THE TESTING OF KA28 - PRESSURE ANALYSIS IN A TWO-PHASE RESERVOIR

Malcolm A. Grant
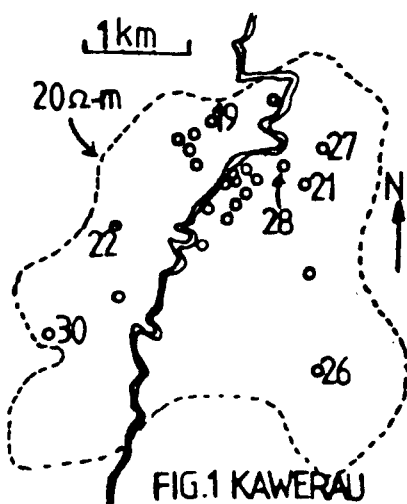Applied Math. Div., DSIR, Box 1335 Wellington N.Z.

ABSTRACT

Examples of two-phase pressure transient analysis are given, for injection and discharge. Transients measured in KA28 are used to identify the fluid feeding the well and to measure permeability.

INTRODUCTION

Kawerau geothermal field in New Zealand has been exploited at a low level (20 MWe) since 1956. Separated steam is used by a pulp mill. The field has an area of 10 sq. km. (1). Investigatory drilling has continued slowly (2,3).
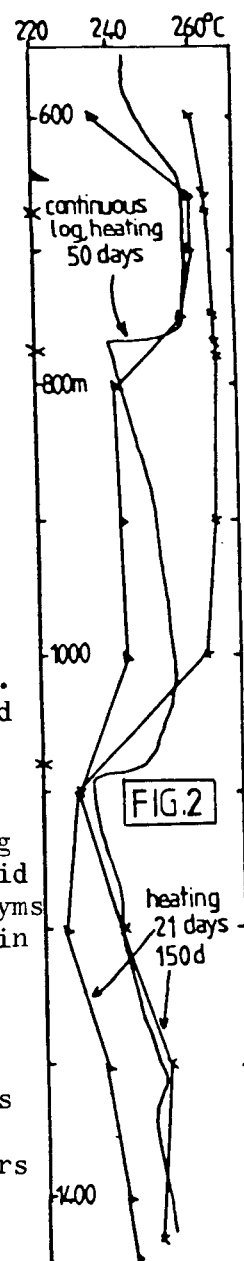
The reservoir consists of fractured volcanics over a greywacke basement (4). Base temperature is over 290°C. Permeability is on average very good, and also very erratic. KA21 found immeasurably large permeability in the greywacke at 1100m, in 286° water. Its flow of 600 t/h makes it the world's largest producer (electrical equivalent). KA30 at the

FIG.1 KAWERAU

other end of the field is nearly as good. Between are some duds and some good wells.

KA28

KA28 was drilled as a stepout, 300m from KA21. It was a surprise and a disappointment, as it found lower temperature and permeability. Temperature increases to 266° at 770m (Fig.2), similar to the adjacent wells. Beneath there is cooler water.

Detailed measurements with a surface-recording spinner and temperature tool identify zones of fluid loss or gain at 674m, 778m and around 1080m. (M. Syms pers. comm.) The two upper feeds are very similar in character and are hereafter lumped together as a single upper feed, represented by values at 700m. Stable downhole temperature at 700m is 264°, and reservoir pressure 62 bars gauge. Temperature at 1080m is about 230°, and reservoir pressure 93 bars gauge (5). The quoted reservoir pressures are the measured downhole pressures at which no fluid enters or leaves the well at that depth. They are not the same as stable downhole pressures (6), as a well cannot in general reach equilibrium at two depths.

FIG.2

The lower zone, in a temperature inversion, must contain liquid water. Pressure at the upper zone is 12.8 bars above saturation for pure water. Kawerau discharges contain up to 1% of gas, and partial pressures of up to 20 bars are observed. The upper zone might be boiling. The 150-day temperature profile is very smooth above 800m, and could be a boiling-point profile due to the upflow of boiling fluid from 778m to 674m (6); suggesting two-phase conditions at this depth.

Normally the completion testing and warmup would identify the dominant feed to the well, and the type of fluid in it. This was not possible in KA28. The well might produce: 230° liquid; 264° liquid; 264° two-phase; or a combination of the first with one of the latter. In a double-feed well, interzonal flows (7) normally cause oscillatory or erratic pressure transients. In the case of KA28, transient analysis of the injection and discharge tests indicates performance consistent with a well with one dominant feed, that feed containing two-phase fluid.

INJECTION

The usual completion test for New Zealand wells consists of cold water injection at various rates with measurement of downhole pressure and temperature. Two transients were measured (Fig.3), both at pump shut from $11\frac{1}{2}$ l/s. In the second test a good result was obtained. In the first test (34731) the chart trace becomes irregular after 3 minutes, and agrees with the later test before then. The common straight line has a slope of 1.4 bar/cycle, giving (8,9)
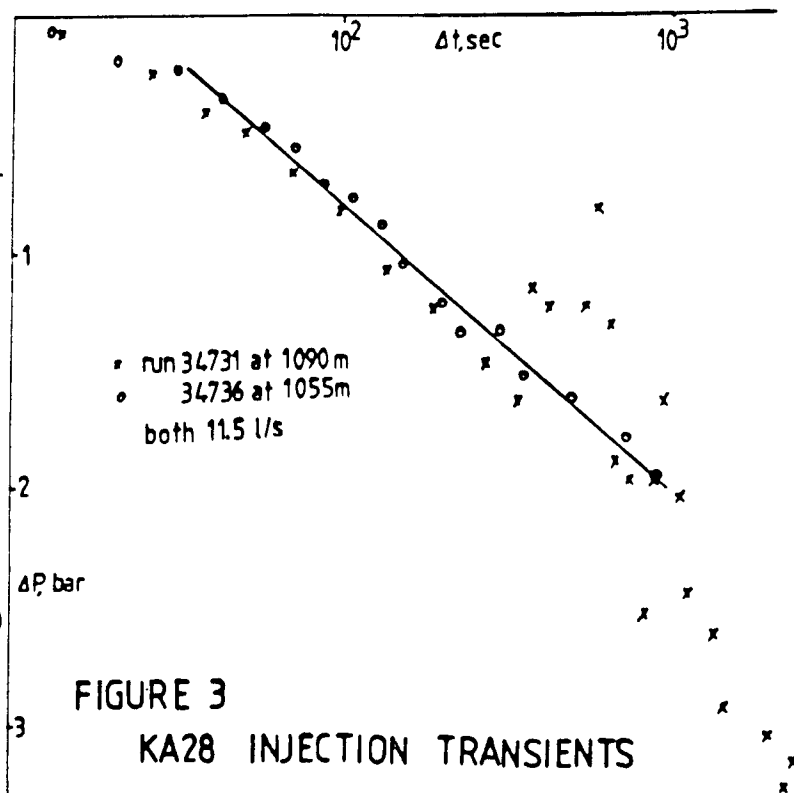

FIGURE 3

KA28 INJECTION TRANSIENTS

(figure labels: Δt,sec, 10^2, 10^3; run 34731 at 1090m; 34736 at 1055m; both 11.5 l/s; ΔP, bar)

$$kh/\mu_t = (11.5 \times 10^{-3})(2.303)/(4\pi \times 1.4 \times 10^5) = 1.5 \times 10^{-8} \ m^3/pa.s$$

In an injection test it is assumed that there is a cold water region near the well, beyond which is heated injected water and hot reservoir fluid. The region affected by pressure change is much greater than the injection volume, so that the value of kh/μ_t measured reflects the reservoir fluid, not the injected water (H.J. Ramey, pers. comm.) Aquifer thickness, porosity, and reservoir fluid compressibility are all unknown, although ϕh is presumably less than 100m or so. Evaluating for skin gives:

$$\phi c_t h e^{-2s} = 6.7 \times 10^{-5} \text{ m/pa}$$

The assumption of a single-phase feed can now be examined. If the well is water-fed, feed temperature is $230-264°$. Then $\mu_t = \mu_w \cong 110 \times 10^{-6}$ pa.s, and $c_t = c_w \cong 1.4 \times 10^{-9}$ pa^{-1}, giving

$$kh \cong 1.7 \text{ darcy-metre}, \quad \phi h e^{-2s} \cong 50,000 \text{ m}$$

Skin must be negative (about -3). With the kh of 1.7 d-m, the expected discharge would be over 300 t/h, at water enthalpy.

Transient measurements should normally be made opposite the well's major feed, to minimise the effects of changes of fluid density in the well. It was hoped that good permeability would be found at depth in KA28, so measurements were made near 1080m. So long as the record does not oscillate, pressure changes during injection are the same at all depths in the well, and so this analysis remains valid, whatever the feed depth of the well.

DISCHARGE

This was delayed because of proximity to the mill. After heating for 7 months, there was 23 days' discharge (Fig4). During this, two output (deliverability) tests were performed (Fig5) and two pressure recoveries. The maximum flow recorded was 165 t/h and the enthalpy was 1200-1350 kJ/kg. (5) $264°$ water has enthalpy 1155 kJ/kg. Performance is not consistent with production from an aquifer containing

FIGURE 4 DISCHARGE HISTORY

FIGURE 5 OUTPUT TESTS

compressed liquid. It now remains to be seen if it is consistent with production from one aquifer of two-phase fluid.

Gas content was 0.63-0.74%, by mass, measured at enthalpies of 1200-1250 kJ/kg. The gas was mainly carbon dioxide. $264°$ water with a partial pressure of 12.8 bar contains 0.59% CO_2. Thus the pressure and temperature are saturated, for the actual reservoir fluid.

A pressure buildup at 750m, run 34864, gives a respectable straight line (Fig. 6), after a period dominated by storage and skin. The slope of the straight line is 10 bar/cycle. The flow was 135 t/h = 37.5 kg/s, at 1285 kJ/kg. From the mass flow and slope

$$kh/\nu_t = (2.303)(37.5)/(4\pi \times 10 \times 10^5) = 6.9 \times 10^{-6} \text{ m-s}$$
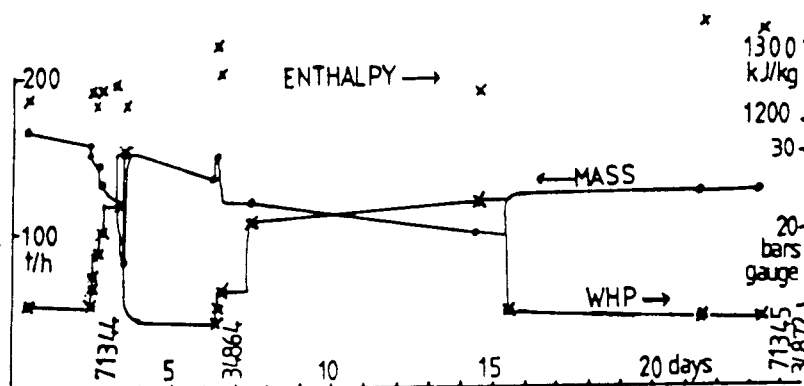
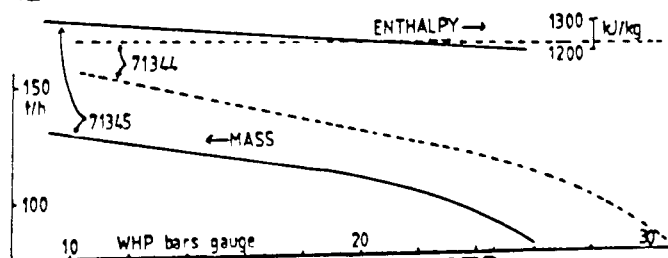Note that it is kh/ν_t that is the measured quantity. The discharge is measured as a mass flow, and this cannot be converted to a volume flow without knowledge of the flowing density ρ_t at reservoir conditions. This density is not equal to liquid water density.

Matches to Ramey log-log type curves (9) were tried, but no match was possible.

The skin equation uses kh/μ_t, and so the unknown density ρ_t enters it. Evaluating

FIGURE 6
DISCHARGE
TRANSIENTS

run 34872
124 t/h
1320 kJ/kg
1100 m

run 34864
135 t/h
1285 kJ/kg
at 750 m

$$\rho_t \phi c_t h e^{-2s} = 3.1 \times 10^{-3} \text{ kg/pa.m}^2$$

The density ρ_t is found from the discharge enthalpy (10). The enthalpy before shut-in was 1285 kJ/kg. At 264° this enthalpy corresponds to a steam-water mixture that contains 7.9% by mass of steam, and the density of this mixture is 235 kg/m³. Using this value, the discharge test implies

$$kh/\mu_t = (kh/\nu_t)(1/\rho_t) = 2.9 \times 10^{-8} \text{ m}^3/\text{pa.s}$$

However the enthalpy of the well has varied, with the lowest value being 1200 kJ/kg. There is a strong argument that there should be used not the parameters of the disturbed situation, but those of distant reservoir fluid. This fluid has flowing enthalpy equal to that discharged by the well at small flows. The greater enthalpy at larger flow rate reflects extraction of heat from rock near the well. (13). The enthalpy of 1200 kJ/kg corresponds to a density of 430 kg/m³, and hence

$$kh/\mu_t = 1.6 \times 10^{-8} \text{ m}^3/\text{pa.}$$

COMBINED RESULTS

Alternatively, one could take the results of the injection and discharge tests and use them to find the flowing density:

$$\rho_t = \mu_t/\nu_t = (kh/\nu_t)/(kh/\mu_t) = 450 \text{ kg/m}^3$$

Using this density, the skin equation gives for the discharge test

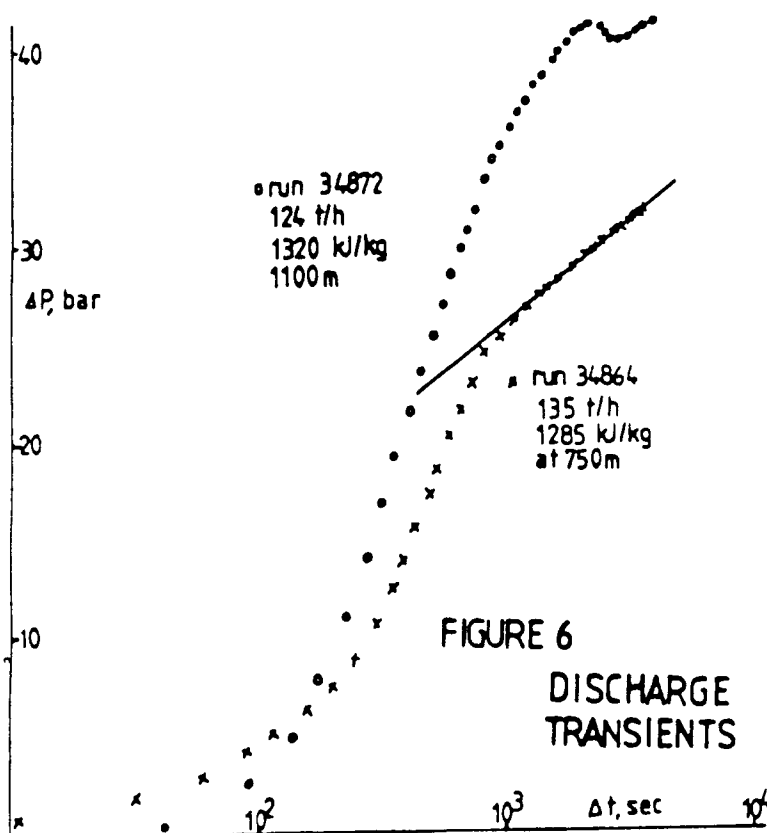$$\phi c_t h e^{-2s} = 7 \times 10^{-6} \text{ m/pa}$$

There is now a consistent interpretation of the discharge and injection transients, where all parameters refer to fluid distant from the well:

$$kh/\mu_t = 1.5 \times 10^{-8} \ m^3/pa.s$$

$$kh/\nu_t = 6.9 \times 10^{-6} \ m\text{-}s$$

$$\rho_t = 450 \ kg/m^3$$

$$h_t = 1200 \ kJ/kg$$

$$\phi hc_t \, he^{-2s} = (7\text{-}70) \times 10^{-6} \ m/pa$$

Two-phase compressibility with gas present and saturation near unity is given by (11)

$$\frac{1}{\phi c_t} = \frac{\rho_w \rho_s}{\rho_w - \rho_s} \frac{dP_s}{dT} \frac{h_s - h_w}{\langle \rho C \rangle} + \frac{1}{\phi a} \frac{M_g}{18} \frac{\rho_s P_g}{\rho_w P_s}$$

where P_g is gas partial pressure, M_g gas molecular weight, and $a = a(T)$ is the solubility of gas. The first term on the right is the two-phase compressibility of pure water (10), while the second corresponds to isothermal dissolution-exsolution of gas, and is equivalent to the corresponding expression (8) for oil & gas.

A simpler numerical expression can be given, to save looking up steam tables. For a volumetric specific heat of the wetted rock $\langle \rho C \rangle = 2.5 \ MJ/m^{3} \, ^{\circ}C$, and with pressures in bars and compressibility in bar^{-1},

$$c_t^{-1} = \frac{\phi}{48} P_s^{1.66} + 8 P_g P_s^{-0.21}$$

The first term is accurate to $\frac{1}{2}\%$ for $150\text{-}300^{\circ}$ (10). The second term is limited by accuracy in solubility data, but is probably within 5% over $200\text{-}300^{\circ}$.

The compressibility varies strongly with partial pressure and temperature. Partial pressure falls rapidly as pressure is drawn down, and it is common for the compressibility to change by a factor of 10 at wellface during drawdown and recovery. Again the choice is made to evaluate at undisturbed reservoir conditons, in which case the second term dominates in all New Zealand fields except Wairakei. At 264° and a partial pressure of 12.8 bar, $c_t = 2.2 \times 10^{-7} \ pa^{-1}$, so

$$\phi he^{-2s} = 40\text{-}400 \ m.$$

A small negative skin is implied.

The final task is to calculate kh from the value of kh/μ_t or kh/ν_t. This requires definition of the relative permeability functions. From the enthalpy of 1200 kJ/kg

$$k_{rw}/k_{rs} = (\nu_w/\nu_s)(h_s - h_t)/(h_t - h_w) = 5.4$$

If fracture relative permeabilities are assumed (13), $k_{rw} + k_{rs} = 1$, and $k_{rw} = .84$, $k_{rs} = .16$. Then

$$1/\mu_t = (k_{rw}/\mu_w + k_{rs}/\mu_s)$$

gives $\mu_t = 59 \times 10^{-6}$ pa.s, or about half that of liquid water. Then

$$kh = \mu_t \cdot (kh/\mu_t) = 0.88 \ \text{darcy-metre}$$

A different value, 3.0 d-m, would result from the use of Corey relative permeabilities. And this estimate is even more sensitive to the enthalpy than the fracture value. If the results of a test are used in modelling, it is important that consistent assumptions are used for the relative permeabilities. It may be better to report not kh but the measured test result: kh/μ_t for injection test and kh/ν_t for discharge test.

PROBLEMS OF TWO-PHASE ANALYSES

These divide into practical problems due to fluid behaviour in the well and theoretical ones due to the flow in the reservoir. The practical problems are much the same as for high-temperature water-fed wells: misidentification of storage and skin or special feature, pressure gauge at wrong depth in the well, interzonal flow effects. In KA28, the humped response of run 34872 has been discarded. But there remains a nagging doubt that a lesser amount of the same effect could be present in 34864, so that the chosen straight line is not real.

The theoretical problems peculiar to two-phase are the gross nonlinearity of the parameters, and the variations in enthalpy (which is also a nonlinear effect). The compressibility is a strongly varying function of pressure and partial pressure - as is the compressibility of a dry gas - and there appears no simple alternative to taking the undisturbed value. This means possible errors in skin, perhaps up to ± 2. More important is the variation in the flowing viscosities and density, ν_t, μ_t, & ρ_t. They vary strongly with saturation, or, equivalently, with flowing enthalpy h_t and temperature. They are also dependent upon the ill-defined relative permeabilities. If the flowing enthalpy is everywhere constant or nearly so, a pseudopressure can be defined, analogous to the gas pseudopressure. The requirement of constant enthalpy can be satisfied in steady flow (14) or if water is immobile (15).

However, in transient flows the dominant nonlinear effect is the changing of the flowing enthalpy (13). And the viscosity is so sensitive to the enthalpy that it is difficult even in principle to measure it accurately enough (12). An accurate analysis would require a match to both pressure and enthalpy histories. The author has tried enthalpy transient analyses, without success to date. Lacking such a better technique, simple analyses based on constant parameters are the only easily useable alternative now available. Fortunately results at large drawdown can be quite close to linear behaviour (13).

CONCLUSION

In the past year, two-phase transient analyses have become sufficiently polished to yield sometimes credible results, including agreement between interference and single-well test, between discharge and injection tests, and between repeat tests. At KA28, the dominant feed has been identified as two-phase, and the characteristics of the two-phase fluid defined; and the cause of the poor production identified as low intrinsic permeability.

ACKNOWLEDGEMENTS

REFERENCES

1. Macdonald, W.J.P., & Muffler, L.J.P., 1972 "Recent Geophysical Exploration of the Kawerau Geothermal Field, North Island, New Zealand" N.Z. Jl. Geol. & Geoph., 15, 3, pp303-317

2. Smith, J.H., 1970 "Geothermal Development in New Zealand", 1st. U.N. Symposium, Pisa, pp232-47

3. Donaldson, I.G., & Grant, M.A., "Heat Extraction from Geothermal Reservoirs" in Geothermal Systems: Principles and Case Histories ed. Rybach & Muffler, Wiley-InterScience

4. Nairn, I.N., 1977 "Geology of Kawerau Geothermal Field: Preliminary Report on New Data" unpub. internal report, DSIR

5. MWD, 23/5/1980 "Kawerau Geothermal Field: Well KA28 Report on Measurements Sept 1979 - April 1980 Including Output Test 71345"

6. Grant, M.A., 1979 "Interpretation of Downhole Measurements in Geothermal Wells" report 88, App. Math. Div, DSIR

7. Grant, M.A., Bixley, P.F. & Syms, M.C. "Instability in Well Performance" Trans. Geothermal Resources Council, 3, pp275-8

8. Matthews, C.S. & Russell, D.G., 1967 Pressure Buildup and Flow Tests in Wells , SPE-AIME

9. Earlougher, R.C., 1977 Advances in Well Test Analysis SPE-AIME

10. Grant, M.A. & Sorey, M.L., 1979 "The Compressibility and Hydraulic Diffusivity of a Water-Steam Flow" Water Resources Research, 21, pp684-6

11. Grant, M.A., 1978 "Two-phase linear geothermal pressure transients, a comparison with single-phase transients" NZ Jl.Sci. 21, pp355-364

12. O'Sullivan, M.J., "A Similarity Method for Geothermal Well Test Analysis" to be published

13. Sorey, M.L., Grant, M.A., & Bradford, E., 1980 "Nonlinear Effects in Two-phase Flow to Wells in Geothermal Reservoirs" Water Resources Research, 16, 4, pp767-777

14. Pritchett, J.W., 1979 "A Semi-Analytical Description of Two-Phase Flow near Producing Wells in Hydrothermal and Geopressured Reservoirs" 5th Annual Workshop, Stanford Univ., pp173-82

15. Grant, M.A., 1978 "The Pseudopressure of Saturated Steam" 4th Annual Workshop, Stanford Univ., pp78-83

NOTATION

This follows ref. 10.

APPENDIX: DATA

On the next page are given the data for the two pressure buildups after discharge, and the two pressure falloffs after injection, illustrated in Figures 6 & 3. Flowing profiles were also measured before each buildup, and these are also given. Flow data and other information is given in text.

34731 Δt sec	$-\Delta P$ bar	34736 Δt sec	$-\Delta P$ bar	34864 Δt sec	ΔP bar	34872 Δt sec	ΔP bar
14	0.10	13½	0.10	10	0.8	44	0.4
26	0.25	21	0.25	31	1.9	88	1.7
39	0.40	33	0.30	58	2.9	132	4.1
51	0.50	44	0.45	87	4.1	176	6.7
71	0.70	59	0.55	114	5.2	220	10.0
100	0.85	73	0.65	158	6.2	264	13.1
138	1.10	90	0.85	195	7.4	308	15.8
191	1.25	169	0.90	249	8.8	352	18.3
275	1.55	134	1.00	295	10.4	396	20.6
346	1.70	157	1.20	341	12.2	440	23.6
385	1.20	209	1.40	378	13.8	484	24.4
432	1.25	240	1.50	424	15.5	528	25.9
564	1.25	314	1.50	482	17.3	572	27.4
609	0.85	370	1.75	528	18.7	617	28.6
655	1.35	525	1.85	590	20.3	661	29.6
688	1.95	759	2.00	656	21.8	705	30.6
753	2.05	906	2.20	729	23.1	793	32.2
853	2.65	960	2.20	833	24.6	837	33.2
902	2.05			935	25.3	881	33.8
989	1.70	P_{wf}=92.6		1064	26.1	969	34.6
1081	2.10			1226	26.9	1035	35.3
1151	2.55			1359	27.4	1101	35.9
1384	2.70			1454	27.8	1211	36.9
1447	3.05			1662	28.3	1321	37.4
1993	3.15			1870	28.8	1431	38.1
2317	3.40			2077	29.5	1497	38.5
2400	3.30			2285	29.8	1651	39.0
				2493	30.3	1761	39.4
P_{wf}=98.6 bars gauge				2701	30.6	1806	39.6
				2908	30.9	2092	39.9
				3116	31.2	2224	39.7
				3324	31.4	2334	39.4
				3600	31.7	2422	39.1
						2642	39.1
				P_{wf}=25.2		2862	39.2
						3083	39.4
						3303	39.7
						3600	40.0

P_{wf}=31.0

Flowing profiles

34864 & 27814 Z m	P b.g.	T °C	34872 & 27824 Z m	P b.g.	T °C
1100	36.2	243	1400	48.1	251
1060	35.6	242	1300	40.9	247
780	26.0	226	1200	33.9	241
750	25.1	223	1100	31.0	236
680	22.5	218	1060	29.9	233
660	22.1	216	900	25.4	223
0	12.4		760	19.9	211
			660	16.9	202
			0	8.6	