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A STEAM/WATER COUNTERFLOW MODEL OF A VAPOUR DOMINATED GEOTHERMAL RESERVOIR WITH SURFACE RECHARGE & DEEP DRAINAGE

David W. Jenson

Geothermal Energy New Zealand Limited

P.O. Box 37-231, Auckland, N.Z.

ABSTRACT

A 2 dimensional steam/water counterflow model of a Vapour Dominated Geothermal Reservoir has been developed. If liquid recharge is applied *at* the surface & deep drainage is available, a range of conditions *can* be established where natural *chokes* are formed in the reservoir. These chokes lead to a liquid dominated region overlying a vapour dominated region. The pressure *(or* depth) *at* which a choke will form is controlled by a narrow range *of* surface conditions. A selection of vertical sections have been constructed which model a series of possible reservoir conditions. These range *from* natural surface activity where the vapour dominated region is close to the surface through to the boundary *of* the vapour reservoir *at* its intersection with deep liquid dominated conditions. An interesting feature of *the* model is that vapour dominated conditions can first form at a pressure of 33 Bars(abs). This phenomenon appears to be unrelated to the maximum enthalpy of steam condition which occurs at a similar pressure.

INTRODUCTION

Vapour Dominated Geothermal Reservoirs have a number of very interesting features, explanations for which. to date, do not appear to have been universally accepted.
These features include:

(i) What appears to be a stable layer of water lying on top of a body of steam.

(ii) Steam reservoirs which always seem to occur at pressures in the region of 30 - 35 Bars(abs), with *a* pressure gradient *close* to steam static which in some reservoirs is continuous to indeterminate depth.

(iii) Production histories which can only be explained if relatively large amounts of Liquid water are present in the reservoir.

Explanations for the existence of a stable liquid condensate layer overlying a steam zone have been suggested by. among others, Schubert & Straus(1979 & 1980) and Schubert, Straus & Grant(1981).
The explanations referred to cite the Clapeyron equilibrium relationship coupled with relatively low rock permeabilities as providing a suitable mechanism.

James(1968) and McNitt(1977) have described the formation of natural steam zones in terms of the muimum enthalpy of saturated steam as both features seem to occur at similar' pressures

Mountfort(1980) has estimated the water content of the Kamojang reservoir in terms of residual saturations with a small quantity of mobile water present, and Grant(1979) has carried out a correlation based on the transient response of gaseous contaminants in the steam.

The classic model of a vapour dominated reservoir is that proposed by White. Muffler & Truesdell(1971) which relies on an overlying cap rock

The author has developed a reservoir model where, if recharge water is added at the surface and a counterflow conditions are assumed with steam rising from depth, a range of conditions occurs where a natural choke will be established which effectively restricts the upward flow of steam and the downward flow of water. Liquid dominated conditions can thus occur above the choke, and vapour dominated conditions below. The formation of this choke. which appears to be independent of geological features or rock permeabilities leads to reservoir models that are remarkably similar to real reservoirs.

Features of the model include-

(i) Formation of natural boundaries which can be @ in uniformly permeable conditions purely is a function of the properties of steam & water.

(ii) Natural surface activity can occur in the same uniform conditions without affecting the other features of the model.

(iii) The first formation of vapour dominated conditions occurs at a pressure of 33 Bars(abs), and this feature seems to be independent of the maximum enthalpy of steam condition.

(iv) An estimate of actual reservir permeability leads directly to the calculation of recharge and hence the steam/water proportions throughout the reservoir, and the full range of reservoir simulation calculations can be performed.

A conceptual model is first developed where the mass & energy balance required to maintain thermodynamic equilibrium throughout a vertical section is calculated. Determination of a range of possible conditions leads to a two dimensional model *that* is modified to approximate real conditions. Finally, the conceptual model is *corrected so that* gravity, viscosity and relative permeability effects are included.

CONCEPTUAL MODEL

If one considers the standard model of a vapour dominated geothermal reservoir. overlain by a condensate layer and underlain by a deep brine level, the vertical section is is shown in Fig 1.

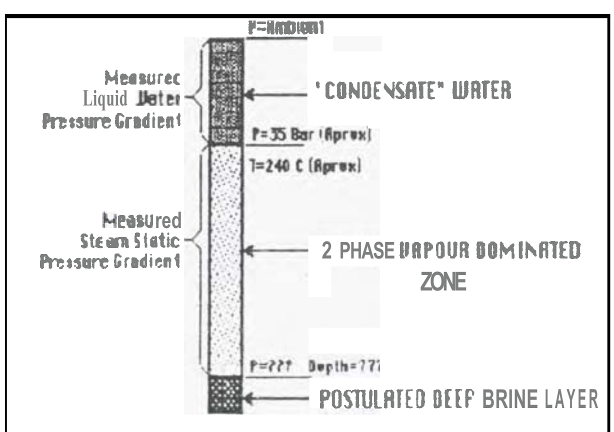

FIG 1-VAPOUR DOMINATED RESERVOIR-VERTICAL SECTION

If such a system is in a state of thermodynamic equilibrium throughout its depth, and a counterflow model is assumed then the steam/water proportions and relative flow rates can be calculated for any point on the vertical section.

Consider a unit inflow of water at the top of the system. This water will be heated by conduction & convection until it attains the saturation temperature for depth. Upon reaching this temperature, the water can co-exist with steam rising from below. As the water continues to descend through the rising steam it must gradually increase in temperature so that saturation conditions are maintained. Because the water is in intimate contact with the steam, and all temperatures, including the rock temperature, are controlled by boiling point for depth conditions, the water will be heated (with a corresponding increase in enthalpy) either directly or indirectly, by the condensation of *steam*.

The separate steam & water masses found at any depth (equivalent to pressure) in the reservoir, based on a unit inflow of water at the top of the system can be calculated by performing a sequential mass & balance energy balance for *every* pressure interval as shown in Fig 2

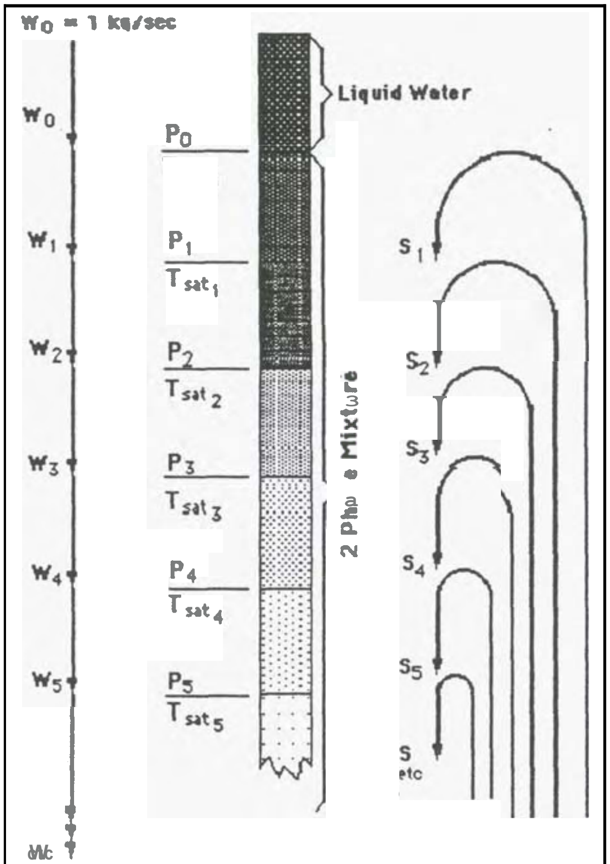

FIG 2 - ENERGY & MASS BALANCE

Let P_0 be the pressure where the unit inflow of water, W_0, first attains saturation temperature, $T_{sat\,0}$.

Then the mass of steam, S_1, condensed as W_0 passes through the pressure interval P_0-P_1 and increases in temperature from $T_{sat\,0}$ to $T_{sat\,1}$ is approximately

$$S_1 = W_0(h_{f1}-h_{f0})/h_{fg1}$$

$$\& \quad W_1 = W_0 + S_1$$

and similarily,

$$S_2 = W_1(h_{f2}-h_{f1})/h_{fg2} + S_1 - S_1(h_{g1}/h_{g2})$$

$$\& \quad W_2 = W_1 + S_2 + S_1 - S_1(h_{g1}/h_{g2})$$

where

$$S_1 - S_1(h_{g1}/h_{g2})$$

is a correction made to the steam & water flows to account for the fact that water will be condensed out or evaporated by the rising steam if the pressure is below or above that where the maximum enthalpy of steam occurs (31.19 Bar)

Steam & water masses, at every pressure interval, can then be calculated in a similar way as follows-

$$S_3 = W_2(h_{f3}-h_{f2})/h_{fg3} + (S_1+S_2)(1-(h_{g2}/h_{g3}))$$

$$W_3 = W_2 + S_3 + (S_1+S_2)(1-(h_{g2}/h_{g3}))$$

$$S_4 = W_3(h_{f4}-h_{f3})/h_{fg4} + (S_1+S_2+S_3)(1-(h_{g3}/h_{g4}))$$

$$W_4 = W_3 + S_4 + (S_1+S_2+S_3)(1-(h_{g3}/h_{g4}))$$

$$S_5 = W_4(h_{f5}-h_{f4})/h_{fg5} + (S_1+S_2+S_3+S_4)(1-(h_{g4}/h_{g5}))$$

$$W_5 = W_4 + S_5 + (S_1+S_2+S_3+S_4)(1-(h_{g4}/h_{g5}))$$

etc, down to the critical point, if necessary, and for a range of values of P_0.

A typical table of results is as shown in part, in Fig 3, where, in this example, P_0 - 3 Bars.

P (Bar)	Storm Condensed	Water Loss/Gain	Water Flow (kg/s)	Steam Flow (kg/s)
1.0000			1.0000	0.0000
1.2000			1.0000	0.0000
1.4000			1.0000	0.0000
1.6000			1.0000	0.0000
1.8000			1.0000	0.0000
2.0000			1.0000	0.0000
2.2000			1.0000	0.0000
2.4000			1.0000	0.0000
2.6000			1.0000	0.0000
2.8000			1.0000	0.0000
3.0000			1.0000	0.0000
3.2000	0.0044	0.0000	1.0044	0.0044
3.4000	0.0042	0.0000	1.0086	0.0086
3.6000	0.0040	0.0000	1.0126	0.0126
3.8000	0.0039	0.0000	1.0166	0.0166
4.0000	0.0038	0.0000	1.0203	0.0203
4.2000	0.0036	0.0000	1.0239	0.0239
4.4000	0.0035	0.0000	1.0274	0.0274
4.6000	0.0034	0.0000	1.0309	0.0309
4.8000	0.0033	0.0000	1.0342	0.0342
5.0000	0.0032	0.0000	1.0374	0.0374
5.2000	0.0032	0.0000	1.0405	0.0405
5.4000	0.0031	0.0000	1.0436	0.0436
5.6000	0.0030	0.0000	1.0466	0.0466
5.8000	0.0030	0.0000	1.0495	0.0495
6.0000	0.0029	0.0000	1.0524	0.0524
6.2000	0.0028	0.0000	1.0552	0.0552
6.4000	0.0028	0.0000	1.0579	0.0579
6.6000	0.0027	0.0000	1.0606	0.0606
6.8000	0.0027	0.0000	1.0632	0.0632
7.0000	0.0026	0.0000	1.0658	0.0658
8.0000	0.0124	-0.0001	1.0781	0.0781
9.0000	0.0115	-0.0001	1.0895	0.0895
10.0000	0.0106	-0.0001	1.1002	0.1002
11.0000	0.0102	-0.0001	1.1103	0.1103
12.0000	0.0097	-0.0001	1.1198	0.1198
13.0000	0.0093	-0.0001	1.1290	0.1290

FIG 3

STEAM & WATER MASSES

P_0 = 3 BAR

if the volume occupied by the steam/water mixture at each pressure interval is calculated ie,

$$V_n = W_n \cdot \nu_{fn} + (S_1+S_2+S_3+ \_\_ + S_n) \cdot \nu_{gn}$$

and if this process is repeated over all pressure intervals and for a range of values of P_0, then a set of results are obtained which can be plotted as the family of curves shown in Fig 4, where each curve represents a particular value of P_0

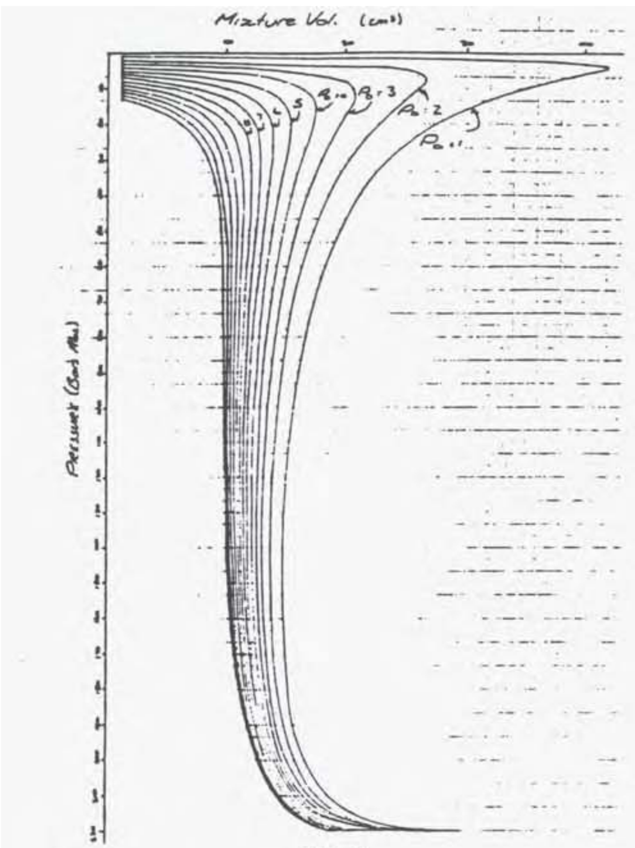

FIG 4

STEAM/WATER MIXTURE VOLUME vs PRESSURE

FOR A RANGE OF VALUES OF Po

An **interesting** phenomenon **can** be noted from Fig 4. For **values** of P_0 between 1 Bar(abs) & 12 **Bar(abs)**, the volume required **to contain** the equilibrium **steam &** water flows **starts at a small value (equal** to the specific volume of water) **at** P_0, **rises to a** maximum **value** at **some** higher **pressure,** and **then falls** off. For values of P_0 greater than 12 Bars(abs), **a similar** maximum **does** not occur **m d the volume required** continues to **increase steadily** rith **increasing pressure**.

For values of P_0 **between about** 2 **Bars(abs) & 12 Bars(abs)** the **volume increases again** at higher **pressures** md **eventually becomes larger** than the **previously determined maximum value**.

The **occurrence of the** upper maximum, which **is controlled** by **a relatively small range** of possible values of P_0 **is suggested** to be **the** feature which **leads** to the formation of vapour dominated **reservoirs and** steam caps above exploited liquid dominated **reservoirs.**

If it is **assumed** that the reservoir has uniform permeability **(any** value), urd **the** calculated value for **the** maximum **volume** it divided by unit thickness. then **an area is** found vhich is **just** sufficient to pass **the** upvard steam md **the dovnvard water flows** required to keep the **reservoir** in equilibrium. **(Based** on a recharge **at the** top **of the system of** 1 **kg/s)**. As the reservoir has uniform permeability. then **this area is also available** above and **belov. the** point vhere **the** maximum occurs. **At** all points vhere **the total available area is greater than that** required **to** pass the equilibrium **flow** rates, the **excess area can fill vith either steam or water.**

At points **in the** reservoir above vhere **the** maximum required **area** occurs, **the** supply of steam **from belov** is choked by the controlling reservoir **area m d** so the **excess area must** fill with **water**.
Conversly, **below the maximum, the** supply of **water** is choked and so the excess **reservoir** area. or volume. **vill fill vith** steam and a ***Vapour Dominated Reservoir*** **vill** result. This vapour dominated condition **will** continue **downwards** until **the** reservoir **area** required to pass the equilibrium **flov rates** becomes greater

than that available at the upper maximum. (Although further development of the model will show that the base water level is probably controlled by the boundary condition where the upper maximum and the lower increase above this controlling value become coincident).

The above argument applies to reservoirs of uniform permeability. We can briefly consider the effects that would occur in a real reservoir where the permeability is far from uniform. What happens in this case is that the controlling permeability is the *minimum* permeability (which can still have any value), and all other permeabilities found in the reservoir will be greater than this minimum. Where greater permeabilities occur above the choke point, then even *more* water can accumulate, and if greater permeability than the minimum occurs below the choke point then more steam can accumulate.

For values of P_0 greater than about 12 Bars(abs) where no maximum occurs, the reservoir area required to pass the equilibrium flow rates is always less than the controlling area (where ever it may occur at depth) so the excess area available will always fill with water and so Vapour Dominated conditions will not be encountered anywhere in the reservoir.

Referring back to Fig 4, for each value of P_0 considered, the maximum volume (or area) can be determined and the difference between this volume and that required at every pressure interval above and below calculated and the excess volume filled with water or steam as the case may be.

The **density** of **these new mixtures (containing** either more **water** or more steam than the equilibrium amounts previously **calculated)** can then be **determined** and **hence the depth of every pressure interval calculated** rith **respect to** tho **top** of tho **system**. The **results are plotted** in Fig **5**.

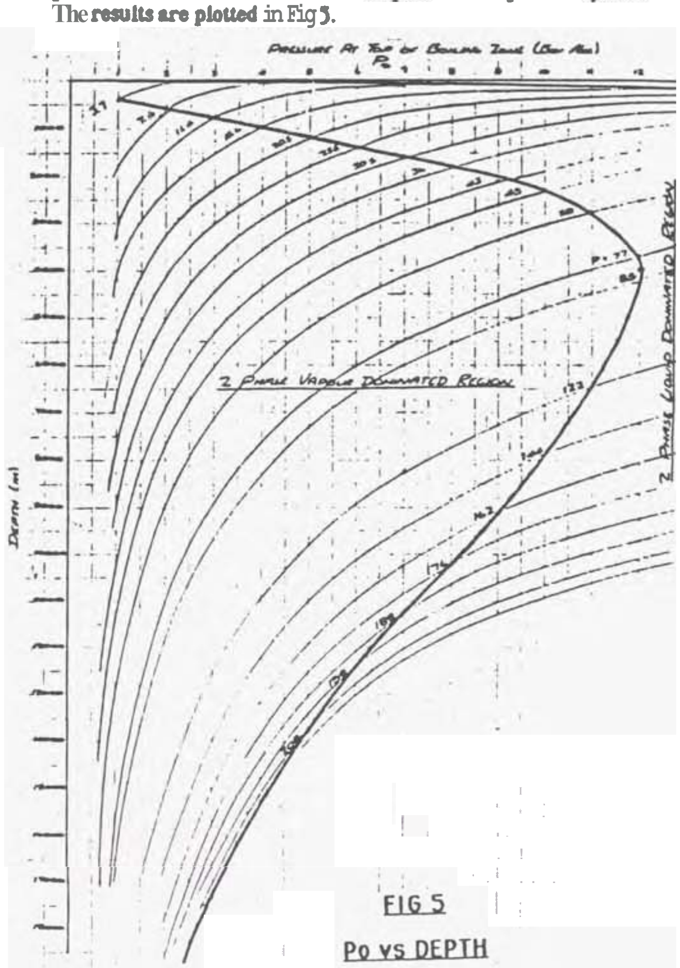

FIG 5

Po vs DEPTH

Points to note from Fig **5** (apart from the **fact that** it bears no resemblance to **m y known** vrpour **dominated** reservoir) **are as follows-**

(i) The **heavy** line is the locus of the depths where the upper **maximum area** or the lower **area equal** to this upper **maximum** occurs. The upper & lower maximums become coincident when P_0 **is** just **over 12 Bars(abs) and at a pressure** of about 85 **Bars(abs)**.

(ii) The lighter **lines are** isobars drawn through the **pressure** corresponding **to** the upper maximum **area and the lower area** corresponding to this for **each value** of P_0

(iii) Note that the terms *liquid dominated* and *vapour dominated* differ slightly from the normal convention The *Liquid Dominated Region* is where excess reservoir volume will fill with water.
The *Vapour Dominated Region* is where excess reservoir volume will fill with steam.
Both of the above regions contain a 2 phase mixture of steam & water
A single phase liquid water zone occurs as a thin wedge at the top of the system.

There **are two modifications that can** be **made** to the **reservoir cross section shown** in **Fig** *4* in order to **make** it more **realistic. Firstly, consider** the boundary *at* P_0=**12 Bars(abs). This is** the **shallowest** depth **at which an external influence can affect the vapour region, as at every other** point to **the left** on the **diagram, steam & water flows** and their relative proportions **are** controlled by **the** choke **that** *occurs* **at** the upper **area maximum.** Thus, the **pressure gradient within the vapour dominated region cannot be affected** by what is happening outside this region (within the **range of conditions that allow a vapour** region to **form** in the **first** place). **However,** when P_0=**12 Bars(abs),** the lower and upper maximum **area locations become** coincident. **Now,** *at* the **lower area** restriction. **similar** conditions to **those** applying *at* the upper **maximum** *occur.* **ie** there **is** just sufficient reservoir **area available to pass** the equilibrium **steam & water flows. Below** this point there **is** insufficient **area** rad either the **steam** or the **water flow will be restricted.** If the **water** flow is **restricted** then the **reservoir** will **gradually fill** up with **water and eventually** the **vapour dominated reservoir will disappear.** Therefore, the **steam flow must** be restricted and the **water allowed to drain. Thus the** lower **reservoir area** restriction **will** roughly **approximate** the deep water level with **most** of the **steam being produced by boiling** from this surface.

From Fig 5, this deep **water** level **will** *occur at* **a** pressure of approximately 85 **Bars(abs).** Thus. the **first** modification **we can make** to **Fig 5 is to reconstruct the 85 Bars(abs) isobar and make** it horizontal. The result is shown in Fig 6. which **is a** slightly more realistic **looking reservoir** cross section.

The second modification that can be **made is** to ignore regions of the vapour dominated region with pressures **less than** 31.19 **Bars(abs)** (corresponding to the maximum enthalpy of **steam),** simply because **vapour** dominated reservoirs do not **seem** to *occur* **at pressures below this** value. **This** point occurs **at approximately** P_0=**7.2 Bars(abs).** The reservoir is then **made symmetrical** about this **value of** P_0 **and** the cross section **as** shown in Fig 7 plotted.

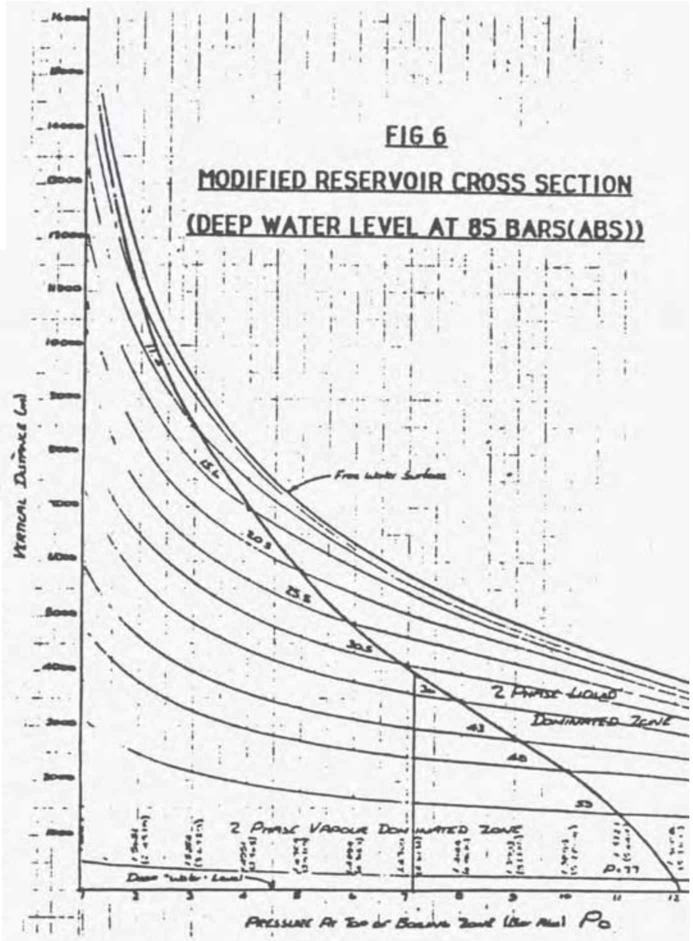

FIG 6

MODIFIED RESERVOIR CROSS SECTION

(DEEP WATER LEVEL AT 85 BARS(ABS))

(iii) The conditions that determine the maximum depth of the deep water layer have been established. (As the existence of the vapour dominated region depends on there being adequate drainage for the recharge water & condensate, a higher zone of impermeable rock will lead to a reduction in this maximum possible depth)

(iv) The slope of the isobars on top of and to the sides of the vapour dominated region will enable excess recharge water to flow away, which is important as the amount able to enter the vapour dominated region is strictly controlled by the maximum area limitation.

(v) The heat source is centrally located and the slope of the isobars in the vapour dominated region will allow the rising steam some horizontal movement towards the boundaries.

The reservoir cross section plotted in Fig 7 has a number of encouraging features. Among these are

(i) The existence of a vapour dominated reservoir is governed only by the thickness of the relatively thin top liquid **water** layer. If the thickness of this layer is outside *certain* limits it appears the the vapour **dominated** region collapses into **two** phase liquid dominated conditions. In other **words,** there **seems** to be no dependence on geological conditions or rock permeabilities. (Although **these features** can play *a* significant role in modifying the **standard** model)

(ii) The model has naturally occurring boundaries. created by the properties of steam alone

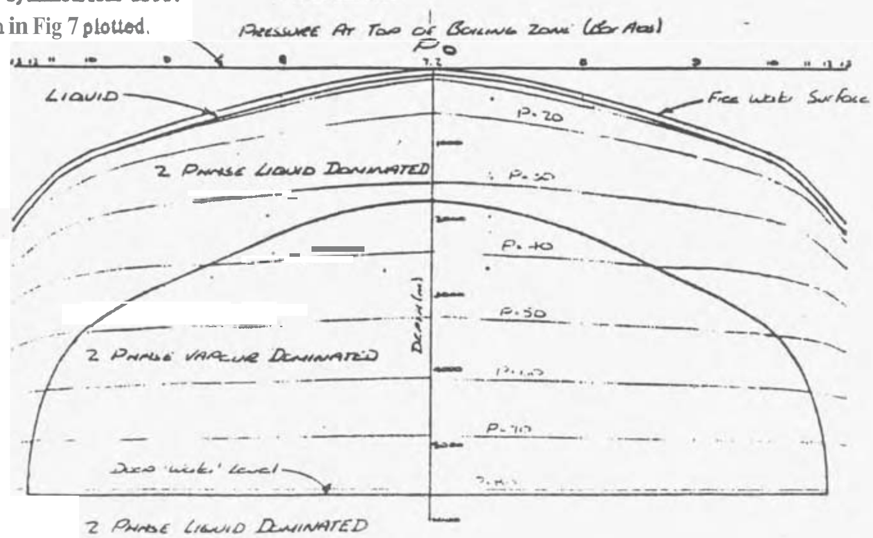

FIG 7

DEVELOPED CROSS SECTION OF RESERVOIR

(vi) Information is made available to assist with reservoir modelling. The insertion of estimated actual rock permeabilities should enable at least an order of magnitude estimate of the recharge water flow to be made and hence the determination of the natural heat flux available for exploitation at any particular depth. (Note that the reservoir shown in Fig 7 has no surface features and that the free water surface could be at ambient temperature. Thus the total available steady state power of a reservoir of this type could be 'quenched' by the recharge water and dissipated by deep drainage.)

(vii) The proportions of *mobile* steam and water within the vapour dominated region have been established (These proportions are not greatly affected by the properties of the reservoir rock) and consequently the reservoir pressure gradient can be established by calculating the mixture density at each pressure interval. For reference, Fig 8 shows the pressure gradient generated by this model (About 15% of the corresponding hydrostatic gradient in the vapour dominated region), compared with the normally assumed pressure gradient derived from the vertical section shown in Fig 1.

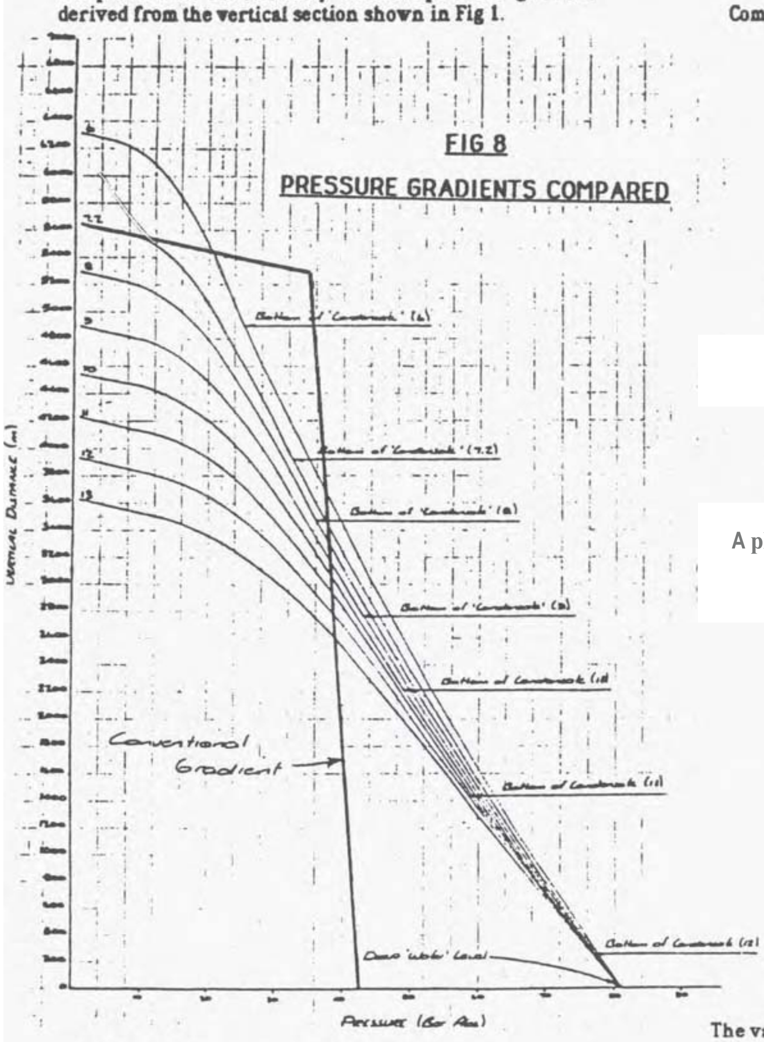

FIG 8

PRESSURE GRADIENTS COMPARED

It will be noted from Figs 7 & 8 that the depth to the point where vapour dominated conditions occur is somewhat deeper than normally found in nature. However, as previously mentioned, this model is based on uniform rock permeability and any increased permeability over and above the controlling minimum permeability will allow more water to accumulate in the liquid dominated region, increasing the pressure gradient, and raising the whole system.

It must be remembered however, that this is a conceptual model, where although mass & energy balance requirements have been satisfied, Darcy's flow equation, which is used to take into account gravity, viscosity & relative permeability effects has not been applied. So, although the conceptual model has been useful for developing a reservoir model that assists in understanding the features (and annomolies) found in a real reservoir it should be put on a firmer mathematical footing

MATHEMATICAL BASIS

Darcys Law for two phase flow can be written as follows-

$$U_W = -K(K_{rw}/v_w)(\Delta P - p_w g) \quad \text{———} \quad 1$$

$$U_s = -K(K_{rs}/v_s)(\Delta P - p_s g) \quad \text{———} \quad 2$$

With $U_w = w_w/A$ & $U_s = - w_s/A$

1 & 2 can be rearranged for counter flow conditions such that

$$\Delta P = p_w g - w_w v_w / K.K_{rw}.A \quad \text{———} \quad 3$$

$$\& \quad \Delta P = w_s v_s / K.K_{rs}.A + p_s g \quad \text{———} \quad 4$$

Combining 3 & 4

$$p_w g - p_s g = w_s v_s / K.K_{rs}.A + w_w v_w / K.K_{rw}.A$$

$$KA = \frac{w_s v_s / K_{rs} + w_w v_w / K_{rw}}{p_w g - p_s g} \quad \text{———} \quad 5$$

For straight line relative permeabilities (although in practice any permeability relationship can be used)

$$K_{rs} + K_{rw} = 1$$

$$\text{and} \quad KA = \frac{K_{rw}(w_s v_s - w_w v_w) + w_w v_w}{(p_w g - p_s g)(K_{rw} - K_{rw}^2)} \quad \text{——} \quad 6$$

A plot of this function has the form as shorn in Fig 9.

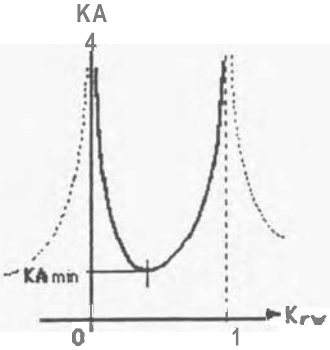

FIG 9 - PLOT OF EQUATION 6

The value KA_{min} represents the minimum reservoir area required for a given rock permeability to pass the equilibrium steam and water flows calculated at each pressure interval.
The value of K_{rw} corresponding to this condition can be found by differentiating 6 with respect to K_{rw}.

$$\frac{dKA}{dK_{rw}} = \frac{(w_s v_s - w_w v_w)(p_w g - p_s g)K_{rw}^2 - 2.(w_w v_w)(p_w g - p_s g)K_{rw} - (w_w v_w)(p_w g - p_s g)}{(p_w g - p_s g)(K_{rw} - K_{rw}^2)}$$

$$\text{and at} \quad \frac{dKA}{dK_{rw}} = 0$$

$$(w_s v_s - w_w v_w) K_{rw}^2 + 2.(w_w v_w) K_{rw} - (w_w v_w) = 0$$

Which has one root of K_{rw} between zero & one. Substituting this value in 6 gives the value of KA_{min} at each pressure interval.

This calculation can be repeated for all pressure increments and over a range of values of P_0 and a family of curves of KA_{min} vs P similar to those shown in Fig 4 obtained.

Curves plotted for low values of P_0 have the same characteristic maximum value as found in the conceptual model (in this use KA) which can be used to recalculate K_{rw} at all pressure increments above and below the interval where this maximum value of KA_{min} occurs.

Rearranging 6

$$KA(p_w g - p_s g) K_{rw}^2 + (w_s v_s - w_w v_w - KA(p_w g - p_s g)) K_{rw} + w_w v_w = 0$$

Which when solved gives the two values of K_{rw} which occur when an [illegible] greater than the minimum required to pass the equilibrium flows is available. Thus, at all pressure intervals above and below the interval where KA is a maximum, there is a choice of value of K_{rw} - representing either a higher or lower volume fraction of water than occurs when $KA = KA_{min}$. Using the same logic that was used in the argument for the conceptual model, the higher value of K_{rw} (ie higher water content) can be chosen for intervals above where KA is a maximum, and the lower value of K_{rw} (ie higher steam content) below.

The revised reservoir model can thus be developed using exactly the same procedure as that developed for the conceptual model.

Vapour dominated conditions occur over only a very small range of values of P_0 ie between $P_0 = 1$ & $P_0 = 2.6$ Bars(abs) approximately but the reservoir model produced is extremely interesting.

Calculations as detailed as those performed when constructing the conceptual model have not yet been completed. The model produced therefore lacks the resolution. but sufficient information is available to plot the reservoir section shown in Fig 10. Fig 10 is equivalent to Fig 6 of the conceptual model but includes additional detail below the horizontal isobar drawn to a pressure of 60 Bars(abs).

In Fig 10, the upper & lower KA maximums are coincident at a pressure of 33 Bars(abs) approx. thus, this isobar has been drawn horizontally as in the conceptual model.
Similar interpretations as made using the conceptual model can be made to this model. but with the following important modifications or exceptions;

(i) The occurrence of the coincident upper & lower KA maximums at 33 Bars(abs) is extremely significant as this is where the first formation of vapour dominated conditions will take place in the reservoir. The formation of natural steam which occurs at about this pressure in real reservoirs therefore may not be due to some property related to the maximum enthalpy of steam (which occurs at a pressure of 31.19 Bars(abs)), but could arise naturally as the result of counter flow reservoir conditions.

(ii) We do not need to discard half the model, as had to be done with the conceptual model. but instead can allow some surface activity in the form of surface water close to the boiling point of steam vents which can occur at $P_0 = 1$ or less.

(iii The natural boundaries still occur but in order for this model to fit a real reservoir, the theory put forward in the conceptual model concerning the position of the deep water level has to be modified somewhat in order that the vapour dominated region can have a reasonable thickness at pressures at or above 33 Bars(abs). It will be noted from Fig 10, that when the 33 Bar isobar is made

tend to be drained away from the vapour dominated region ie conditions outside the reservoir can have no effect. However, below the horizontal isobar, the isobar slope will allow external pressure conditions to affect the reservoir and the reservoir pressure will reflect conditions outside ie liquid dominated. This effect will occur for any isobar that is made horizontal. We could, in theory, have a horizontal water surface at the critical point, 221 Bars(abs). In this case there would be a very large vapour dominated reservoir with a higher pressure gradient than its suroundings. In practice though, it seems that the deep water level will occur just above the deepest permeable drainage zone. Further investigation of the deep reservoir may reveal a maximum possible depth, but unfortunately, it is not possible at the moment to make a prediction based on the properties of a uniformly permeable reservoir.

(iv) An actual value of KA is generated for each value of P_0 considered. Substitution of a value for average rock permeability will allow the reservoir [illegible] required to accept a recharge of 1 kg/sec to be readily estimated. This figure can be used in a range of reservoir engineering calculations.

(v) Fig 11 is an extract of the data produced for $P_0 = 2.0$ Bars(abs). It will be noted that in the Vapour Dominated region (between P=9 & 60 Bars(abs)), the value of K_{rw} (the water volume fraction in effect) lies approximately in the range .34-.38. Thus the pressure gradient in this region is about 30% of the equivalent hydrostatic pressure gradient.

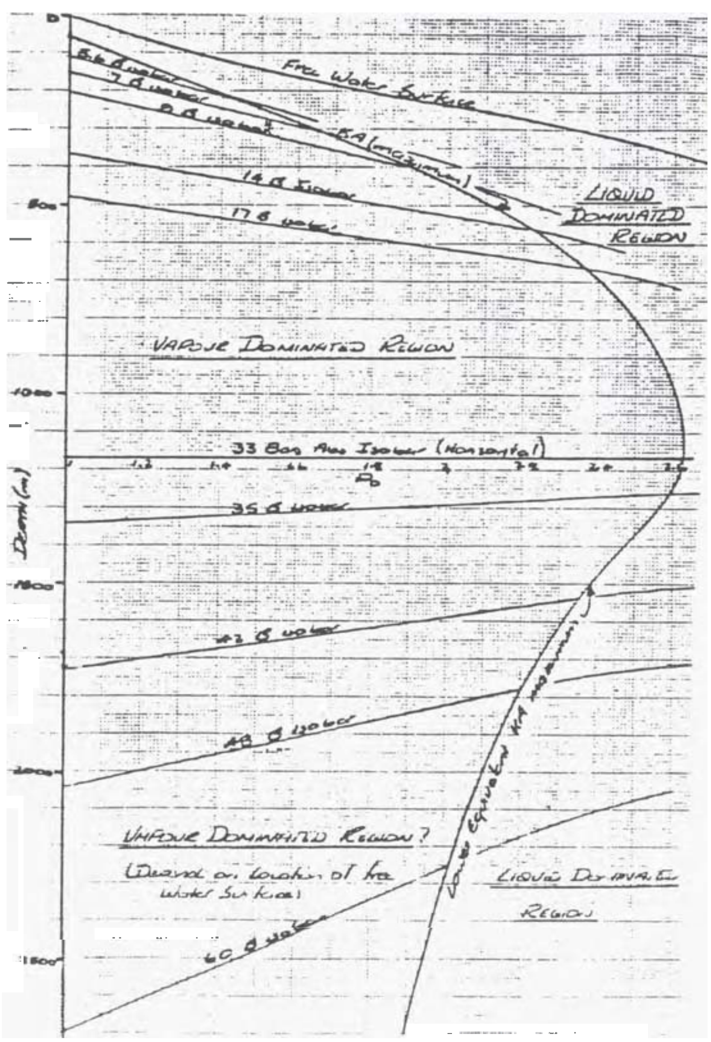

FIG 10

CROSS SECTION OF A POSSIBLE REAL RESERVOIR

P (Bar)	KA (m^4)	Krw (Liq. Dom.)	Krw (Vap. Dom)	dP (Pa/m)	Depth (m)
1	1.274E-10				
1.2		1.0000	0.2374	7143.1029	3.1253
1.4		1.0000	0.2273	7212.1778	6.2743
1.6		1.0000	0.2210	7247.2403	9.4616
1.8		1.0000	0.2144	7287.3884	12.6845
2		1.0000	0.2082	7324.8267	15.9437
2.2	5.967E-11	0.9316	0.2208	7189.5792	19.3182
2.4	7.365E-11	0.8745	0.2312	7075.8883	22.8016
2.6	8.325E-11	0.8275	0.2409	6970.5146	26.3933
2.8	9.045E-11	0.7875	0.2494	6877.3052	30.0899
3	9.68E-11	0.7502	0.2601	6765.6280	33.9049
3.2	1.016E-10	0.7187	0.2683	6677.0784	37.8284
3.4	1.053E-10	0.6928	0.2763	6591.8958	41.8614
3.6	1.076E-10	0.6738	0.2804	6542.3502	45.9841
3.8	1.111E-10	0.6478	0.2906	6438.5091	50.2335
4	1.136E-10	0.6263	0.2979	6360.9817	54.5956
4.2	1.158E-10	0.6069	0.3061	6276.4767	59.0782
4.4	1.174E-10	0.5915	0.3125	6208.0049	63.6726
4.6	1.183E-10	0.5812	0.3149	6176.6983	68.3529
4.8	1.189E-10	0.5739	0.3172	6146.8932	73.1190
5	1.204E-10	0.5581	0.3244	6073.1057	78.0068
5.2	1.218E-10	0.5425	0.3336	5982.3628	83.0335
5.4	1.227E-10	0.5305	0.3391	5924.5169	88.1746
5.6	1.235E-10	0.5197	0.3459	5855.8404	93.4422
5.8	1.238E-10	0.5137	0.3478	5830.8133	98.7986
6	1.242E-10	0.5085	0.3509	5794.8734	104.2555
6.2	1.24E-10	0.5092	0.3481	5811.8672	109.7629
6.4	1.25E-10	0.4943	0.3582	5715.7376	115.4306
6.6	1.256E-10	0.4837	0.3654	5644.4380	121.2386
6.8	1.262E-10	0.4721	0.3739	5562.7699	127.2015
7	1.266E-10	0.4617	0.3816	5488.0085	133.3162
8	1.263E-10	0.4660	0.3722	5538.5292	154.1691
9	1.274E-10	0.4151	0.4151	5135.6998	177.0348
10	1.267E-10	0.4531	0.3774	4781.7407	201.9981
11	1.269E-10	0.4434	0.3820	4843.5216	227.0428
12	1.269E-10	0.4447	0.3839	4811.4804	252.6569
13	1.267E-10	0.4524	0.3777	4726.3761	279.1420
14	1.268E-10	0.4493	0.3803	4733.9317	305.9939
15	1.263E-10	0.4620	0.3697	4608.8803	333.9946
16	1.258E-10	0.4720	0.3614	4507.8793	363.0524
17	1.261E-10	0.4667	0.3673	4536.3289	392.3548
18	1.256E-10	0.4757	0.3596	4446.7519	422.6831
19	1.252E-10	0.4853	0.3540	4352.9103	454.1102
20	1.252E-10	0.4860	0.3548	4333.3718	486.1259
21	1.251E-10	0.4880	0.3546	4303.5517	518.8135
22	1.247E-10	0.4942	0.3512	4240.3611	552.4450
23	1.239E-10	0.5073	0.3432	4122.1283	587.5109
24	1.241E-10	0.5047	0.3459	4131.8330	622.9633
25	1.241E-10	0.5062	0.3458	4108.6975	659.0866
26	1.241E-10	0.5053	0.3471	4104.8673	695.7155
27	1.237E-10	0.5115	0.3436	4044.6178	733.3689
28	1.236E-10	0.5147	0.3446	4009.3239	771.8369
29	1.237E-10	0.5147	0.3451	3999.5221	810.8833
30	1.24E-10	0.5118	0.3501	4012.7746	850.2835
31	1.238E-10	0.5149	0.3485	3979.1901	890.5029
32	1.239E-10	0.5161	0.3506	3960.3292	931.4029
33	1.234E-10	0.5225	0.3467	3901.5857	973.4152
34	1.236E-10	0.5210	0.3506	3904.0419	1015.8971
35	1.237E-10	0.5210	0.3509	3895.8415	1058.9656
36	1.24E-10	0.5179	0.3559	3911.2493	1102.3596
37	1.239E-10	0.5198	0.3548	3888.4056	1146.5066
38	1.241E-10	0.5180	0.3589	3894.9106	1191.0772
39	1.24E-10	0.5201	0.3589	3870.0440	1236.4346
40	1.239E-10	0.5233	0.3583	3838.2812	1282.6719
42	1.245E-10	0.5173	0.3664	3868.9623	1355.3906
44	1.248E-10	0.5148	0.3724	3872.5739	1429.0416
46	1.249E-10	0.5147	0.3764	3858.2612	1503.9699
48	1.254E-10	0.5101	0.3841	3878.8367	1579.4993
50	1.26E-10	0.5005	0.3957	3935.5468	1654.9246
52	1.265E-10	0.4918	0.4071	3984.9059	1730.3878
54	1.268E-10	0.4854	0.4168	4017.5541	1806.2019
56	1.273E-10	0.4671	0.4377	4135.1036	1880.7975
58	1.271E-10	0.4753	0.4280	4061.3063	1957.7024
60	1.277E-10	#NUM!	#NUM!	#NUM!	#NUM!

MAXIMUM VALUE OF KA
LIQUID DOMINATED ZONE
VAPOUR DOMINATED ZONE
GREATER THAN UPPER KA

FIG 11

RESULTS TABLE FOR Po= *2.0* Bars(abs)

Space does not permit a discussion concerning the apparent disappearance of the condensate layer. however. the author is currently re-evaluating measurements taken in the so called condensate & vapour regions of some real reservoirs.

The difficulty of interpreting downwell pressure & temperature measurements taken in two phase reservoirs is well known. Interpreting these measurements by comparing them with the theoretical well conditions described in this paper as opposed to trying to describe the reservoir in terms of the measurements is leading to some very interesting observations wbicb will be reported in a future paper

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NOTATION

- A — Area (m^2)
- g — Acceleration due to gravity ($=9.81\ m/s^2$)
- h_f — Specific enthalpy of liquid (kJ/kg)
- h_g — Specific enthalpy of vapour (kJ/kg)
- h_{fg} — Latent heat of evaporation (kJ/kg)
- K — Permeability (m^2)
- k_{rw} — Relative permeability with respect to water
- k_{rs} — Relative permeability with respect to steam
- P — Pressure (Bar or Pa)
- P_o — Pressure at first water saturation temperature (Bar)
- S_n — Steam condensed in each pressure interval (kg/s)
- T — Temperature (C)
- U_w — Mass flux density of water (kg/m^2s)
- U_s — Mass flux density of steam (kg/m^2s)
- v_f — Specific volume of water (m^3/kg)
- v_g — Specific volume of steam (m^3/kg)
- V — volume (m^3)
- W_n — Water flov (kg/s)
- W_w — Water flov (kg/s)
- W_s — Steam flov (kg/s)
- Δ — Change in
- ν_w — Kinematic viscosity of water (m^2s)
- ν_s — Kinematic viscosity of steam (m^2s)
- ρ_w — Density of water (kg/m^3)
- ρ_s — Density of steam (kg/m^3)

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