10 3/74

WAIRAKEI AND LARDERELLO: GEOTHERMAL POWER SYSTEMS COMPARED

By RUSSELL JAMES, Chemistry Division, Department of
Scientific and Industrial Research, Wellington

(*Received for publication, 30 July 1968*)

Summary

A comparative study is made of the exploitation for electric power of the superheated steam reservoir at Larderello, Italy, and the pressurised hot-water aquifer at Wairakei, New Zealand. It is concluded that these apparently dissimilar fields are both based on a liquid phase, the only significant difference being the greater relative depth of the underlying water at Larderello.

In contrast to some published ideas, it is submitted that dry-steam reservoirs can only exist with their top levels comparatively close to the ground surface and at a pressure not exceeding about 30 atmospheres. This has important implications in drilling for superheated steam, as expensive deep-drilling equipment is not required to reach the top of such a reservoir.

Future trends for both systems are predicted; the influence of dissolved chemicals in the water phase and noncondensible gases in the steam phase is considered.

THE LARDERELLO STEAM RESERVOIR

The first country to undertake the exploitation of a geothermal region for electric power on a large scale was Italy, where a number of power stations are now operating. The total electric energy drawn from the 15 km^2 of the Larderello main production field may be considered as approximately 10^4 MW-yr, i.e. 400 MW for 25 years. Although the early shallow drilling gave wet mixtures, it was found on drilling below the superficial water layer that a large steam reservoir with a pressure of about 30 atmospheres was penetrated. This reservoir steam, which was initially dry saturated (Chierici, 1961), becomes superheated when expanded through the vertical borepipe to the operating wellhead pressure of 5 atm. abs. Over the many years of discharge, the output of the boreholes has decreased and a continuous drilling programme is necessary to sustain the required flow-rate (Burgassi, 1961); during the same time, the enthalpy of the superheated steam at the wellheads has generally increased until it is well over that directly obtainable by separation from a water source (Chierici, 1961).

The causes of declining output and rising enthalpy have been the subject of study by many workers, both in Italy and elsewhere. Early theories suggested that the steam was of magmatic origin, released slowly into the main reservoir at depth; however, this is discounted because isotope studies (Chierici, 1961) have indicated that most steam is of meteoric

---

origin (i.e. rainwater). Th
systems, both steam and
accepted as being correct.
enthalpy exceeds that of
the reservoir.

Facca and Tonani (196
with water, which flashes
order of one metre from
distance they suggest that
and that not only is steam
separated by gravity and t
on entering the hole from
further suggest that the ste
paths through the permea
that the subsequent reduc
planation for the high deg

This argument is unten
from water has a maximu
be reduced by 30 cal g in a
in steam velocity on enteri
back to its original value.
this type of medium can a
retards the thermo-dynam
technical literature classi
that which takes place th
through the porous mediu
high steam velocity, the flo
in small diameter tubes.
pressure drop of the orde
occur in a distance of ab
only 5 cm length of a pass
on the water by the exp
phases within this distance
water flow, up to the spee
diameter, confirm this (Ja

Another serious objectio
alone enters the drillhole is
would occur at the spheri
recognized by Facca and T
within a matter of hours
theory as likely. If, on the
at high speed from a distan

origin (i.e. rainwater). This is in line with studies of other geothermal systems, both steam and hot-water (White, 1961), and is now generally accepted as being correct. The problem has been to explain why the steam enthalpy exceeds that of saturated steam if a water phase is present in the reservoir.

Facca and Tonani (1963) consider that the reservoir is actually filled with water, which flashes to a steam-water mixture within a radius of the order of one metre from the bottom of the borehole. Over this short distance they suggest that the pressure drops from about 30 atm to 10 atm and that not only is steam liberated as a result, but the associated water is separated by gravity and the steam becomes superheated as it slows down on entering the hole from the porous walls of the surrounding rock. They further suggest that the steam attains the speed of sound within the minute paths through the permeable medium prior to entering the drillhole, and that the subsequent reduction of velocity within the drillhole is the explanation for the high degree of super-heat.

This argument is untenable however, because steam newly separated from water has a maximum possible enthalpy of 670 cal/g and this would be reduced by 30 cal/g in accelerating to Mach 1. The subsequent decrease in steam velocity on entering the drillhole would merely bring the enthalpy back to its original value. Nor does it appear possible that flow through this type of medium can attain high velocity, because frictional resistance retards the thermo-dynamic expansion to that of constant enthalpy (the technical literature classically defines a constant enthalpy expansion as that which takes place through a porous plug). Even assuming the paths through the porous medium to be sufficiently wide and smooth to permit high steam velocity, the flow in these paths would still approximate to that in small diameter tubes. James (1964) has shown experimentally that a pressure drop of the order suggested by Facca and Tonani (1963) would occur in a distance of about 50 diameters, that is, it would extend over only 5 cm length of a passage 1 mm wide. Because of drag forces exerted on the water by the expanding steam, gravitational separation of the phases within this distance would not be possible. Tests on flashing steam-water flow, up to the speed of sound, through tubes as small as 1·7 mm diameter, confirm this (James, 1966b).

Another serious objection to the suggestion that a separated steam phase alone enters the drillhole is that under these conditions chemical deposition would occur at the spherical water face and choke off the flow; this was recognized by Facca and Tonani (1963) who calculated that it would occur within a matter of hours—nevertheless, they continued to regard their theory as likely. If, on the other hand, flashing hot water enters a drillhole at high speed from a distance of five centimetres, it is not at all certain that there will be sufficient time for deposition of minerals to take place in the short passage.

A final point can be made that Wairakei bores, tapping hot water, do not discharge superheated steam, but a steam-water mixture.

The case for a water-filled reservoir at Larderello having been rejected, that for a steam-filled reservoir is now considered, the liquid water phase being completely absent. Taking the exploitation area of Larderello to be 15 km^2 as adopted by Elder (1966), and assuming the draw-off over the last 25 years to have given 400 MW of electric power, the quantity of steam required approaches 10^{12} kg, assuming a turbine consumption of nearly 10 kg/kWh (Chierici, 1961). To decrease the hydrostatic steam pressure in the reservoir from an initial 30 atm to a final 20 atm (say) requires a steam zone with a depth far exceeding the depth of the Mohorovicic discontinuity, which in normal continental areas is about 35 km. As any steam released at such depths in volcanic regions would almost certainly be magmatic, with a temperature of approximately 1,000°c, and as its expansion, on moving to higher levels, would take place at constant enthalpy, it is clear that if such steam were tapped by boreholes, it would have much higher enthalpy than is found in practice. The isotope evidence is also inconsistent with this hypothesis, and it must, therefore, be considered untenable.

A compromise solution is now considered, in which the top levels of the Larderello reservoir are filled with steam and the lower levels contain water. This was suggested by Elder (1965) who placed the steam-water interface just beyond the reach of the deepest borehole drilled. In this case, the total mass of steam withdrawn would result in the removal of an equivalent 1 km^3 of the deep hot water, leading to a drop in the water surface by 660 metres. This water would be removed as steam by the boreholes, and the resulting decrease in the top reservoir pressure would cause increased evaporation from the deep water surface, thus constantly replenishing the lost steam. The increased length of the steam path, from say 2 to 2·66 km, would result in a fall in flow-rate of about 25% in 25 years (i.e. 1% per year) if the top steam pressure was held constant. Because the bores have actually reduced this pressure, the rate of evaporation must have risen, but not enough to maintain the original conditions. Increased drilling has therefore been found necessary at Larderello to meet the required power demands of the turbo-generators.

In an attempt to explain how a steam phase, leaving an evaporative water surface at a depth of 2 km, can attain the magnitude of superheat associated with the low wellhead pressures, Elder (*op. cit*) applied a study of the evaporation from surface hot pools by Banwell (1957) to the deep hot water interface. His main assumption—which he emphasized—was that the evaporative vapour in the immediate vicinity of the water surface

---

was reduced signific
remained at the origin
in order to account f
but Elder made no a
But this is not fea
on a water surface a
saturation pressure) t
frothing steam-water
still 30 atm. This wo
specific gravity of the
top 120 metres of the
to a rise in the froth
upper surface tempe
imposed steam press
This is necessary to r
water interface, a mo
of Elder (1965).
Elder's hypothesis
at higher temperatu
corollary of this argu
steam pressure of 10
of 312°c. If so, such
attractive for geothe
existence of steam re
The theme develop
based upon a steam-
and the initial steam
the ground surface) i
steam column (abou
surface would be 33
with the water surfac
the initial Larderell
condition, the frictio
steam reservoir is co
movement of this ste
enthalpy, which, for
the reservoir the ste
its pressure. Figure
be at point (a) and at
it is evident that the
portion of the dry sa
enthalpy. Througho

was reduced significantly below 30 atm pressure (to about 20 atm) but *remained at the original temperature* of 235°C; this assumption was necessary in order to account for the observed enthalpy of 685 cal/g in the boreholes, but Elder made no attempt to justify it in physical terms.

But this is not feasible, because a reduction in imposed steam pressure on a water surface at a boiling temperature of 235°C, from 30 atm (the saturation pressure) to as low as 20 atm, would lead to the generation of a frothing steam-water mixture down to the level where the pressure is still 30 atm. This would involve the top 120 metres of water, taking the specific gravity of the hot water as 0·82. The flashing and frothing of this top 120 metres of the water would result in a volumetric expansion leading to a rise in the froth surface by about 330 metres and reduction in its upper surface temperature to bring it into equilibrium with the newly imposed steam pressure (at 20 atm this temperature would be 214°C). This is necessary to retain temperature-pressure equilibrium at the steam-water interface, a more plausible requirement than the main assumption of Elder (1965).

Elder's hypothesis leads him to conclude that evaporation can proceed at higher temperatures still, without producing a steam-water zone. A corollary of this argument is that reservoirs may exist at, say, a saturated steam pressure of 100 atm, with an associated water surface temperature of 312°C. If so, such high pressure and temperature steam would be very attractive for geothermal power. However, as will be made clear, the existence of steam reservoirs with these qualities is most unlikely.

The theme developed in the present work, and applied to Larderello, is based upon a steam-water interface assumed at a depth of about 2·5 km and the initial steam pressure at the top of the reservoir (within 0·5 km of the ground surface) is taken as 30 atm. Due to the hydrostatic head of the steam column (about 3 atmospheres) the pressure imposed on the water surface would be 33 atm. This is considered to be nearly in equilibrium with the water surface (at 240°C) from which a slow evaporation supplies the initial Larderello natural steam flow. For this unexploited original condition, the frictional pressure-drop from the bottom to the top of the steam reservoir is considered negligible for very small flows. The vertical movement of this steam would lead to expansion at approximately constant enthalpy, which, for the stable condition envisaged, means that throughout the reservoir the steam would be close to the saturated temperature for its pressure. Figure 1 shows the condition of the steam at the interface to be at point (a) and at the top of the steam reservoir to be at point (b), hence it is evident that the constant enthalpy expansion coincides with the flat portion of the dry saturated steam line, which occurs at maximum possible enthalpy. Throughout the 2 km depth of the steam reservoir, the steam

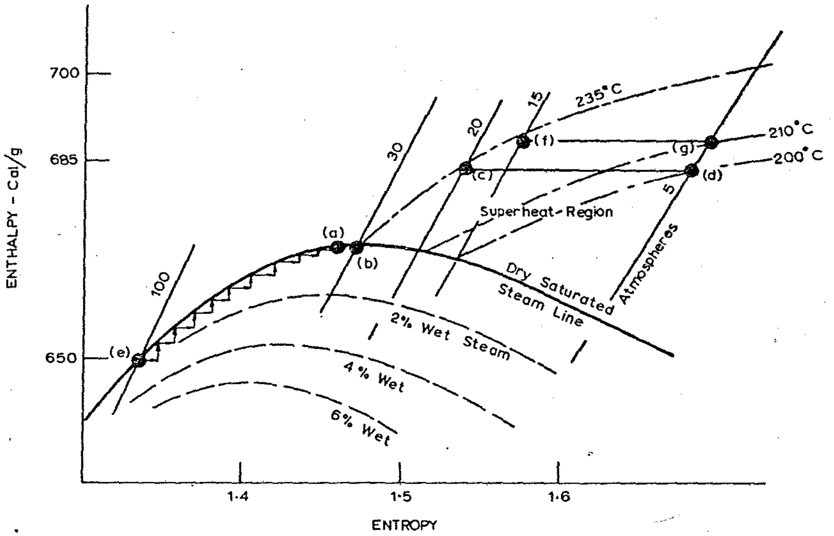

FIG. 1—Enthalpy—entropy diagram for steam (superheated, dry and moist)

and volcanic rock co-exist with temperature equilibrium of 240°c at the bottom and 235°c at the top. Because of the large heat content of the rock, which has the effect of inertia, a reduction in pressure within the steam reservoir due to exploitation by discharging boreholes will not lead to a significant drop in temperature. The magnitude of the thermal inertia can be shown by taking volcanic rock of porosity 0·1, specific gravity 2·5, and specific heat 0·2, in contact with slightly superheated steam at 30 atm pressure and specific heat 0·66. If thermal inertia is defined as the ratio of the change in heat content of the rock to the change in heat content of the steam in the pore spaces of the rock, for a small change in temperature, then for these conditions it is found to be approximately 420 (dimensionless).

Taking this into consideration, in Fig. 1, the condition line of falling reservoir pressure under exploitation would now nearly follow that of constant temperature instead of constant enthalpy. This may be illustrated by assuming, for example, that the top pressure falls from 30 atm to 20 atm* and that constant temperature conditions apply. The enthalpy of the steam would then increase to 685 cal/g instead of remaining at a constant enthalpy value of 670 cal/g. This is shown as locus (b)—(c) of

---

*Taking Elder's (1965) values of porosity = 0·1 and permeability = 3 millidarcy, a frictional pressure-drop of about 10 atm would be required over the depth of the reservoir to give the exploitation draw-off rate of 4 (10)^6 kg/h over 15 km^2.

Fig. 1. The effect
steam in 25 years
reduce the accom
This result has be
steam to the heat l
over the range 0·1

Hence the top
pressure decreases
largely follows a c
high discharges wi
wellhead pressure
200°c (if the drop

It should be not
pressure over the t
15 atm with a fall
about 230°c. On
this will now give
reduced flow-rate,
Both these phenon
superheat of the w

Ma

Because of the e
of 30 atm and a
higher pressure st
appeared possible,
New Zealand as h
steam-water inter
would be associat
However, no poc
field; at Wairakei,
of less than 20 a
210°c.

In order to de
likely phenomena.
steam-water interf
by point (e) on F
gives a slow flow
The steam-rock t
expansion of the

Fig. 1. The effect of thermal inertia in a reservoir yielding 10^{12} kg of steam in 25 years with a drop in pressure from 30 to 20 atm, would be to reduce the accompanying temperature drop from 21°C to less than 2°C. This result has been calculated by equating the heat gained by the rising steam to the heat lost by the volcanic rock, and is not sensitive to porosity over the range 0·1 – 0·3.

Hence the top temperature falls from 235°C to 233°C while the top pressure decreases to 20 atm. As the further steam expansion up a borehole largely follows a constant enthalpy expansion (except near the outlet at high discharges with velocities approaching that of sound), the flow to a wellhead pressure of 5 atm follows line (c) – (d) to a final temperature of 200°C (if the drop of 2°C is taken into account), at the wellhead value.

It should be noted that with continuing years of draw-off the reservoir pressure over the top regions may drop still further from 20 atm to say, 15 atm with a fall in temperature from the isothermal value of 235°C to about 230°C. On expanding through the borehole along path (f) – (g), this will now give an *increased* temperature of 210°C at the wellhead but a reduced flow-rate, owing to the fall in pressure at the bottom of the hole. Both these phenomena have been noted at Larderello, namely, increasing superheat of the wellhead steam and diminishing discharge.

Maximum Pressure of Dry Steam Reservoirs

Because of the existence of the Larderello steam reservoir with a pressure of 30 atm and a maximum temperature of 240°C, the discovery of still higher pressure steam reservoirs at perhaps deeper horizons has always appeared possible, particularly as water temperatures have been found in New Zealand as high as 260°C at Wairakei and 295°C at Waiotapu. If a steam-water interface exists at the latter temperature, for instance, it would be associated with a steam pressure of about 80 atm (1200 psia). However, no pockets of high pressure steam have been found in either field; at Wairakei, the few dry-steam bores operate with bottom pressures of less than 20 atm and flows derived from a steam-water interface at 210°C.

In order to demonstrate whether high pressure steam reservoirs are likely phenomena, a system is assumed to exist with a temperature at the steam-water interface of 312°C and a pressure of 100 atm; this is indicated by point (e) on Fig. 1. Evaporation from the underlying water surface gives a slow flow of steam upwards through the porous permeable strata. The steam-rock temperatures are in equilibrium with constant enthalpy expansion of the steam to regions of lower pressure (the system is considered as a natural one, i.e. exploitation by drilling is not taking place). It would be seen that the path representing such an expansion would lead from point (e) horizontally into the wet steam region, to give a continuous condensation up to a maximum wetness of 5% water from the flowing stream. The scrubbing action of the porous strata in removing water from the ascending vapour is shown by a series of zig-zag steps connecting point (e) to the top of the saturated steam curve where maximum enthalpy occurs. A constant water reflux downwards with a mass of about 5% of the ascending steam would take place, controlled by gravity. Gradual water logging of the interstices of the rocks would occur, with an increasing resistance to the steam flow. Eventually the amount of water held up in the rocks together with the counter-current steam flow would lead to flooding of the reservoir with a continuous water phase. Thus the water surface would move upwards, resulting in reduced pressure and temperature at the rising interface with the change in hydrostatic head. The evaporated steam would effectively follow the saturated steam line from (e) to the top of the curve close to points (a) and (b). It is only after the water has risen up to a surface pressure of about 30 atm that disengagement of steam from the interface can occur leading to steam at a maximum enthalpy value of 670 cal/g.

Of course, with drilling of this top region and steam draw-off sufficient to reduce the reservoir pressure below the stabilized natural state, the thermal inertia of the rock will cause the steam above the interface to now follow closely an isothermal expansion as has been mentioned. In relatively permeable rock, the flooding until the water surface is stabilised at about 30 atm pressure would result in thermal convection in the water phase and it is only close to the interface that the boiling point relation to hydrostatic pressure would occur (i.e. the saturated steam pressure associated with steam temperature). The initially assumed 100 atm pressure level would now be well under the water surface at a temperature below the saturated value of 312°c; at Wairakei it does not exceed 260°c at such high pressures. Where the rock is less permeable, however, thermal convection in the water continuum would be less free and the presence of numerous stagnant steam-gas bubbles would result in the temperature at various depths closely following the boiling point with hydrostatic pressure, as had been noted at Broadlands, for example. The same general result would eventuate, in that steam would be disengaged from water only at a point where the pressure has fallen to about 30 atm. This would not be affected by the small amount of wetness (order of 1%) caused by the potential energy requirements of elevating steam through a vertical distance of 2 km, as the small amount of water evolved would be removed in the manner already described.

Chemic

The chemical conce
0·25% dissolved salt
temperature-pressure
the discovery of a hot
1,600 metres near Nila
very high concentratio
exceeded 270°c and th
conclude that it was pr
a density-stratified int
metres. This seems ver
higher still. If a steam
owing to the high sa
approximately 22°c. If
this could be an altern
by Craig (1966), but
draw-off would then le
of the rocks. For exam
lent to the removal of
in the deposition of 0
surface (assuming the b
with respect to the sal
completely fill the voi
relatively static water

For a water surface f
as previously calculate
deposits would need t
affects permeability, na
rock particles. With t
conclusion that minera
the top steam with a
accord with the Italia
indicates that the Calif
of the order of 20%. He
and at the sides of the
concentration.

It is therefore assume
merely underly a zone
may occur, whose size
below the ground surfa
might account for the

Chemical Concentrations in the Deep Water

The chemical concentration in the hot water at Wairakei is only about 0·25% dissolved salts and has a negligible effect on the steam-water temperature-pressure relationship as published in steam tables. However, the discovery of a hot brine with 33·2% salt content in a hole drilled to 1,600 metres near Niland, California, indicates that it is possible to obtain very high concentrations. According to White (1963), the brine temperature exceeded 270°C and the specific gravity (at 20°C) was 1·262; this led him to conclude that it was probable that this fluid underlay less dense water with a density-stratified interface above the first casing perforation at 1,500 metres. This seems very likely, with perhaps a steam-water interface much higher still. If a steam-brine interface existed, calculations indicate that, owing to the high salt content, the boiling point would be raised by approximately 22°C. If such a fluid underlies the Larderello steam reservoir, this could be an alternative explanation of the high superheat, as suggested by Craig (1966), but further concentration of the chemicals with steam draw-off would then lead to gross mineral deposition within the interstices of the rocks. For example, with the Larderello total steam draw-off equivalent to the removal of about 1 km^3 of the bottom water, this would result in the deposition of 0·138 km^3 of minerals below the evaporation water surface (assuming the brine to be initially either saturated or supersaturated with respect to the salt content). For a rock porosity of 0·1, this would completely fill the voids to a depth of the order of 100 metres below a relatively static water surface over an area of 15 km^2.

For a water surface falling by 660 meters from a depth of 2 km to 2·66 km as previously calculated for the Larderello field under exploitation, the deposits would need to fill only that small fraction of the porosity which affects permeability, namely within the continuous cracks between discrete rock particles. With this order of deposition it is difficult to avoid the conclusion that mineral deposition would rapidly seal off the water from the top steam with an impermeable barrier in a manner too severe to accord with the Italian experience. A recent work by Helgeson (1967) indicates that the California brine is not saturated, having a concentration of the order of 20%. He presents reasons for saline gradients existing above and at the sides of the field leading to regions of much reduced chemical concentration.

It is therefore assumed here that such concentrated brines, when present, merely underly a zone of more dilute water, above which a steam reservoir may occur, whose size depends on the depth of the final water surface below the ground surface. Reverse osmosis as described by Sharples (1966) might account for the flow from the top of the brine reservoir of water of relatively low chemical content while retaining a higher content in the lower reservoir. In this case the effect of the gross porous media would be analogous to the 'filtering' action of the membrane in reverse osmosis.

Non-condensible Gases in the Steam Phase

Taking a water temperature at the deep interface as 240°C and a non-condensible gas concentration in the overlying steam as 4·5% as at Larderello, it is calculated that the vapour pressure is increased from a saturated steam value of 33 atm to 33·7 atm, where the increase of 0·7 atm is due to the partial pressure exerted by the gas; thus a slight disparity is to be expected between measured values and those in the steam tables.

Employing the formula derived from the study by Banwell (1957) of the evaporation rate *m*, from the surface of hot pools, to the case of deep hot water surfaces at boiling point:

$$m = 6{\cdot}55\,(10)^{-4}\,(\Delta p)\ \text{g/cm}^2\ \text{sec} \quad \ldots\ldots\ldots\ldots\ldots (1)$$

where Δp is the decrease in pressure in atmospheres close to the water surface.

The steam flow at Larderello for 400 MW at a turbine steam rate of 10 kg/kWh is $1{\cdot}11\,(10)^3$ kg/sec.

Taking a wetted surface area at the interface as 15 km² (the whole surface area is considered to contribute to evaporation, hence this is independent of porosity), the evaporation flow-rate is

$$\frac{1{\cdot}11\,(10)^6}{1{\cdot}5\ \ (10)^{11}} = 7{\cdot}37\,(10)^{-6}\ \text{g/cm}^2\ \text{sec.}$$

Substituting in equation (1)

$$\begin{aligned} 7{\cdot}37\,(10)^{-6} &= 6{\cdot}55\,(10)^{-4} \quad (\Delta p) \\ \Delta p &= 0{\cdot}01122\ \text{atm}\ (0{\cdot}1655\ \text{psi}) \end{aligned}$$

Thus the vapour pressure does not grossly decrease at the interface to 20 atm, as suggested by Elder (1965) but, on the contrary, remains at about 33·7 atm, 0·7 atm higher than the saturated pressure of 33 atm, owing to the gas partial pressure. The actual steam pressure reduction of 0·01122 atm to produce evaporation occurs within a few molecular mean free paths of the interface and is very small. It should be mentioned here that a pressure of 40 atm has been reported from Larderello from a deep drillhole with a maximum temperature of 240°C. This temperature, however, is too low to be matched with pressure if steam is the fluid encountered. Two alternatives can explain this aberration; either there is a high gas concentration present—calculations require 10 times the average, i.e. 44% by weight—or the hole penetrates about 90 metres below a water surface. The former explanation is the most probable as transient high gas flows have been reported (Penta, 1954), however, the latter explanation is not impossible as a bore could feasibly give a steam output from upper permeable horizons while penetrating below a water surface into relatively impermeable strata.

The superficial water layer *overlying* the Larderello steam reservoir and one more recently found at the Geysers, California (McNitt, 1961), indicate that the steam near the ground surface would meet increased resistance with water-logging of the rock pores. The most severe restriction on permeability would occur however at the steam-water interface *above* the steam reservoir where condensation of steam would result in the presence of a mass of non-condensible gas bubbles forming a greatly increased local barrier (the Jamin effect) to mass and thermal exchange between the phases. Such a barrier would be concentrated by the slow steam movement upwards and would operate as an effective membrane in holding the interface stable. Although there has been no specific study of the stability of such "membranes" between phases as distinct as a vapour and a liquid, a quasi-stability has been found by List (1966) for a higher density liquid flowing horizontally above another in porous media. Also Wooding (1960) has studied the stability factors involved when a hot liquid slowly rises towards a cold and denser one in porous media.

It was noted by McNitt (1961) that when the steam reservoir pressure at the Geyser was reduced (by the action of discharging boreholes), then the overlying steam-water interface *rose*. Conversely, when the reservoir pressure increased (on closing boreholes) then the interface *fell*. It appeared to tend towards hydrostatically balancing the underlying steam pressure. For a steam pressure initially of 30 atm, a superficial water layer of 300 to 400 metres thickness would suffice for hydrostatic balance. Therefore, drilling to below such a top interface would be required in order to penetrate the steam reservoir, the actual depth depending on the distance from the ground surface to the top of the superficial water layer. Assuming that this is fairly close (usually of the order of 100 metres), the minimum drilling depth to the steam reservoir would be about 0·4 km. Taking account of the various uncertainties involved, it seems that a drilling depth of less than 1 km is all that would be required—which is a generous allowance. Therefore penetration of *all* exploitable dry steam reservoirs should occur within this depth range and most probably at about 0·5 km (most of the productive holes at Larderello are drilled to between 0·4 and 0·6 km).

THE WAIRAKEI HOT WATER RESERVOIR

The effect of the large rate of draw-off of hot water from the reservoir at Wairakei (order of 70 million tonnes* per year) has led to a decrease in

---

*metric ton = 1,000 kilogram = 2,204 lb.

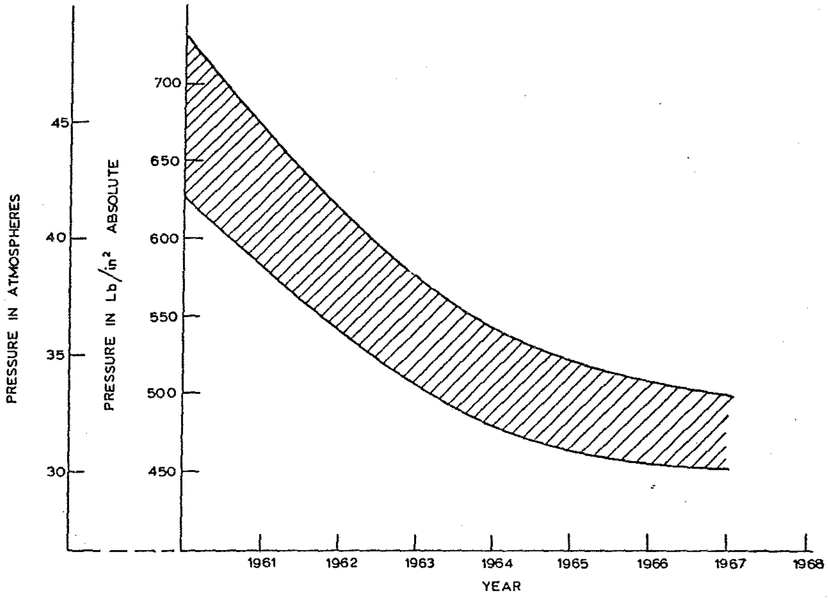

FIG. 2—Pressure decrease within Wairakei aquifer at a depth of about 600 m

pressure within the system. Measurements taken by the Ministry of Works over the last few years at about 600 metres depth (datum horizon taken at precisely 500 ft below sea level) in a number of selected bores within the production area, show the generalised fall given by Fig. 2. The curve is drawn as a fairly wide band as it represents the range of a number of values. It is seen that there is a tendency to level-out compared with the earlier rate of drop and it would appear to be leading to a terminal value of approximately 30 atm pressure, fortuitously close to that already indicated as the maximum possible pressure of geothermal dry steam reservoirs before exploitation. Whether such a final pressure condition is other than transient in an exploited hot water aquifer is difficult to assess at the moment, but it should be noted that the gross field output enthalpy has increased over the last 9 years from about 256 to 272 cal/g owing to the contribution of the large number of shallow bores drawing an increasing amount of free steam. With fall in the water quasi-level, steam is obviously appearing in greater amounts at the top reaches of the reservoir and will eventually lead to dry steam prevailing for the more shallow bores, leading to continuing fall in the reservoir pressure.

Making the simplifying assumption that the reservoir is of finite size without any replenishment, the levelling out of the pressure curve within

---

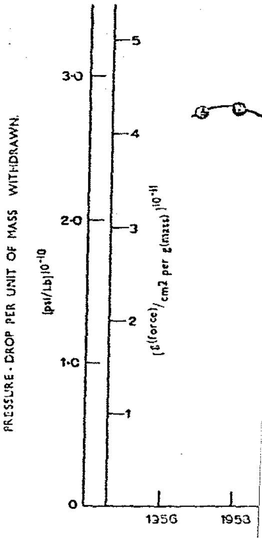

FIG. 3—Variation in p

the system is probab
attaining boiling poi
producing a fraction
volume of steam co
displace a large mass
30 atm, 1 g of steam
pores; this volumetric
rate of fall of the wate
in the internal pressu
mass of draw-off is s
depth which removes
in the annual mass v
tricity demands and

The curve of Fig.
1963 had been prec
which is not unusu
(Price, 1963). Althou
value, this would no
pressure-drop should
time and measureme
has transient stabilit

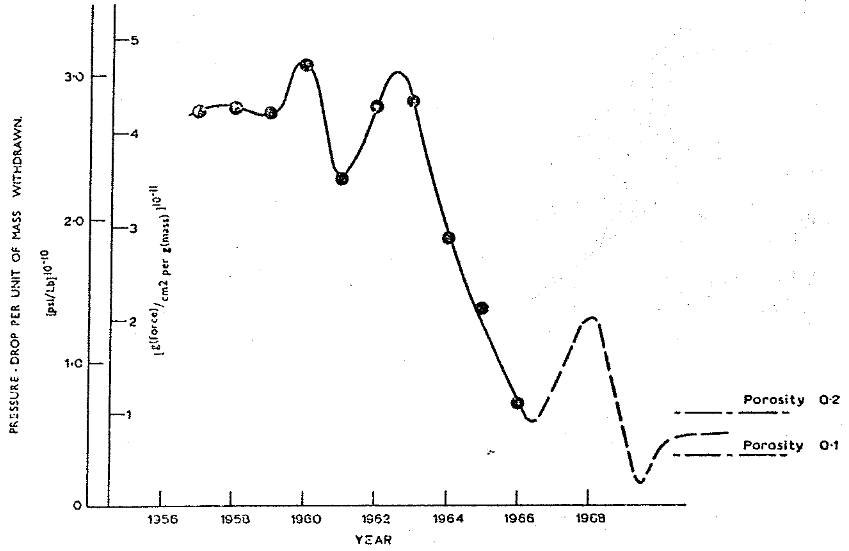

FIG. 3—Variation in pressure-drop within aquifer per pound of fluid removed

the system is probably caused by various hot-water horizons at depth attaining boiling point with drop in hydrostatic pressure, and thereby producing a fraction of steam *in situ*. Because of the greater specific volume of steam compared with water, even a small quantity would displace a large mass of water. For instance, at pressures of the order of 30 atm, 1 g of steam would expel about 50 g of hot water from the rock pores; this volumetric expansion due to steam formation would reduce the rate of fall of the water level and would therefore lead to a marked reduction in the internal pressuredrop. A graph of the yearly pressure-drop per unit-mass of draw-off is shown in Fig. 3 for the same location of 600 metres depth which removes the effect on pressure-drop (at this level) of differences in the annual mass withdrawn from the reservoir due to changing electricity demands and other variables.

The curve of Fig. 3 suggests that the large fall in pressure-drop after 1963 had been preceded by oscillation of the system—a phenomenon which is not unusual when one equilibrium state changes to another (Price, 1963). Although the curve would appear to be approaching a zero value, this would not be a situation attainable with draw-off and so the pressure-drop should again fluctuate before attaining a final value. Only time and measurements will determine if the most recent recorded value has transient stability or whether a series of de-escalations will continue until a gross change in the reservoir occurs when steam eventually prevails in the production zone. Fundamentally, such phenomena as oscillation and quasi-stability are caused by hysteresis (cause and effect being out of phase); this is particularly applicable when the physics of a system are undergoing such macroscopic changes as from water domination to steam control.

Assuming that such hot water horizons attain boiling point within the aquifer and progressively generate steam in proportion to the fall in imposed hydrostatic head with draw-off, it is possible by trial and error, to calculate the final rate of pressure-drop per unit mass withdrawn. As this is markedly influenced by the thermal inertia of the rock, predicted values are given on Fig. 3 for porosities of 0·1 and 0·2; also, an oscillation is imagined prior to a final stability and is sketched in accordingly with an amplitude and frequency roughly approximating to that of 1961 to 1964.

CONCLUSIONS

Due to the mechanics of flow of steam from water in porous media, it appears highly probable that a steam reservoir pressure of the order of 30 atm is the maximum to be found in superheated steam reservoirs. Such a pressure would be contained below a capping layer of ground water, hydrostatically balanced and stabilized by a relatively impermeable inter-facial "membrane" of non-condensible gas, thus the top of the steam zone is, most likely, within a drilling distance of 0·4 – 0·5 km, or less for lower pressure steam reservoirs. Deeper drilling than 1 km would not therefore be necessary for the proving of such dry steam systems—it may, of course, be considered a requirement for geological data or for the tapping of lower hot-water horizons, although these are likely to be relatively impermeable at very much greater depths with increasing rock overburden.

The importance of dry steam reservoirs is that they give a far longer life than those in which the underlying hot water is drawn and flash steam utilized (James, 1966a, 1967); however, the exploitation of the top zone of water-filled aquifers will lead to eventual change-over to dry steam systems, as appears to be in process at the present time at Wairakei. Thereafter the power-life may be considerably prolonged if there remains a reasonable volume of hot water below to supply the large quantities of evaporated steam required for the turbines. With continued draw-off, the steam should also gradually change from an initially dry saturated condition to one with increasing superheat as the thermal inertia of the volcanic rocks exerts a prevailing isothermal influence on steam disposed to expand

---

at constant enthal
superheating of the
surface at a depth
charge, the degree
will decline, leadin
gramme is required
at present at Waira
current with a fall i
But, whereas the It
in New Zealand is
developing within
increasingly displa

BANWELL, C. J. 1957:
Area. *N.Z. Dep. sc*
BURGASSI, R. 1961: P
Rome, Pap. G 65.
CHIERICI, A. 1961: F
Energy, Rome, Pap
CRAIG, H. 1966: Su
Areas. *Trans. Am.*
ELDER, J. W. 1965:
ELDER, J. W. 1966:
N.Z. Dep. scient.
FACCA, G.; TONANI
volcan. 27: 143-89.
HELGESON, H. C. 19
Sea Geothermal S
JAMES, R. 1964: M
Instn mech. Engrs
JAMES, R. 1966a: Po
lics Fluid Mech.
JAMES, R. 1966b:
N.Z. Engng, 21. 4
JAMES, R. 1967: Opt
221.
LIST, E. J. 1966: A C
Proc. 2nd Austr.
MCNITT, J. R. 1961
New Sources Ene
PENTA, F. 1954: Stu
Geofis. 7: 317.
PRICE, D. J. de S.
London.
SHARPLES, A. 1966:
WHITE, D. 1961:
Sources Energy,
WHITE, D. 1963: G
WOODING, R. 1960:
a Porous Mediur

n eventually prevails
mena as oscillation
l effect being out of
ics of a system are
ter domination to

ng point within the
tion to the fall in
by trial and error,
nass withdrawn. As
the rock, predicted
also, an oscillation
accordingly with an
at of 1961 to 1964.

in porous media, it
ure of the order of
n reservoirs. Such a
of ground water,
ively impermeable
is the top of the
of 0·4 – 0·5 km, or
g than 1 km would
steam systems—it
ical data or for the
likely to be relative-
reasing rock over-

ive a far longer life
n and flash steam
on of the top zone
over to dry steam
t Wairakei. There-
f there remains a
large quantities of
nued draw-off, the
lry saturated con-
rtia of the volcanic
isposed to expand

---

at constant enthalpy. This is the explanation presented for such similar superheating of the Larderello production steam when an underlying water surface at a depth of the order of 2·5 km is assumed. With further discharge, the degree of superheating will increase while the reservoir pressure will decline, leading to a fall in output—hence a continuous drilling programme is required to keep up with demand. An analogous situation occurs at present at Wairakei where increase in the field output enthalpy is concurrent with a fall in aquifer pressure; this also leads to a decline in output. But, whereas the Italian reservoir is considered to be relatively stable, that in New Zealand is now passing through instability due to the gross changes developing within the aquifer, as an originally water-filled volume is increasingly displaced by steam.

REFERENCES

BANWELL, C. J. 1957: Origin and Flow of Heat. *In* Physics of the New Zealand Thermal Area. *N.Z. Dep. scient. ind. Res. Bull. 123.*

BURGASSI, R. 1961: Prospecting of Geothermal Fields. *U.N. Conf. New Sources Energy, Rome, Pap. G 65.*

CHIERICI, A. 1961: Planning of a Geothermal Power Plant. *U.N. Conf. New Sources Energy, Rome, Pap. G.62.*

CRAIG, H. 1966: Superheated Steam and Mineral Water Interactions in Geothermal Areas. *Trans. Am. geophys. Un. 47:* 204.

ELDER, J. W. 1965: Physical Processes in Geothermal Areas. *Geophys. Monogr. No. 8.*

ELDER, J. W. 1966: Heat and Mass Transfer in the Earth; Hydrothermal Systems. *N.Z. Dep. scient. ind. Res. Bull. 169.*

FACCA, G.; TONANI, F. 1964: Theory and Technology of a Geothermal Field. *Bull. volcan. 27:* 143-89.

HELGESON, H. C. 1967: Geologic and Thermodynamic Characteristics of the Salton Sea Geothermal System. *Am. J. Sci. 266 (3):* 129-661.

JAMES, R. 1964: Maximum Steam Flow Through Pipes to the Atmosphere. *Proc. Instn mech. Engrs 178.* 473.

JAMES, R. 1966a: Power-Life of a Hydrothermal System. *Proc. 2nd Austr. Conf. Hydraulics Fluid Mech.*

JAMES, R. 1966b: Measurement of Steam-Water Mixtures at the Speed of Sound. *N.Z. Engng, 21.* 437.

JAMES, R. 1967: Optimum Wellhead Pressure for Geothermal Power. *N.Z. Engng, 22:* 221.

LIST, E. J. 1966: A Quasi-Stable Density-Stratified Flow in a Saturated Porous Medium. *Proc. 2nd Austr. Conf. Hydraulics Fluid Mech.*

MCNITT, J. R. 1961: Geology of the Geysers Geothermal Area, California. *U.N. Conf. New Sources Energy, Rome, Pap. G.3.*

PENTA, F. 1954: Studies of Exhalative Hydrothermal Phenomena. (In Italian) *Annali. Geofis. 7:* 317.

PRICE, D. J. de S. 1963: "Little Science, Big Science". Columbia University Press, London.

SHARPLES, A. 1966: Reverse Osmosis. *Sci. Jnl 2, 8:* 38.

WHITE, D. 1961: Preliminary Evaluation of Geothermal Areas. *U.N. Conf. New Sources Energy, Rome, Pap. G.2.*

WHITE, D. 1963: Geothermal Brine Well. *Science N.Y., 139:* 919.

WOODING, R. 1960: Rayleigh Instability of a Thermal Boundary Layer in Flow Through a Porous Medium. *J. Fluid mech. 9:* 193.