Title

DOE-PROJECT ON GEOTHERMAL RESERVOIR ENGINEERING, COMPUTER CODE COMPARISON AND VALIDATION. EVALUATION OF RESULTS FOR PROBLEM 6

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DOE-PROJECT ON GEOTHERMAL RESERVOIR ENGINEERING COMPUTER CODE COMPARISON AND VALIDATION -EVALUATION OF RESULTS FOR PROBLEM 6-

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DOE-PROJECT ON GEOTHERMAL RESERVOIR ENGINEERING COMPUTER CODE COMPARISON AND VALIDATION

-EVALUATION OF RESULTS FOR PROBLEM 6-

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INTRODUCTION

Problem 6 is a reservoir-wide problem, and the only one in the set which involves three-dimensional flow. The reservoir is of "Wairakei-type," with single-phase liquid at depth, overlain by a two-phase zone with immobile steam, and capped off with a zone of colder single-phase water. Production occurs from a well field with completion intervals below the two-phase zone. Parameters are chosen in such a way that boiling in the well field and two-phase flow commence after a certain period of production.

Although the problem is schematic in nature, it is nonetheless a prototype of field-wide studies which would be undertaken to examine alternative reservoir development plans. Typical questions to be addressed by this type of problem would include: at what depth should the wells be completed? what flowrates can be sustained for what length of time by a well field of given areal extension? what is the evolution of downhole pressures and discharge enthalpies?

Problem 6 is probably the most difficult one in the set for numerical simulators, due to its three-dimensional nature and the occurrence of phase transitions with subsequent two-phase flow, including gravitationally induced steam/water counterflow.

PROBLEM DESCRIPTION

The reservoir is a parallelepiped of 4 x 5 km^2 areal extent and 1.8 km thickness. Figure 1 shows the geometric design of the system, and the zoning to be used in the simulation. Tables 1 through 4 give the complete specifications of all parameters. Formation properties vary somewhat with depth, and there is a large contrast between horizontal and vertical permeability. The lower 2/3 of the reservoir is initially filled with liquid water at 280 ^oC temperature. This is overlain by a two-phase region, also at 280 ^oC, which has an immobile steam saturation of 10% by volume. Overlying this is a layer of colder water at T = 160 ^oC. The entire reservoir is gravitationally equilibrated, so that initially there is no fluid flow. The process to be simulated is production from a specified subregion at depth. Production rates increase with time in such a way that boiling in the wellblock and two-phase flow is initiated. In the process, temperatures and pressures are kept to their initial values at the upper and lower boundaries, and at the surface at x = 5 km. The other three reservoir faces are closed ("no flow").

GENERAL DESCRIPTION OF RESERVOIR EVOLUTION

The evolution of the reservoir in response to production can be described as follows. As a consequence of production, pressures drop in the wellblock, so that horizontal and vertical flow towards the wellblock is initiated. Downflow from the two-phase zone gives rise to boiling and increasing vapor saturation. As the pressure decline spreads to the margins of the field, water recharge is initiated. One consequence of this is the occurrence of several phase transitions to single-phase conditions in the two-phase layer. The production rates for the first few years are such (small) that pressures in the wellblock stabilize, resulting in an approximately steady flow pattern. The increase in production rate after four years can not be readily sustained for the given permeabilities. Thus, large pressure drops occur in the grid block which represents the well field, as well as in adjacent grid blocks. This causes several phase transitions to two-phase conditions, and subsequent boiling. This is accompanied by a decline in temperatures and pressures, as well as a buildup of vapor saturation. Steam/water counterflow occurs as steam rises from the shallow two-phase layer, whereas water flows downward towards the production well. Conditions again approach a steady flow until the imposed increase in production rate after six years causes a rapid catastrophic decline of pressures in the production region, thus terminating the problem. This is unfortunate, as somewhat smaller production rates and a longer reservoir life would have allowed a more extensive comparison of simulated results.

COMPARISON OF RESULTS

Figures 2-4 show the simulated time evolutions of some of the more sensitive parameters. It is apparent that there is excellent agreement between the results of S^3, Geotrans, and LBL; whereas Intercomp's calculation is somewhat off. A conspicuous feature of Intercomp's results is that pressures below the well block (in layer 1) do not decline at all in the course of production, which gives rise to more water influx into the well block. As a consequence, well block pressures remain higher, particularly after five years, and vapor saturation and discharge enthalpy remain lower. The deviations become larger after the increase of production rate after six years. The nature of the discrepancies suggests some error in the problem definition rather than an error in Intercomp's simulator. It appears that the lower boundary conditions or the permeability below the well block had not been properly specified.

The quality of agreement between the calcuations of S^3, Geotrans, and LBL is quite remarkable, particularly in view of the significant differences in methodology used in the simulators. S^3 and Geotrans use a finite difference method, whereas LBL's simulator employs an integral finite difference method. The primary dependent variables are, respectively, energy and pressure (S^3), pressure and enthalpy (Geotrans), and energy and density (LBL). Geotrans uses an analytical approximation for thermophysical properties of water substance, whereas S^3 and LBL employ a tabular equation of state.

CONCLUSION

Three of the four simulators used in computing a difficult three-dimensional problem show excellent quantitative agreement. This demonstrates that numerical simulators are capable of producing accurate results for field-wide reservoir depletion problems, involving phase transitions, gravitationally induced steam/water counterflow, and recharge.

ACKNOWLEDGEMENT

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Table 1: Rock properties.

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Grain Density (g/cm^3)	2.5	2.5	2.5	2.5	2.5
Porosity	0.2	0.25	0.25	0.25	0.2
x-Permeability (m^2)	100×10^{-15}	200×10^{-15}	200×10^{-15}	200×10^{-15}	100×10^{-15}
y-Permeability (m^2)	100×10^{-15}	200×10^{-15}	200×10^{-15}	200×10^{-15}	100×10^{-15}
z-Permeability (m^2)	2×10^{-15}	50×10^{-15}	50×10^{-15}	50×10^{-15}	2×10^{-15}
Heat Capacity (J/g-^{o}C)	1	1	1	1	1
Rock Therm. Cond.(w/m-^{o}C)	1	1	1	1	1
Relative Permeability: Corey equations as in Problem #2, except:					
S_{lr} (liquid residual)	0.3	0.3	0.3	0.3	0.3
S_{gr} (gas residual)	0.1	0.1	0.1	0.1	0.1

Table 2: Initial conditions.

Temperature:

Layers 1-4, 280°C everywhere

Layer 5, 160°C

Pressure:

Layer 4: $P_4^o = P_{sat}$ (280°C) $\approx$ 64 Bars

(Steam saturation) $S_s^o = 0.1$ (steam initially immobile)

Layer 5: $P_5^o = P_4^o - (1470\ m^2/s^2) \times (\rho_4^o\text{-liq} + \rho_5^o)$

Layer 3: $P_3^o = P_4^o + (1470\ m^2/s^2) \times (\rho_4^o\text{-liq} + \rho_3^o)$

Layer 2: $P_2^o = P_3^o + (1470\ m^2/s^2) \times (\rho_3^o + \rho_2^o)$

Layer 1: $P_1^o = P_2^o + (1470\ m\ /s\ ) \times (\rho_2^o + 2\rho_1^o)$

Where ρ_4^o-liq = liquid density in Layer 4

These initial conditions (P^o, ρ^o, S_s^o) are functions of z only. Layers 1, 2, 3 and 5 are initially single-phase liquid; layer 4 is initially 2-phase with an immobile steam phase. The pressure distribution is liquid-hydrostatic throughout at zero time.

Table 3: Boundary conditions.

At z = 1.5 km (top surface), maintain $P_{top} = P_5^o - (1470\ m^2/s^2) \times \rho_5^o$ and T = 100°C.

At z = 0, maintain $P_{bottom} = P_1^o + (2940\ m^2/s^2) \times \rho_1^o$ and T = 280°C.

Along planes at x = 0 and y = 0, impose symmetry conditions.

Treat plane at y = 4 km as impermeable and insulated.

Along plane at x = 5 km, maintain initial distributions of P, T, S_s.

Table 4: Production strategy.

All production is taken from a single corner cell (i=1, j=1, k=2).

$0 \leq t \leq 2$ years, $Q(t) = 1000$ kg/s

2 years $< t \leq 4$ years, $Q(t) = 2500$ kg/s

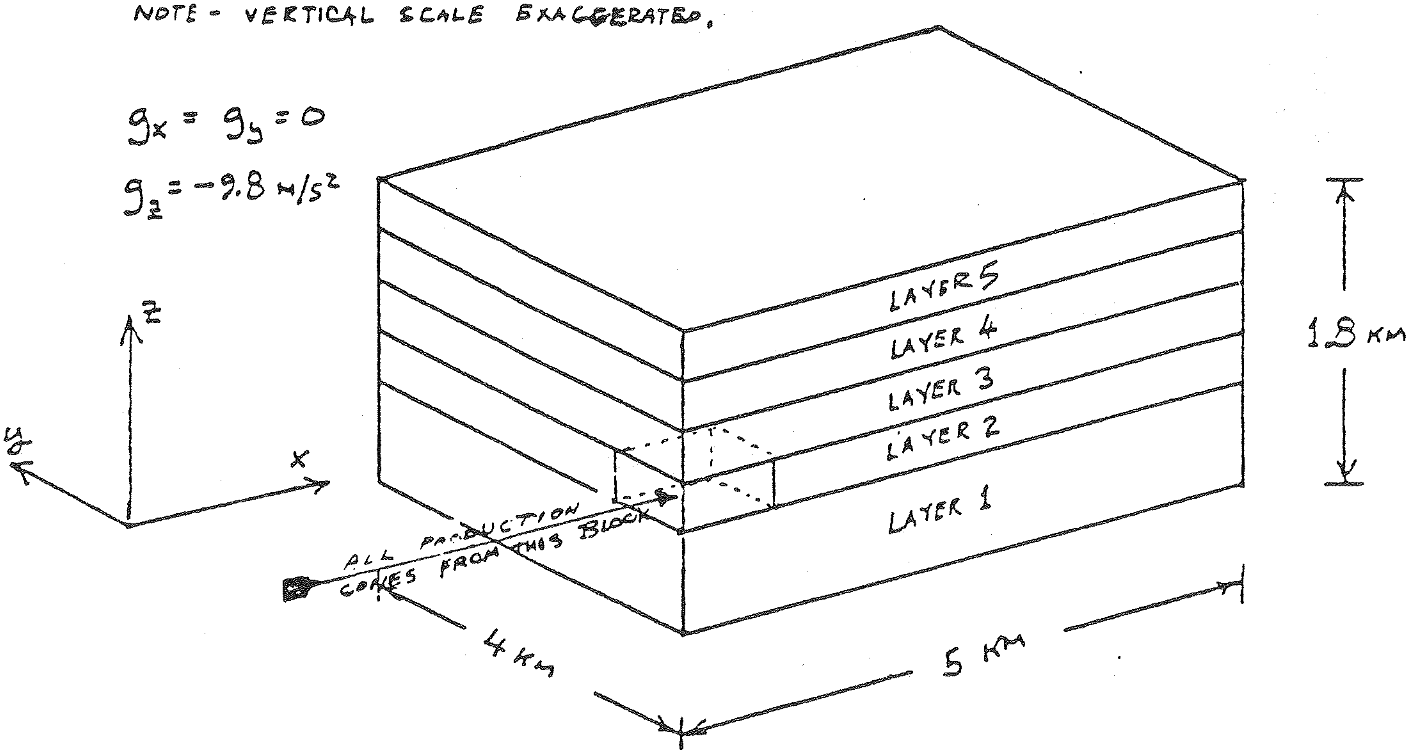
4 years $< t \leq 6$ years, $Q(t) = 4000$ kg/s

$t > 6$ years, $Q(t) = 6000$ kg/s

NOTE - VERTICAL SCALE EXAGGERATED.

$g_x = g_y = 0$

$g_z = -9.8$ m/s^2



LAYER THICKNESSES:
LAYER 1, 0.6 KM
LAYERS 2-5, 0.3 KM EACH

GRID: 5 × 5 × 5
(Horizontal, uniform,
5 zones each direction)

Figure 1: Geometry of the reservoir and mesh design.

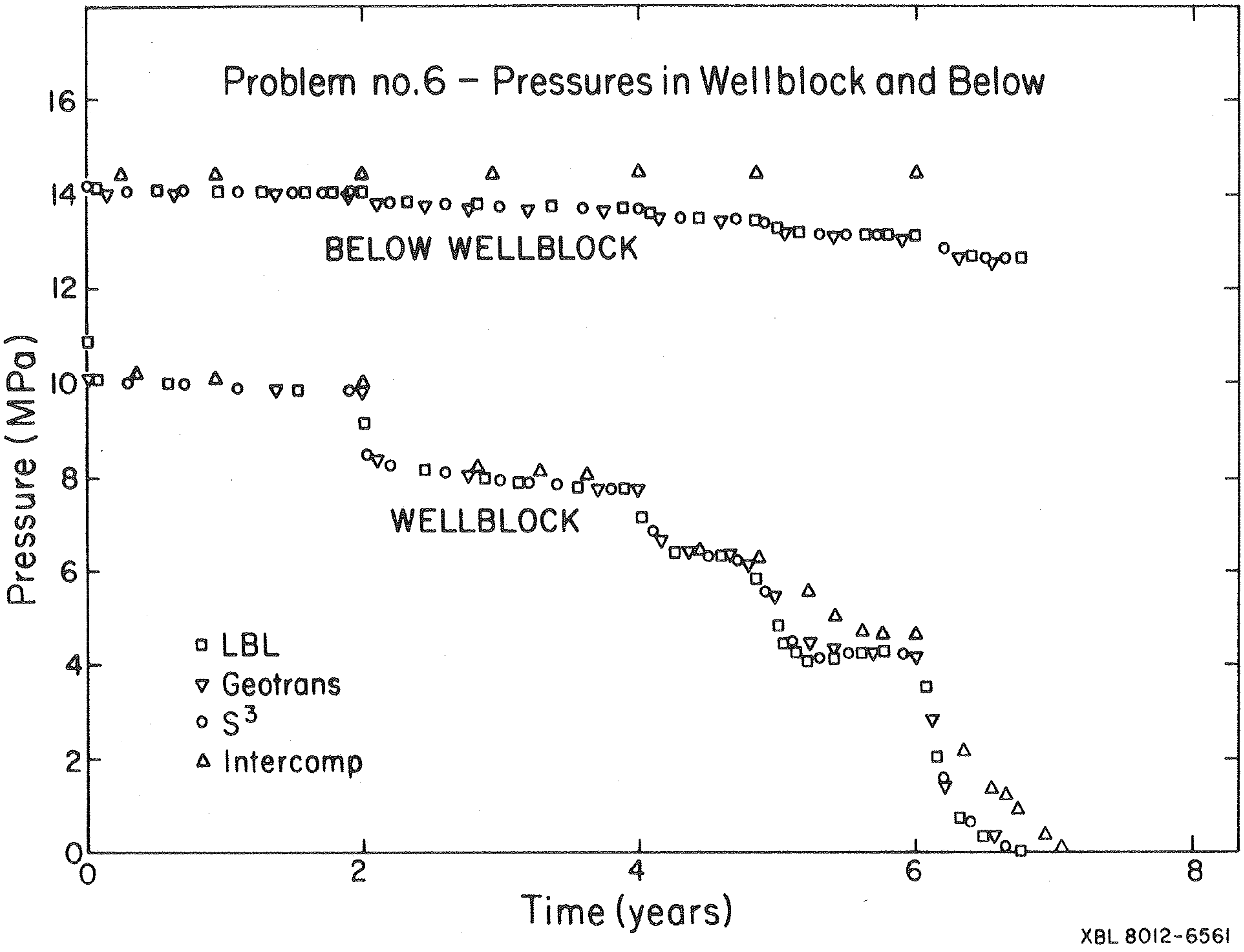


Figure 2: Time dependence of selected pressures.

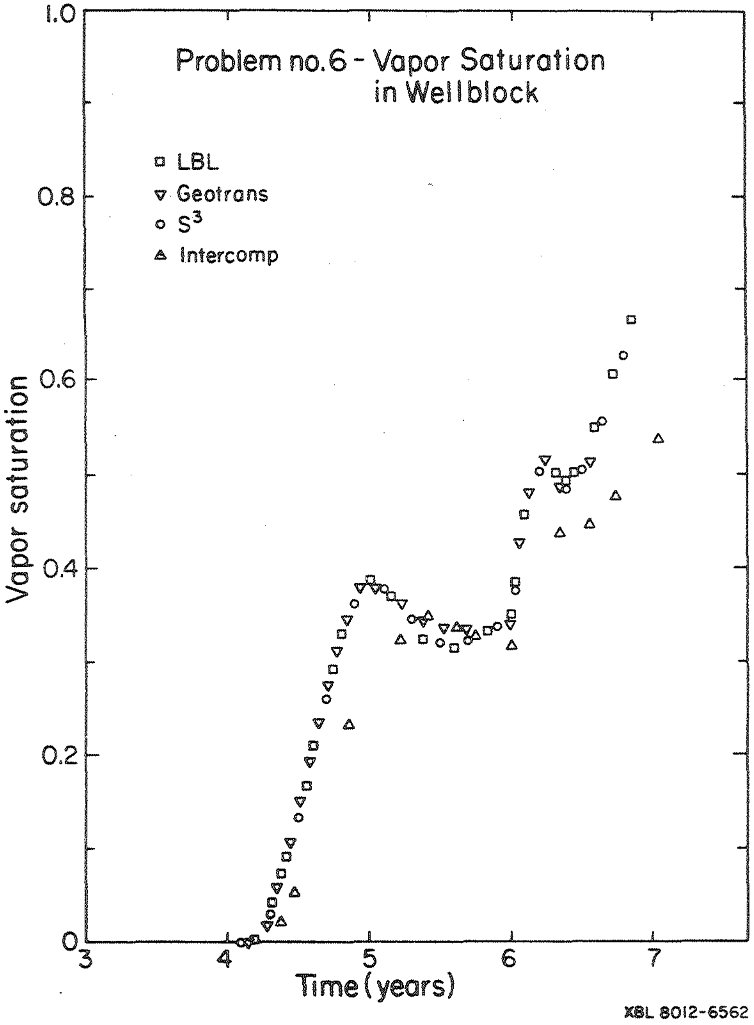


Figure 3: Evolution of vapor saturation in well block.

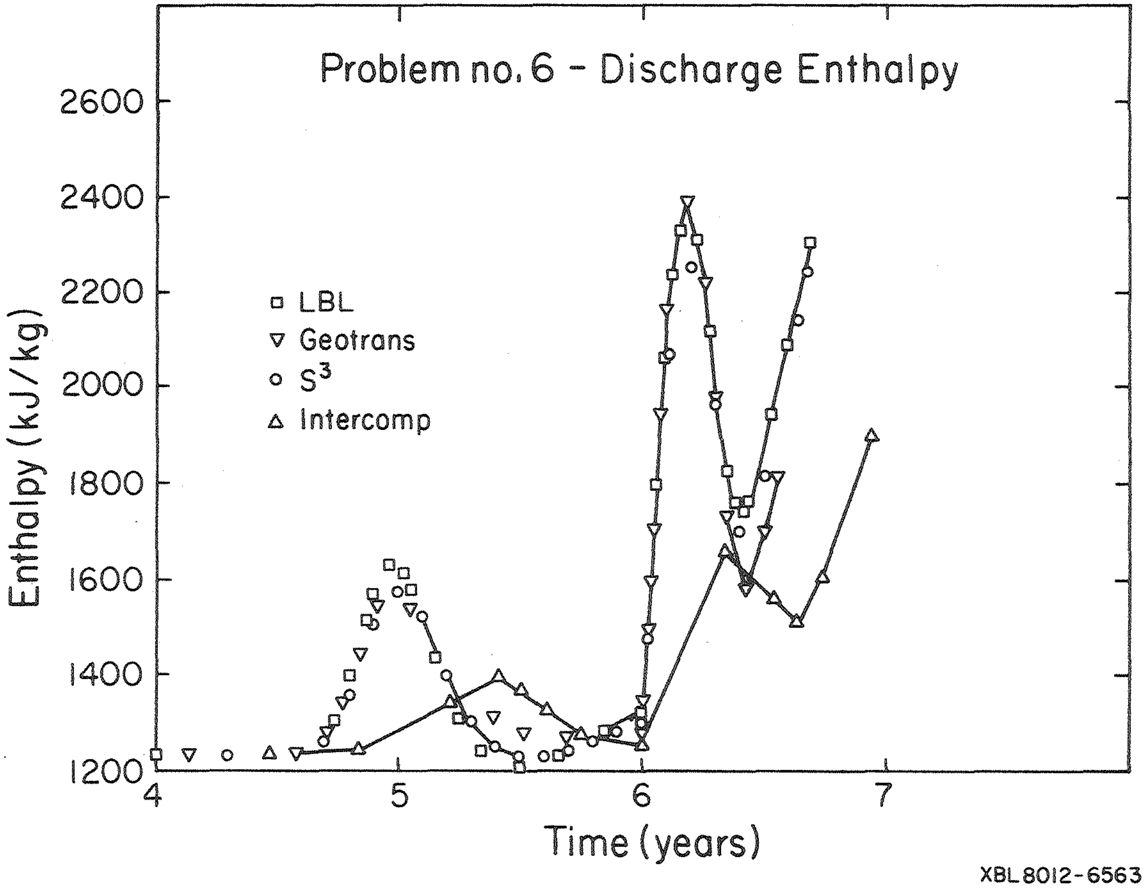


Figure 4: Discharge enthalpy history.