEONZ program should certainly have contributed significantly to the demonstration of geothermal reservoir simulators.

3.0 RESULTS

The results of problems 1 through 5 of the Department of Energy geothermal simulator computer code comparison are given in Sections 3.1 through 3.5. respectively. Tables and diagrams are prefixed by problem number.

3.1 Problem No. 1: 1-D Avdonin Solution

This problem was solved using the mesh specified in the problem statement (see Appendix A). The time step size used was 4.175×10^6 secs, one quarter of that suggested. This size time step was necessary to achieve numerical stability.

The temperature versus radial distance at 10^9 sec is shown in Table 1.1 and in Fig. 1.1, and the temperature at radius 37.5 meters as a function of time is shown in Table 1.2 and in Fig. 1.2.

The properties of water at 165°C and 50 bars calculated by the program thermodynamics package are as follows:

specific heat	= 4.45 KJ/kg°C
kinetic viscosity	= 1.6362×10^{-4} N.s/m ²
density	= 906.596 kg/m ³

TABLE 1.1: PROBLEM 1, TEMPERATURE AT 10^9 SEC

Radius (m)	T(°C)
12.5	160.271
37.5	159.802
62.5	160.163
87.5	160.506
112.5	160.728
137.5	162.267
162.5	162.618
187.5	164.786
212.5	165.279
237.5	167.196
262.5	167.669
287.5	168.900
312.5	169.236
337.5	169.847
362.5	170.035
387.5	170.278
412.5	170.363
437.5	170.441
462.5	170.474
487.5	170.494
512.5	170.505
537.5	170.509
562.5	170.512
587.5	170.512
612.5	170.513
637.5	170.513
662.5	170.514
687.5	170.513
712.5	170.514
737.5	170.514
762.5	170.514
787.5	170.513
812.5	170.513
837.5	170.513
862.5	170.513
887.5	170.513
912.5	170.513
937.5	170.513
962.5	170.513
987.5	170.513

FIG. 1.1: PROBLEM 1

TABLE 1.2: PROBLEM 1, TEMPERATURE AT 37.5 m AS A FUNCTION OF TIME

Time (Secs)	Temperature at 37.5 m
.835(10 ⁷)	169.746
.2505(10 ⁸)	167.482
.4175(10 ⁸)	165.346
.5845(10 ⁸)	163.672
.7515(10 ⁸)	162.439
.9185(10 ⁸)	161.614
.1753(10 ⁹)	160.262
.2588(10 ⁹)	160.123
.3340(10 ⁹)	160.224
.4258(10 ⁹)	160.094
.5093(10 ⁹)	160.012
.5928(10 ⁹)	159.642
.6763(10 ⁹)	159.820
.7598(10 ⁹)	159.962
.8433(10 ⁹)	160.030
.9268(10 ⁹)	160.192
.9435(10 ⁹)	160.076
.9602(10 ⁹)	160.019
.9769(10 ⁹)	159.978
.9936(10 ⁹)	159.916

FIG. 1.2: PROBLEM 1

TABLE 2.1: PROBLEM 2(a)

t/r^2 (Day/m ²)	$r = 0.5$ m		$r = 0.707$ m		$r = 1.0$ m	
	Press, P (MPa)	Flowing Enthalpy h , (MJ/kg)	Pressure (MPa)	Flowing Enthalpy (MJ/kg)	Pressure (MPa)	Flowing Enthalpy (MJ/kg)
0.00001	—	—	—	—	8.9271	1.1338
0.00002	—	—	8.8416	1.1337	8.8411	1.1337
0.00004	8.7142	1.1336	8.7542	1.1336	8.7675	1.1336
0.00008	8.6860	1.1335	8.6700	1.1335	8.6800	1.1335
0.00010	8.6072	1.1335	8.6524	1.1335	8.6499	1.1335
0.0002	8.5442	1.1334	8.5496	1.1334	8.5488	1.1334
0.0004	8.4533	1.1333	8.4513	1.1333	8.4523	1.1333
0.0008	8.3474	1.1332	9.3540	1.1332	8.3528	1.1332
0.0012	8.2936	1.1332	8.2956	1.1332	8.2939	1.1332
0.002	8.2200	1.1331	8.2213	1.1331	8.2195	1.1331
0.004	8.1171	1.1330	8.1199	1.1330	8.1183	1.1330
0.008	8.0161	1.1329	8.0180	1.1329	8.0170	1.1329
0.01	7.9850	1.1329	7.0952	1.1329	7.9843	1.1329
0.02	7.8823	1.1328	7.8831	1.1328	7.8822	1.1328
0.04	7.7810	1.1327	7.7802	1.1328	7.7809	1.1328
0.08	7.6790	1.1327	7.6789	1.1327	7.6795	1.1327
0.1	7.6461	1.1326	7.6463	1.1327	7.6468	1.1327
0.2	7.5451	1.1326	7.5448	1.1327	7.5451	1.1326
0.4	7.4435	1.1325	7.4437	1.1327	7.4434	1.1326
0.8	7.3416	1.1326	7.3421	1.1326	7.3414	1.1326
1.0	7.3092	1.1326	7.3093	1.1326	7.3091	1.1326
1.2	7.2822	1.1326	7.2826	1.1326	—	—
2.0	7.2073	1.1325	7.2077	1.1326	—	—
4.0	7.1056	1.1326	—	—	—	—

FIG. 2.1: PROBLEM 2(a)

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FIG. 2.2: PROBLEM 2(a)

3.2 Problem No. 2: 1-D Well Test Analysis

This problem proved to be the most time consuming of the five, due to the necessity of experimentation with time step size for each of the three problems. All output in this problem was graphed semilog for quick evaluation of Theis-type behavior.

The outer boundary condition (not specified in the problem statement) was taken to be at constant pressure and enthalpy equal to the initial pressure and enthalpy.

Case (a)

The time step sequence used was 10 steps of 10^{-5} days, followed by 100 each of 10^{-4} and 10^{-3} days with the remainder (up to 1 day) at 10^{-2} days.

The pressure and enthalpy as a function of t/r^2 (time/radius squared) are tabulated in Table 2.1 and graphed in Figs. 2.1 and 2.2. The pressures at radii 0.5, 0.707, and 1.0 meters radius (graphed in Fig. 2.1 as a function of t/r^2) are so close to each other as to be indistinguishable on the graph except at very early time. The graph shows the correct Theis semilog straight line behavior.

Case (b)

The two-phase mixture case proved to be the most difficult in terms of time step selection, and required more time steps than did cases a and c. The sequence was 10 steps of 10^{-5} days, followed by 20 steps each of 2×10^{-5} and 5×10^{-5} , followed by 10 of 10^{-4} days, 10 of 2.5×10^{-4} days, 30 of 5×10^{-4} days, 180 of 10^{-3} days, 100 of 1.25×10^{-3} days, and the remainder (up to 1 day) at 1.5×10^{-3} days. The largest time step was thus 1.5×10^{-3} days, compared to 0.01 days in Case a and 2×10^{-3} days in Case c.

The pressure, saturation, and flowing enthalpy at radii 0.5, 0.707, and 1.0 meters as a function of t/r^2 are shown in Table 2.2 and in Figs. 2.3, 2.4, and 2.5. There is good agreement between these results and those of Sorey, Grant, and Bradford (1980) for the same problem (see their Fig. 1).

Case (c)

The sequence of time steps taken was 10 steps at 10^{-5} days, 20 each of 2×10^{-5} and 5×10^{-5} days, 10 each of 10^{-4} and 2.5×10^{-4} days, 30 of 5×10^{-4} days, 180 of 10^{-3} , and the remainder (up to 1 day) of 2×10^{-3} days.

The pressure, saturation, and flowing enthalpy as a function of t/r^2 are tabulated in Table 2.3 and graphed in Figs. 2.6, 2.7, and 2.8.

Case (d): One-Node Problem

This solution was achieved using a single cylindrical grid block of radius 10 m and thickness 1 m. The pressure, saturation, and flowing enthalpy are tabulated in Table 2.4 and graphed in Fig. 2.9.

3.3 Problem No. 3: 2-D Flow in Fracture/Block Medium

This problem was solved using the nodal positions (block-centered) as specified in the problem statement. Setting up of the problem was somewhat complicated by the fact that the well radius is 0.16 m, which puts the well block boundary at the position calculated for the well block node using the geometric progression of block-centered node positions. This difficulty was overcome by overriding the coordinates calculated by the program, so that the well block node lay at 0.159 m radius and the well block boundary lay at 0.16 m. The second and later nodes lay at 0.4 m, 1.0 m, etc., in the normal manner. The single well block exterior to the main grid also required some circuitry in the source code which works on

TABLE 2.2: PROBLEM 2(b)

t/r^2 (Day/m ²)	$r = 0.5$ m			$r = 0.707$ m			$r = 1.0$ m		
	P, (MPa)	Saturation	h(MJ/Kg)	P	Saturation	h	P	Saturation	h
0.00001	—	—	—	—	—	—	3.0000	0.6500	1.3332
0.00002	—	—	—	3.00000	0.6500	1.3332	3.0000	0.6500	1.3332
0.00004	2.9988	0.6489	1.3333	2.9999	0.6499	1.3332	3.0000	0.6500	1.3332
0.00008	2.9977	0.6478	1.3334	2.9998	0.6498	1.3332	3.0000	0.6499	1.3332
0.00012	2.9965	0.6468	1.3337	2.9996	0.6496	1.3332	2.9999	0.6499	1.3332
0.0002	2.9942	0.6448	1.3347	2.9989	0.6489	1.3334	2.9997	0.6497	1.3332
0.0004	2.9886	0.6402	1.3387	2.9961	0.6464	1.3346	2.9983	0.6486	1.3337
0.0008	2.9776	0.6323	1.3522	2.9875	0.6395	1.3415	2.9915	0.6426	1.3379
0.0012	2.9669	0.6258	1.3708	2.9766	0.6322	1.3549	2.9805	0.6346	1.3489
0.002	2.9464	0.6158	1.4151	2.9526	0.6205	1.3972	2.9533	0.6205	1.3914
0.004	2.9003	0.6005	1.5175	2.8974	0.6055	1.5180	2.8930	0.6045	1.5238
0.008	2.8294	0.5876	1.6293	2.8223	0.5946	1.6374	2.8208	0.5949	1.6382
0.01	2.8028	0.5852	1.6616	2.7971	0.5924	1.6668	2.7968	0.5928	1.6657
0.02	2.7186	0.5826	1.7287	2.7189	0.5876	1.7252	2.7195	0.5878	1.7241
0.04	2.6377	0.5820	1.7593	2.7385	0.5843	1.7581	2.6387	0.5843	1.7582
0.08	2.5549	0.5806	1.7768	2.5551	0.5817	1.7769	2.5552	0.5816	1.7770
0.1	2.5279	0.5800	1.7810	2.5280	0.5809	1.7812	2.5280	0.5809	1.7813
0.2	2.4413	0.5783	1.7893	2.4413	0.5787	1.7894	2.4413	0.5787	1.7894
0.4	2.3522	0.5765	1.7937	2.3522	0.5767	1.7937	2.3522	0.5767	1.7938
0.8	2.2606	0.5746	1.7960	2.2606	0.5747	1.7960	2.2605	0.5747	1.7960
1.0	2.2300	0.5738	1.7978	2.2299	0.5739	1.7978	2.2300	0.5739	1.7978
1.2	2.2053	0.5734	1.7971	2.2054	0.5735	1.7971	—	—	—
2.0	2.1346	0.5718	1.7988	2.1347	0.5718	1.7988	—	—	—
4.0	2.0364	0.5696	1.7994	—	—	—	—	—	—

FIG. 2.3: PROBLEM 2(b)

FIG. 2.4: PROBLEM 2(b)

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FIG. 2.5: PROBLEM 2(b)

TABLE 2.3: PROBLEM 2(c)

t/r^2 (Day/m ²)	$r = 0.5$ m			$r = 0.707$ m			$r = 1.0$ m		
	P (MPa)	S	h (MJ/kg)	P	S	h	P	S	h
0.00001	—	—	—	—	—	—	8.9304	1.0	1.3408
0.00002	—	—	—	8.8486	1.0	1.3408	8.8482	1.0	1.3407
0.00004	8.7266	1.0	1.3407	8.7647	1.0	1.3407	8.7776	1.0	1.3407
0.00008	8.6992	1.0	1.3405	8.6840	1.0	1.3406	8.7127	1.0	1.3406
0.00012	8.6238	1.0	1.3406	8.6357	1.0	1.3406	8.6949	1.0	1.3406
0.00020	8.5633	1.0	1.3405	8.6245	1.0	1.3405	8.6791	1.0	1.3406
0.0004	8.5499	0.9995	1.3405	8.6150	1.0	1.3405	8.6612	1.0	1.3405
0.0008	8.5487	0.9972	1.3404	8.6038	1.0	1.3405	8.6437	1.0	1.3405
0.0012	8.5472	0.9942	1.3404	8.5965	1.0	1.3405	8.6315	1.0	1.3405
0.0020	8.5438	0.9876	1.3404	8.5857	1.0	1.3405	8.6119	1.0	1.3405
0.004	8.5344	0.9691	1.3404	8.5631	1.0	1.3404	8.5893	1.0	1.3405
0.008	8.5141	0.9292	1.3404	8.5432	0.9863	1.3404	8.5500	0.9997	1.3404
0.01	8.5037	0.9089	1.3404	8.5338	0.9677	1.3404	8.5448	0.9895	1.3404
0.02	8.4632	0.8346	1.3396	8.4803	0.8623	1.3401	8.4764	0.8560	1.3401
0.04	8.3235	0.7434	1.3405	8.2995	0.7606	1.3413	8.2955	0.7627	1.3418
0.08	7.9319	0.7147	1.3945	7.9363	0.7308	1.3914	7.9328	0.7299	1.3916
0.1	7.7845	0.7208	1.3981	7.7800	0.7308	1.3991	7.7759	0.7311	1.3995
0.2	7.3056	0.7126	1.4245	7.3037	0.7175	1.4235	7.3055	0.7180	1.4227
0.4	6.7808	0.7059	1.4327	6.7854	0.7072	1.4312	6.7876	0.7074	1.4307
0.8	6.2175	0.6969	1.4329	6.2208	0.6968	1.4323	6.2220	0.6969	1.4322
1.0	6.1449	0.6895	1.4394	6.1427	0.6911	1.4901	6.1416	0.6910	1.4404
1.2	5.6994	0.6671	1.5050	5.6973	0.6691	1.5051	—	—	—
2.0	5.4969	0.6768	1.4481	5.4951	0.6780	1.4485	—	—	—
4.0	4.7671	0.6631	1.4549	—	—	—	—	—	—

FIG. 2.6: PROBLEM 2(c)

FIG. 2.7: PROBLEM 2(c)

FIG. 2.8: PROBLEM 2(c)

TABLE 2.4: PROBLEM 2(d), ONE NODE CASE

Time, t (Days)	Pressure, P (MPa)	Saturation, S	Flowing Enthalpy h MJ/kg
.0001	2.9957	0.6461	1.3437
.0002	2.9912	0.6422	1.3652
.0004	2.9813	0.6345	1.4114
.0008	2.9579	0.6189	1.5164
.0012	2.9291	0.6033	1.6377
.002	2.8532	0.5718	1.9163
.004	2.5590	0.4924	2.5445
.006	2.1908	0.4138	2.7720
.008	1.8286	0.3373	2.7987
.010	1.4955	0.2630	2.7958
.011	1.3414	0.2267	2.7935

FIG. 2.9: ONE NODE PROBLEM

rectangular meshes only. To achieve the single protruding well block, it was necessary to include an entire column of 11 nodes, the upper 10 of which were then given zero transmissibilities in all directions.

The problem statement did not specifically state whether or not gravity effects were to be included. Both cases were tried with and without gravity with essentially identical results. Case a showed a 0.01% change in some properties at later times when gravity was added; however, the solution was also marginally less stable numerically, which could have given rise to this very small difference. In Case b, there was no difference in any parameter at any time between the gravity included and gravity excluded cases.

The time differencing scheme suggested in the problem statement proved to be insufficient to ensure stability of the solution. The scheme used was an initial time step of 10^{-5} days (0.864 secs) with a constant multiplying factor of 1.04 (instead of the 1.05 suggested) at each subsequent time step. The number of time steps required to reach 10^4 secs was then 140.

The pressures at the well and at the (2.5,0.25) node are tabulated for Case a in Table 3.1, and graphed in Figs. 3.1 and 3.2, respectively. The same two pressures for Case b are tabulated in Table 3.2 and graphed in Figs. 3.3 and 3.4. The saturation at the (2.5,0.25) node for Case b is also tabulated in Table 3.2.

3.4 Problem No. 4: 2-Phase System with Drainage

This problem was the only one of the five which included the effects of gravity. Boiling occurs in the hydrostatic column of liquid due to production at the bottom, and cold water is drawn in at the top.

TABLE 3.1: PROBLEM 3(a)

Time (Secs)	Pressure at Well (MPa)	Pressure at (2.5,0.25) (MPa)
0.864	2.949	3.05
2.6784	2.835	3.05
4.6656	2.802	3.05
6.8256	2.766	3.05
9.1584	2.748	3.05
11.664	2.733	3.05
14.3424	2.722	3.05
17.28	2.711	3.05
27.648	2.686	3.04
45.792	2.654	3.034
63.6768	2.635	3.030
86.2272	2.618	3.020
104.544	2.606	3.013
138.0672	2.586	3.003
180.4032	2.566	2.988
457.1424	2.473	2.919
744.8544	2.427	2.877
875.0592	2.412	2.861
1792.2816	2.321	2.792
2667.168	2.278	2.757
4283.1936	2.233	2.717
6870.528	2.185	2.666
8699.184	2.137	2.637
9410.7744	2.132	2.633
10180.426	2.121	2.624

FIG. 3.1: PROBLEM 3(a)

FIG. 3.2: PROBLEM 3(a)

TABLE 3.2: PROBLEM 3(b)

Time (Secs)	Pressure at Well (MPa)	Pressure at (2.5,0.25) (MPa)	Saturation at (2.5,0.25)
0.864	3.004	3.05	0.2
2.6784	2.956	3.05	0.2
4.6656	2.946	3.05	0.2
6.8256	2.931	3.05	0.2
9.1584	2.918	3.05	0.2
11.664	2.906	3.05	0.2
14.3424	2.895	3.05	0.2
17.28	2.885	3.05	0.2
27.648	2.860	3.05	0.2
45.792	2.834	3.05	0.2
63.6768	2.818	3.05	0.2
86.2272	2.803	3.05	0.2
104.544	2.793	3.05	0.2
138.0672	2.779	3.05	0.1999
180.4032	2.765	3.05	0.1999
457.1424	2.717	3.047	0.1989
744.8544	2.692	3.042	0.1974
875.0592	2.684	3.040	0.1968
1792.2816	2.648	3.026	0.1924
2667.168	2.628	3.015	0.1891
4283.1936	2.601	2.999	0.1840
6870.528	2.568	2.976	0.1771
8699.184	2.550	2.963	0.1729
9410.7744	2.543	2.958	0.1713
10180.426	2.536	2.952	0.1697

FIG. 3.3: PROBLEM 3(b)

FIG. 3.4: PROBLEM 3(b)

The problem is one-dimensional; however, the program does require a cross-sectional area in the other dimension. The solution was set up as a cylinder of radius 2 km; that is, an area 12.566 km^2 .

In order to achieve the constant pressure and temperature inlet conditions, a thin (10^{-5} m) grid block was added to the top of the mesh ($D = 0$), and its pressure and temperature held constant.

The time sequence consisted of 10 time steps of 0.1 day, followed by 9 of 1 day, 93 of 2 days, 120 of 5 days, and the remainder (up to 40 years) of 10 days.

The history of discharge enthalpy at $D = 2 \text{ km}$, recharge rate, and cumulative recharge at $D = 0$ are tabulated in Table 4.1 and graphed in Figs. 4.1, 4.2, and 4.3, respectively.

For the graph of pressure, temperature, and saturation, it was not possible to determine these values at the specified depths of 0.5, 1.0, 1.5, and 2.0 km because the grid specified did not have nodes at these points. The parameters are therefore tabulated for $D = 0.55, 1.05, 1.55$, and 1.95 km in Table 4.2. Values of saturation not listed in the table are all 1.0.

Pressure/time curves are graphed in Fig. 4.4, temperature/time curves are graphed in Fig. 4.5, and saturation/time curves are graphed in Fig. 4.6.

3.5 Problem No. 5: Flow in a 2-D Areal Reservoir

This problem also proved difficult in terms of time step selection, since in both Cases a and b there were times at which the solution became numerically unstable due to rapid changes of condition in the model reservoir. In neither case did these changes become evident in the specified output variables; however, there were reproducible events which occurred

TABLE 4.1: PROBLEM 4

Time (Days)	Discharge Enthalpy (MJ/kg)	Recharge Rate (kg/S)	Cumulative Recharge (kg)
1	1.3958	0.3255E-03	0.1760E02
2	1.3958	0.1360E-02	0.1553E03
4	1.3957	0.5903E00	0.7089E05
6	1.3955	0.2298E01	0.3557E06
8	1.3954	0.6370E01	0.1258E07
10	1.3953	0.1269E02	0.3131E07
14	1.3951	0.2513E02	0.1028E08
20	1.3948	0.5699E02	0.3409E08
30	1.3942	0.1164E03	0.1139E09
40	1.3937	0.1755E03	0.2453E09
60	1.3932	0.2776E03	0.6523E09
90	1.3931	0.3038E03	0.1424E10
120	1.3930	0.3059E03	0.2215E10
150	1.3930	0.3074E03	0.3010E10
180	1.3929	0.3089E03	0.3809E10
210	1.3928	0.3103E03	0.4611E10
270	1.3927	0.3133E03	0.6228E10
365	1.3925	0.3181E03	0.8820E10
450	1.3923	0.3225E03	0.1117E11
550	1.3920	0.3285E03	0.1399E11
730	1.3915	0.3432E03	0.1920E11
1000	1.3907	0.3823E03	0.2764E11
1500	1.3894	0.3945E03	0.4489E11
2000	1.3882	0.3762E03	0.6148E11
2500	1.3871	0.3751E03	0.7761E11
3000	1.3859	0.3757E03	0.9393E11
3650	1.3844	0.3673E03	0.1146E12
4000	1.3836	0.3717E03	0.1258E12
7300	1.3760	0.3491E03	0.2282E12
10000	1.3688	0.3310E03	0.3075E12
10950	1.3600	0.3219E03	0.3342E12
12000	1.3339	0.3125E03	0.3631E12
14000	2.1502	0.3080E03	0.4158E12
14600	2.5037	0.3321E03	0.4323E12

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FIG. 4.1: PROBLEM 4

FIG. 4.2: PROBLEM 4

FIG. 4.3: PROBLEM 4

TABLE 4.2: PROBLEM 4

Time t, Days	D = 0.55 km			D = 1.05 km			D = 1.55 km			D = 1.95 km		
	Press P, MPa	Temp. T °C	Sat S	P	T	S	P	T	S	P	T	S
1	5.297	164	1	9.313	290.999	1	12.843	301	1	15.583	309	1
2	5.296	164		9.291	290.999		12.816	300.999		15.554	309	
4	5.278	163.999		9.201	290.995		12.721	300.998		15.457	309	
6	5.244	163.998		9.115	290.991		12.633	300.996		15.368	308.999	
8	5.201	163.996		9.032	290.987		12.548	300.995		15.283	308.999	
10	5.152	163.994		8.952	290.983		12.467	300.993		15.201	308.999	
14	5.072	163.990		8.835	290.977		12.349	300.991		15.082	308.998	
20	4.903	163.981		8.612	290.964		12.123	300.986		14.856	308.996	
30	4.617	163.965		8.261	290.942		11.770	300.977		14.501	308.992	
40	4.343	163.95		7.933	290.92	1	11.439	300.97		14.169	308.99	
60	3.924	163.91	1	7.565	290.87	0.997	11.073	300.96		13.765	308.98	
90	3.862	163.88		7.556	290.79	0.985	11.034	300.94		13.756	308.97	
120	3.854	163.85		7.548	290.71	0.973	11.026	300.93		13.748	308.96	
150	3.846	163.82		7.539	290.63	0.962	11.017	300.92		13.739	308.95	
180	3.839	163.79		7.530	290.55	0.950	11.009	300.91		13.731	308.94	
210	3.832	163.77		7.522	290.47	0.938	10.999	300.90		13.722	308.92	
270	3.817	163.71		7.504	290.31	0.914	10.980	300.88		13.702	308.90	
365	3.794	163.62		7.476	290.04	0.877	10.947	300.85		13.670	308.87	
450	3.772	163.53		7.448	289.78	0.844	10.915	300.82		13.637	308.84	
550	3.742	163.43		7.410	289.43	0.805	10.868	300.78		13.591	308.80	
730	3.669	163.24		7.313	288.52	0.737	10.746	300.72		13.469	308.74	
1000	3.479	162.94		7.062	286.12	0.653	10.499	300.62		13.222	308.64	
1500	3.418	162.32		6.883	284.38	0.670	10.222	300.44		12.945	308.46	
2000	3.497	161.75		6.727	282.84	0.608	9.988	300.27		12.713	308.78	
2500	3.495	161.18		6.594	281.51	0.560	9.846	300.09		12.571	308.11	
3000	3.485	160.61		6.641	281.98	0.527	9.574	299.92		12.300	307.93	
3650	3.516	159.88		6.583	281.39	0.495	9.334	299.68		12.061	307.70	
4000	3.490	159.49		6.570	281.26	0.492	9.178	299.56	1	11.906	307.57	
7300	3.560	155.91		6.651	282.08	0.490	7.734	292.43	0.846	10.453	306.40	
10000	3.621	153.15		6.724	282.81	0.488	6.988	285.41	0.540	9.307	305.22	1
10950	3.658	152.22	1	6.765	283.22	0.488	7.004	285.56	0.495	8.918	303.07	0.870
12000	3.697	151.22		6.824	283.80	0.489	7.091	286.40	0.496	8.249	297.10	0.840
14000	3.701	149.40		6.773	283.29	0.480	6.914	284.69	0.474	6.908	284.63	0.593
14600	3.566	148.82		6.568	281.24	0.471	6.640	281.97	0.452	6.553	281.09	0.539

FIG. 4.4: PROBLEM 4

FIG. 4.5: PROBLEM 4

FIG. 4.6: PROBLEM 4

at about 1600 days in Case a and at 365 and 1305 days in Case b, which required time step retirement.

The sequence of time steps taken for Case a was 10 steps of 0.1 days, 20 of 0.2, 10 of 0.5, 91 of 1, 709 of 2, 150 of 0.5, 40 of 0.1, 100 of 0.02, 100 of 0.1, and the remainder (to a total of 3650 days) at 0.2 days. The total number of time steps was 2250. In Case b, the sequence was 10 steps of 0.1 days, 20 of 0.2, 10 of 0.5, 91 of 1, 132 of 2, 10 of 0.1, 20 of 0.2, 20 of 0.5, 20 of 1, 452 of 2, 100 of 0.1, and the remainder at 2 days. The total number of time steps for Case b was 2053.

The required output for Case a is tabulated in Table 5.1. The pressure history in zones (3,3) and (7,6) are graphed in Fig. 5.1. The temperature history in zone (3,3) is graphed in Fig. 5.2. The history of flowing enthalpy in Zone (3,3) is graphed in Fig. 5.3, and the history of total mass of steam in the system is graphed in Fig. 5.4.

The required output for Case b is tabulated in Table 5.2. The pressure histories are graphed in Fig. 5.5, and the temperature, flowing enthalpy, and mass of steam histories are graphed in Figs. 5.6, 5.7, and 5.8, respectively.

It should be noted that problem 5 was solved using a 13x8 grid instead of the 12x8 grid specified. The additional column of nodes was used to achieve the prescribed constant pressure and temperature boundary condition. The specified problem is two-dimensional; however, the program does need to use a thickness in the third dimension. The thickness used was 10 m, although essentially identical results were obtained with a thickness of 1 m over a shorter test period.

TABLE 5.1: PROBLEM 5(a)

Years	Days	Pressure (3,3) (MPa)	Pressure (7,6) (MPa)	Temperature (3,3) (°C)	Flowing Enthalpy (3,3) (MJ/kg)	Total Mass of Steam (10 ⁴ kg)
0	.1	3.4002	3.6517	239.9735	1.0421	0.0
	181	3.2406	3.4651	237.1724	1.0418	6.09680
1	365	3.1833	3.4381	236.1421	1.0388	10.4610
	545	3.1311	3.4123	235.1915	1.0365	13.0624
2	729	3.0849	3.3854	234.3397	1.0306	14.0945
	913	3.0576	3.3665	233.8335	1.0178	13.7931
3	1097	3.0189	3.3494	233.1082	1.0093	12.5288
	1277	3.0461	3.3480	230.2079	0.9955	11.0082
4	1461	3.0410	3.3412	227.8894	0.9846	9.09301
	1644	3.0582	3.3472	225.6389	0.9739	7.17780
5	1824	3.0683	3.3519	223.3214	0.9630	5.77520
	2008	3.0705	3.3528	221.0456	0.9525	4.50597
6	2192	3.0735	3.3586	218.7512	0.9416	3.37035
	2372	3.0825	3.3628	216.5430	0.9313	2.59738
7	2556	3.0796	3.3634	214.2573	0.9206	1.94288
	2740	3.0837	3.3674	211.9349	0.9098	1.38869
8	2920	3.0851	3.3698	209.7420	0.8996	1.03283
	3104	3.0843	3.3708	207.5029	0.8893	0.753980
9	3288	3.0851	3.3726	205.2940	0.8791	0.521211
	3468	3.0861	3.3744	203.2346	0.8696	0.415931
10	3648	3.0846	3.3747	201.2343	0.8603	0.350803

FIG. 5.1: PROBLEM 5(a)

FIG. 5.2: PROBLEM 5(a)

FLOWING ENTHALPY AT (3,3), MJ/kg

FIG. 5.3; PROBLEM 5(a)

FIG. 5.4: PROBLEM 5(a)

TABLE 5.2: PROBLEM 5(b)

Years	Time (Days)	Pressure (3,3) (MPa)	Pressure (7,6) (MPa)	Temperature (3,3) °C	Flowing Enthalpy (3,3) (MJ/kg)	Total Mass of Steam (10 ⁴ kg)
1	.1	3.4002	3.6517	239.9735	1.0421	0.0
	185	3.2390	3.4645	237.1278	1.0416	6.322
	365	3.1833	3.4381	236.1421	1.0388	10.461
	548	3.2133	3.6027	236.6818	1.0263	9.126
2	732	3.2192	3.6236	235.3139	1.0198	7.973
	912	3.2290	3.6375	233.5647	1.0115	7.048
3	1096	3.2261	3.6426	231.7822	1.0030	6.153
	1276	3.2386	3.6511	229.8940	0.9941	5.3999
4	1462	3.2340	3.6541	227.7168	0.9838	4.869
	1642	3.2345	3.6573	225.2059	0.9720	4.357
5	1826	3.2281	3.6601	222.3555	0.9585	3.946
	2010	3.2208	3.6609	219.1790	0.9437	3.529
6	2190	3.2143	3.6622	215.8179	0.9279	3.083
	2374	3.2156	3.6669	212.3865	0.9120	2.726
7	2554	3.2131	3.6695	208.9580	0.8960	2.498
	2738	3.2084	3.6708	205.4445	0.8798	2.299
8	2922	3.2010	3.6707	201.9043	0.8635	2.065
	3102	3.1976	3.6723	198.5256	0.8479	1.826
9	3286	3.1935	3.6738	195.1384	0.8324	1.600
	3466	3.1889	3.6747	191.8742	0.8175	1.394
10	3650	3.1830	3.6748	188.5993	0.8026	1.163

FIG. 5.5: PROBLEM 5(b)

FIG. 5.6: PROBLEM 5(b)

FLOWING ENTHALPY AT (3,3), MJ/kg

FIG. 5.7: PROBLEM 5(b)

FIG. 5.8: PROBLEM 5(b)

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PROBLEM STATEMENT

#1. 1-D Avdonin Solution

PHYSICAL DESCRIPTION

This problem involves one-dimensional, radial, steady-state flow, and unsteady heat transport in a single-phase liquid. The purpose is to test heat conduction and convection in the single-phase compressed water region.

PROBLEM SPECIFICATIONS

Water at 160°C is injected into the fringe of a geothermal reservoir of temperature 170°C . This problem looks at one well and assumes a quasi steady-state flow field is set up very rapidly. The boundary conditions for flow are: injection rate, $q = 10 \text{ kg/sec}$, specified at the well face, and pressure = 50 bars at an outer radius of 1000m. For heat transport, the temperature at the well face is 160°C and at the outer radius is 170°C . Initial temperature is 170°C everywhere in the reservoir, and the initial pressure is 50 bars. Boundary conditions and initial conditions are shown below.

Properties

permeability = 10^{-12} m^2

density rock = 2500 kg/m^3

specific heat of rock = $1.0 \text{ J/g}^\circ\text{C}$

thermal conductivity = $20 \text{ W/m}^\circ\text{C}$

reservoir thickness = 100m

porosity = $.2$

Thermal properties for water

provided by modeler

specify constants: specific heat, viscosity and density of water
(165°C , 50 bars).

Numerical grid and time step data

time steps = $1.67 \times 10^7 \text{ sec}$

grid-spacing = 25m

OUTPUT SPECIFICATIONS

- 1) Temperature versus radial distance at 10^9 sec
(60 time steps)
- 2) Take node at $r = 37.5\text{m}$ and give solution of temperature versus time.

COMMENTS

For constant density, viscosity, and heat capacity of water, an analytical solution is available for this problem. For example, this solution is a limiting case of the problem solved by Avdonin, 1964.

PROBLEM STATEMENT

#2. 1-D Well Test Analysis

PHYSICAL DESCRIPTION

This problem involves a set of three constant discharge, transient well test cases. Each case has 1-D radial flow to a line sink (zero radius well) in a homogeneous porous media. In Case a the fluid is single-phase liquid; in Case b the fluid is a two-phase mixture with both water and steam mobile; and in Case c the fluid changes from compressed liquid to a two-phase mixture as a flash front propagates away from the well. For each case, either an exact analytical solution (Theis solution) or an accurate semi-analytical solution is available for comparison with numerical solutions. Solutions will consist of pressure, saturation, and flowing enthalpy changes as functions of t/r^2 (time/distance squared).

PROBLEM SPECIFICATIONS

The following initial and boundary conditions and parameter values are to be used:

Specification	Case a	Case b	Case c
Initial pressure (bars)	90	30	90
Initial liquid saturation	1	.65	1
Initial temperature ($^{\circ}\text{C}$)	260	233.8 ^{1/}	300
Porosity	.20	.15	.20
Permeability ($\text{D} \cdot 10^{-12} \text{m}^2$)	.01	.24	.01
Thickness (m)	100	100	100
Discharge (kg/s)	14.0	16.7	14.0
Rock heat capacity ($\text{kJ/m}^3\text{C}$)	2650	2000	2650
Rock compressibility	0	0	0
Relative permeability functions ^{2/}	1-ph	Corey	Corey
Rock thermal conductivity	0	0	0

^{1/} Saturation temperature at 30 bars

$$\text{^{2/} } k_{rw} = [S - S^*], k_{rs} = [(1 - S^*)^2] \cdot [1 - (S^*)^2], S^* = [(S - .3)/(.65)],$$

S = liquid saturation

NUMERICAL SOLUTIONS

Analytical results for each case indicate that solutions for pressure, saturation, and flowing enthalpy are functions of t/r^2 . To minimize computational requirements while avoiding the significant spatial discretization errors, the following nodal arrangement should be used for each case.

$$r_n = 0.5 (\sqrt{2})^{n-1} \quad n = 1, 26$$

Total simulation time in each case should be 1 day. For the grid specification given above, an initial time step near 10^{-4} or 10^{-5} days is suggested for accurate solutions at early times.

ONE NODE TWO-PHASE PROBLEM

To facilitate evaluation of numerical solutions for two-phase flow, an additional problem under Case b conditions should be run. It involves 1 grid block with volume = 314 m^3 and constant discharge of 16.7 kg/s for .01 days. A constant time step of 10^{-4} days should be used, and the enthalpy of the discharge fluid should be weighted according to the mobility of each fluid phase (as in Cases b and c).

OUTPUT SPECIFICATIONS

Results for each case, except for the one-node problem, should consist of plots of pressure in bars, liquid saturation (Cases b and c), and flowing enthalpy in kJ/kg (Cases b and c) as functions of $\log(t/r^2)$ in days/m^2 for nodal points at 0.5 m, 0.707 m and 1.0 m from the well. The corresponding data in tabular form should also be provided. Data covering 5 log cycles for Cases a and K, and 4 log cycles

for Case b should be included in the plots and tabulations. Specification of the time step variation utilized should also be provided. Results for the one-node problem should consist of plots of pressure, liquid saturation, and discharge enthalpy versus time, along with the corresponding data tabulations.

PROBLEM STATEMENT

#3. 2-D Flow to a Well in Fracture/Block Media

PHYSICAL DESCRIPTION

This problem represents a simplification of the general problem of well testing in fractured geothermal reservoirs. As shown in the following sketch, a well producing at constant discharge is open to a horizontal fracture of infinite lateral extent. Vertical flow in the block and radial flow in the fracture, each obeying Darcy's law,

is to be simulated. The upper boundary of the block and the lower boundary of the fracture are impermeable, and the well has a finite radius with well-bore storage.

PROBLEM SPECIFICATIONS

For application to vapor-dominated reservoirs, steam flow in the block and fracture will be simulated. Parameter specifications for two cases are listed below:

Specification	Case a	Case b
Initial pressure (bars)	30.5	30.5
Initial liquid saturation <u>1/</u> (in block)	0	.2
Initial temperature ($^{\circ}\text{C}$) <u>2/</u>	234	234
Porosity in fracture	.1	.1
Porosity in block	.1	.1
Permeability in fracture (10^{-12}m^2)	.3	.3
Permeability in block (10^{-12}m^2) <u>3/</u>	.00003	.00003
Thickness of fracture (m)	.1	.1
Thickness of block (m)	1.0	1.0
Well discharge (kg/s)	.028	.028
Well radius (m)	.16	.16
Rock heat capacity ($\text{kJ/m}^3\text{C}$)	2570	2570
Rock compressibility	0	0
Rock thermal conductivity	0	0

1/ Initial liquid saturation is zero in the fracture in both cases

2/ Saturation temperature at 30.5 bars

3/ Horizontal permeability in block is zero in both cases

In Case a, liquid saturation is zero everywhere (no boiling). In Case b, immobile liquid boils in the blocks but not in the fracture. Relative permeability to steam is 1.0 in both cases.

NUMERICAL SOLUTION

A computational grid consisting of 1 well block, 10 logarithmically-spaced nodes in the fracture, and 100 nodes of equal vertical thickness in the block should be used. For those codes using finite difference techniques, either block-centered or face-centered nodal

patterns could be used provided that nodal positions were approximately the same as those shown below. The porosity and permeability in the well block should be set to 1.0 and $30 \times 10^{-12} \text{ m}^2$ (or larger), respectively.

Total simulation time should be 10^4 s or more, and to define the pressure history at the well face an initial time step of 1 s should be used. Minimum simulation time of 10^4 s would be reached in about 130 time steps if a time step multiplication factor of 1.05 were used.

OUTPUT SPECIFICATIONS

Results Cases a and b should consist of plots of pressure as a function of time (time), along with the corresponding data in tabular form. For each case, plot pressure at the well face, and pressure at a point located 2.5 m from the center line of the well and 2.5 m above the top of the fracture. Include a tabulation of liquid saturation versus time for this same point in the block under Case b conditions. The required data for each case should cover at least 4 log cycles in time.

PROBLEM STATEMENT

#4. Expanding 2 Phase System with Drainage

PHYSICAL DESCRIPTION

This problem involves 1-D vertical flow under both single and two phase conditions. An initially hydrostatic column of liquid is disturbed by mass withdrawal at the bottom. Boiling occurs in portions of the column, and inflow of cold water is induced at the top.

PROBLEM SPECIFICATIONS

1-D Cartesian (Vertical) Geometry

$$g = 9.8 \text{ m/s}$$

Rock Properties

	Layer "A" (0 < D < 1 km)	Layer "B" (1 km < D < 2 km)
Grain Density (g/cm ³)	2.5	2.5
Porosity	0.15	0.25
Permeability (m ²)	5×10^{-15}	100×10^{-15}
Heat Capacity (J/g-°C)	1	1
Grain Thermal Conductivity (W/m - °C)	1	1
Relative Permeability Functions: Corey (as specified in Problem #2)		

Boundary Conditions

At $D = 0$ (Surface), $P = 1.013$ Bar (~ 1 atm), $T = 10^\circ\text{C}$

At $D = 2$ km, see below.

Initial Conditions

$$T(D) = [10 + 280 (D/1 \text{ km})]^\circ\text{C} \quad 0 \leq D \leq 1 \text{ km}$$

$$= [270 + 20 (D/1 \text{ km})]^\circ\text{C} \quad 1 \text{ km} \leq D \leq 2 \text{ km}$$

$$P(D) = 1.013 \text{ Bar} + \int_0^D \rho g \, dD; \text{ hydrostatic.}$$

Production Strategy

From $t = 0$, to 40 years extract fluid from the bottom of the system ($D = 2$ km) at a rate of $100 \text{ kg/s} - \text{km}^2$.

OUTPUT SPECIFICATIONS

Plot and Tabulate: Discharge enthalpy history of the produced fluid. Recharge rate and cumulative recharge at the surface ($D = 0$).

$P(t)$, $T(t)$ and $S(t)$ at $D = 0.5, 1.0, 1.5$ and 2.0 km.

PROBLEM STATEMENT

#5. Flow in a 2-D Areal Reservoir

PHYSICAL DESCRIPTION

This problem involves multiphase flow in a 2-D horizontal reservoir. Mass is produced at one point in the reservoir, and recharge is induced over one of the lateral boundaries.

PROBLEM SPECIFICATIONS

2-D Areal Geometry

Region is horizontal (gravity neglected; $g_x = g_y = 0$) and of uniform thickness; extends over $0 \leq x \leq 300$ meters, $0 \leq y \leq 200$ meters

Finite - difference zoning as indicated: 12 x 8 grid (96 zones total) of uniform size $\Delta x = \Delta y = 25$ meters.

Rock Properties (Uniform over Grid):

Rock Grain Density = 2.5 g/cm^3

Porosity = 0.35

Permeability ($k_x = k_y$) = $2.5 \times 10^{-14} \text{ m}^2$

Heat Capacity of Rock Grain = $1 \text{ J/g-}^\circ\text{C}$

Rock Thermal Conductivity = $1 \text{ W/m.}^\circ\text{C}$

Relative Permeabilities -- Corey Equations as in Problem #2 with

$$S_{lr} = 0.3, S_{gr} = 0.1$$

Boundary Conditions: (See Figure Below)

Impose no convection, no conduction (impermeable, insulated) along:

$$y = 200\text{m}, 0 \leq x \leq 300\text{m}$$

Maintain initial P, T along $x = 300\text{m}, 0 \leq y \leq 200\text{m}$

($P \approx 36$ bars, $T = 160^\circ\text{C}$); see below

Initial Conditions:

Pressure initially uniform, and equal to saturation pressure at 240°C , plus 2.5 bars:

$$P(t = 0, 0 \leq x \leq 300\text{m}, 0 \leq y \leq 200\text{m}) =$$

$$= P_{\text{sat}}(240^\circ\text{C}) + 2.5 \text{ bars}$$

Note that $P_{\text{sat}}(240^\circ\text{C}) = 33.5$ bars, so $P_0 \approx 36$ bars

Initial temperatures for each zone are provided on the table on the next page. They are given approximately by:

$$T(t=0) = 240^\circ\text{C} \text{ for } r \leq 100\text{m}$$

$$= \left[240 - 160 \left(\frac{r-100\text{m}}{200\text{m}} \right)^2 + 80 \left(\frac{r-100\text{m}}{200\text{m}} \right)^4 \right]^\circ\text{C}$$

$$\text{for } 100\text{m} < r < 300\text{m}$$

$$= 160^\circ\text{C} \text{ for } r \geq 300\text{m}$$

where $r = \sqrt{x^2 + y^2}$

Initial Temperatures ($^{\circ}\text{C}$) $T_{ij}(t=0)$:

212.07	210.18	206.41	200.81	193.59	185.18	176.31	168.09	162.03	160.00	160.00	160.00	$j=1$
224.92	223.16	219.54	213.95	206.41	197.16	186.79	176.31	167.13	161.12	160.00	160.00	$j=2$
234.31	232.93	229.92	224.92	217.70	208.29	197.16	185.18	173.71	164.58	160.11	160.00	$j=3$
239.31	238.62	236.74	232.93	226.64	217.70	206.41	193.59	180.56	169.11	161.54	160.00	$j=4$
240.00	240.00	239.77	237.76	232.93	224.92	213.95	200.81	186.79	173.71	163.85	160.00	$j=5$
240.00	240.00	WELL	239.77	236.74	229.92	219.54	206.41	191.85	177.68	166.22	160.26	$j=6$
240.00	240.00	240.00	240.00	238.62	232.93	223.16	210.18	195.36	180.56	168.09	160.77	$j=7$
240.00	240.00	240.00	240.00	239.31	234.31	224.92	212.07	197.16	182.06	169.11	161.12	$j=8$
$i=1$	$i=2$	$i=3$	$i=4$	$i=5$	$i=6$	$i=7$	$i=8$	$i=9$	$i=10$	$i=11$	$i=12$	

X

Production Strategy for Case A

A fully-penetrating production well is located at $x = 62.5\text{m}$, $y = 62.5\text{m}$ (at the center of zone $i=3$, $j=3$). Starting at $t=0$, it produces fluid at the constant rate of 0.05 kilograms/sec-meter of thickness. The well radius is 15 cm and no skin effect is present.

Production Strategy for Case B

A production well is present, identical to Case A. In addition, an injection well is located at $x = 162.5\text{m}$, $y = 137.5\text{m}$, at the center of zone $i=7$, $j=6$. The well is fully penetrating, has no skin effect,

and is of radius 15 cm. The injection well is inoperative until $t = 1$ year (3.1536×10^7 sec). Thereafter, it begins injecting water at $T = 80^\circ\text{C}$ at a rate of 0.03 kilograms/sec-meter of thickness.

OUTPUT SPECIFICATIONS

In both cases, the time domain of interest is

$$0 \leq t \leq 10 \text{ years } (3.1536 \times 10^8 \text{ sec}).$$

For cases A & B, plot and tabulate:

- (1) Pressure history in zones $i=3, j=3$ and $i=7, j=6$.
- (2) Temperature history in zones $i=3, j=3$.
- (3) History of discharge (flowing) enthalpy in zone $i=3, j=3$.
- (4) Variation with time of total mass of steam in the system per meter of thickness.

Optional (For those with subgrid well model):

- (5) What is the sandface pressure history for the production well in cases A & B?
- (6) What is the sandface pressure history for the injection well in Case B?
- (7) What is the sandface steam saturation history at the production well in cases A & B?