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VAPLIQ HYDROTHERMAL SYSTEMS, AND THE VERTICAL PERMEABILITY OF LOS AZUFRES, MEXICO, GEOTHERMAL RESERVOIR

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ABSTRACT

We identify a new category of natural hydrothermal systems intermediate between liquid- and vapor-dominated. This category is characterized by a "vapliq" vertical pressure profile, which is nearly vaporstatic in the shallower portion of the system, and nearly boiling-point-for-depth at depth. The prototype of these systems is the geothermal field of Los Azufres, Mexico. To explore the thermohydrological conditions conducent to this type of system, we propose a 1-D vertical scenario based on generally accepted conceptual models of liquid- and vapor-dominated geothermal reservoirs. We use the corresponding mass and thermal energy transport equations to establish that a necessary condition for the existence of 2-phase hydrothermal systems is that the absolute value of the vertical thermal flux must exceed Q_{min}, a parameter that depends only on the values of the pressure and of the thermal conductivity at the boiling point of the system. The values of Q_{min} are typically 1-4 times the average terrestrial flux. We also find that geothermal systems in which convective heat transport is accomplished by the well-known heat-pipe mechanism can exist only if the corresponding heat flux exceeds Q_{min} and the permeability at the boiling point of the system is smaller than k_{Bmax}, a parameter that depends only on the values of the pressure and of the thermal conductivity at the boiling point. Typical values of k_{Bmax} are $1\text{-}3\times10^{-18}$ m^2, suggesting a reason for the fact that all vapor-dominated systems are associated with very-low matrix permeability formations. Applying these insights, and the mass and heat transport equations to Los Azufres, we conclude that a contrast of 1-3 orders of magnitude exists between the vertical permeability at the boiling point and that corresponding to the vapor-dominated portion of the system. We propose that similar permeability contrasts may be responsible for the characteristic composite pressure profiles observed in other vapliq systems.

INTRODUCTION

The Los Azufres, Mexico, geothermal field presented in its natural state (Iglesias et al., 1985a; 1985b) an unusual pressure profile (Fig. 1) revealing a transition between a vapor- and a liquid-dominated hydrothermal system. Traditionally, geothermal reservoirs unperturbed by exploitation have been classified as either liquid-dominated or vapor-dominated. Thus, it seems relevant to ask whether similar hydrothermal systems exist, and to investigate the thermohydrological conditions conducent to their existence. Furthermore, the profile of Fig. 1 offered an oportunity to obtain insights on the vertical permeability and on other parameters of the system, that we attempted to exploit.

The thermohydrologic conditions for the existence of both liquid- and vapor-dominated systems have been addressed by several authors (e.g., Martin et al., 1976; Grant et al., 1982; Pruess, 1985). In the first part of this paper we explore the particular conditions conducting to the formation of vapliq systems. Then, we apply the results to obtain insights on the distribution of the vertical permeability and on other parameters of Los Azufres.

VAPLIQ SYSTEMS

The existence of a third type of geothermal reservoir, in which a transition between the traditionally recognized types is observable, has been demonstrated in Los Azufres, Mexico (Iglesias et al., 1985a; 1985b). We propose the name "vapliq" for these systems.

Vapliq systems are characterized by a vertical pressure profile which is nearly vaporstatic in the shallower portion of the system, and nearly boiling-point-for-depth at depth. The geothermal field of Los Azufres, Mexico, displays the prototype profile (Fig. 1).

We are aware of at least two more examples of vapliq systems, both in Italy. Pruess et al. (1987) persuasively argued that in its natural state the Larderello geothermal field also showed a transition between liquid- and vapor- dominated. And in Poggio Nibbio the pressure profile (Celati et al., 1976) offers clear evidence of the existence of another vapliq system.

ON CONDITIONS FOR THE EXISTENCE OF VAPLIQ SYSTEMS.

To explore the conditions for the existence of vapliq systems we consider the following 1-D vertical scenario, based on generally accepted conceptual models of liquid- and vapor-dominated geothermal systems. The unperturbed reservoir is in steady state. In the central part of the system, where there is a net wpward mass flow, the mass and heat transfer only have vertical components. We assume that at the base of the system there is hot compressed liquid that flows upwards nearly isoenthalpically (e.g., White, 1967). The fluid pressure decreases as it ascends, until the saturation pressure is reached. At this so called boiling point of the system ($p=p_B$, elevation $z=z_B$), the flow becames 2-phase. At this point, the liquid saturation $S_L=1$. As the flow proceeds to shallower horizons, pressure and liquid saturation decrease. Eventually, S_L reaches a value small enough for the vapor to become the pressure-controlling phase. At this transition point $p=p_{trans}$, $z=z_{trans}$. For $p<p_{trans}$ $(z>z_{trans})$ the pressure gradient is comparable with a vaporstatic gradient.

In this scenario conservation of mass can be represented by

$$F = F_L + F_V \tag{1}$$

where F, the net mass flux, is constant, and F_L and F_V, the liquid and vapor fluxes respectively, are, with z pointing upwards,

$$F_L = -(k k_L/\mu_L)\ \rho_L\ [\nabla p + \rho_L g] \tag{2}$$

$$F_V = -(k k_V/\mu_V)\ \rho_V\ [\nabla p + \rho_V g] \tag{3}$$

where k stands for absolute permeability, k_α, μ_α, ρ_α, for relative permeability, viscosity, and density of phase α, respectively, and g is gravity acceleration.

Similarly, energy conservation can be expressed as

$$Q = Q_{cond} + Q_{conv} \tag{4}$$

where Q, the thermal flux, is constant, and the conductive and convective fluxes are

$$Q_{cond} = -K\gamma\nabla p, \tag{5}$$

$$Q_{conv} = h_L F_L + h_V F_V, \tag{6}$$

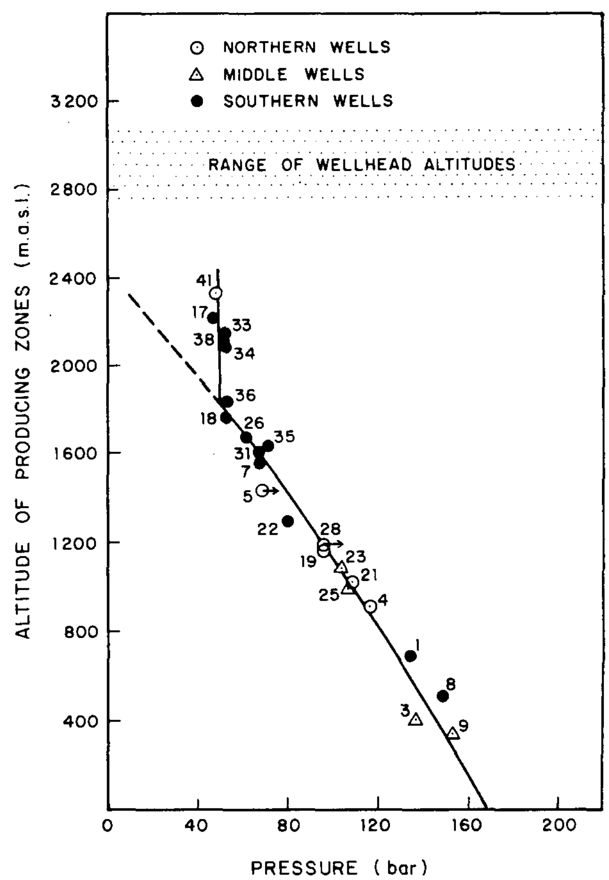

Fig. 1. Vapliq pressure profile observed at Los Azufres (after Iglesias et al., 1985b).

respectively. Here K is thermal conductivity, and $\gamma=(dT/dp)$.

At $p=p_B$, $k_L=1$, $k_V=0$, and from (1) and (6) the (constant) net mass flux is

$$F = [Q-K\gamma g\rho_L]_B/[h_L+(K\gamma\mu_L/k\rho_L)]_B \qquad (7)$$

In the compressed-liquid region FL>0 for the fluid to ascend. Thus, since in that region $F=F_L$ and F is constant in the system,

$$F > 0 \qquad (8)$$

It follows from (7) and (8) that in the central ascending part of 2-phase hydrothermal systems

$$Q > (K\gamma g\rho_L)_B \qquad (9)$$

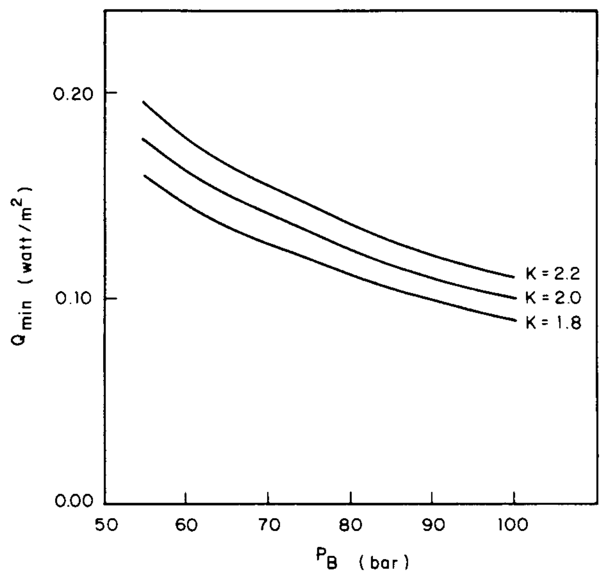

Fig. 2. Typical values of Q_{min}.

Note that Q_{min} only depends on K_B and p_B (or T_B, the temperature at the boiling point). Fig. 2 illustrates this dependence for some typical values of both variables. Considering that the average normal thermal flux at the surface of the Earth is approximattely 0.060 W m^{-2} (e.g., Elder, 1976; Jessop et al., 1976), we conclude that typical values of Qmin are about 1-3 times the average value of the normal terrestrial flux.

The heat-pipe mechanism is responsible for convective heat transfer in vapor-dominated hydrothermal systems (White et al., 1971; Martin et al., 1976; Pritchett, 1979; Strauss and Schubert, 1981; Pruess, 1985; Pruess et al., 1987). In these systems steam flows upward, condensates in the cooler upper regions, and results in liquid condensate flowing downwrad. A characteristic of this mechanism is that high heat fluxes are possible with negligibly small net mass fluxes. Heat pipes can also occur in liquid-dominated systems (e.g. Martin et al., 1976). Thus, in our scenario we assume that vapor-liquid counterflow occurs somewhere in the 2-phase region. For this to happen, F_L, which is positive for p> p_B (z< z_B), must change sign at some point characterized by $p=p_*$ ($z=z_*$), with $p_* < p_B$. From (2), and (6) we get

$$Q - (K\gamma\rho_L g)_*-h_{V*}F = 0 \qquad (10)$$

an expression that can be inverted to obtain p_*, if Q, p_B, k_B and K_* are known. In Fig. 3 we present results for p_B = 86 bar Tthe boiling point at Los Azufres), and $K_B=K_*=2$ $Wm^{-1}$$^oC$. This figure demostrates that in this case, for p_* to be smaller than p_B, k_B must be smaller than a certain value that we call k_{Bmax}. In other words, if the vertical distribution of thermal conductivity is uniform, a necesary condition for the existence of liquid-vapor counterflow (i.e. $p_* p_B$) is that the vertical permeability at the boiling point of the system must be smaller than k_{Bmax}. Fig. 3 also shows that k_{Bmax} corresponds to $p_*=p_B$. From this last condition and (10) we find

$$k_{Bmax} = [K\gamma\mu_L/\rho_L)/(h_V - h_L)]_B \qquad (11)$$

that only depends on K_B and p_B. Fig. 4 illustrates some typical values of k_{Bmax} for this case. These results indicate that the vertical permeability at the boiling point of hydrothermal systems with vapor-liquid couterflow, such as vapliq and vapor-dominated systems, must be relatively small, about $1\text{-}3\times10^{-18}$ m^2 for p_B in the range 50-100 bar, if the vertical distribution of thermal conductivity is approximately uniform. These results are compatible with the small matrix permeabilities measured in the Los Azufres andesites (Iglesias et al., 1987).

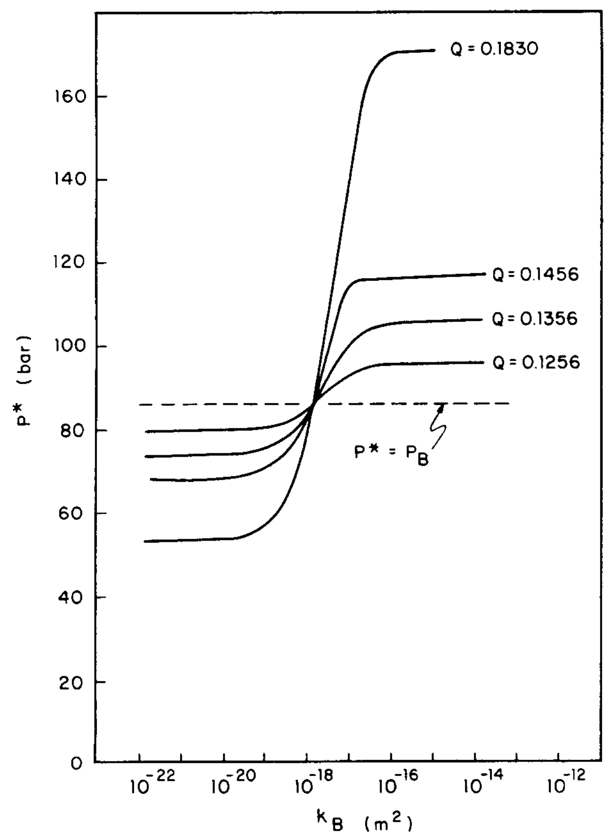

Fig. 3. The pressure at which F_L changes sign as a function of the vertical permeability at the boiling point and the thermal flux.

If the distribution of thermal conductivity deviates significantly from uniformity, i.e. $K_B=K*$, K_B can be greater than indicated in Fig. 4. In the few cases we have already explored, the maximum values obtained for K_B exceeded those of Fig. 4 by about one order of magnitude.

We belive these results are related to the fact (e.g., Pruess and Narashiman, 1982) that all known vapor-dominated systems are associated with low matrix permeability formations. Research is in progress to confirm or deny this suggestion.

THE VERTICAL PERMEABILITY DISTRIBUTION AT LOS AZUFRES

The observed pressure profile at Los Azufres is shown in Fig. 1. The boiling point of the system is approximately at p_B=86 bar, z_B=1300 m.a.s.n. (Iglesias et al., 1985b). Knowing p_B, one can estimate

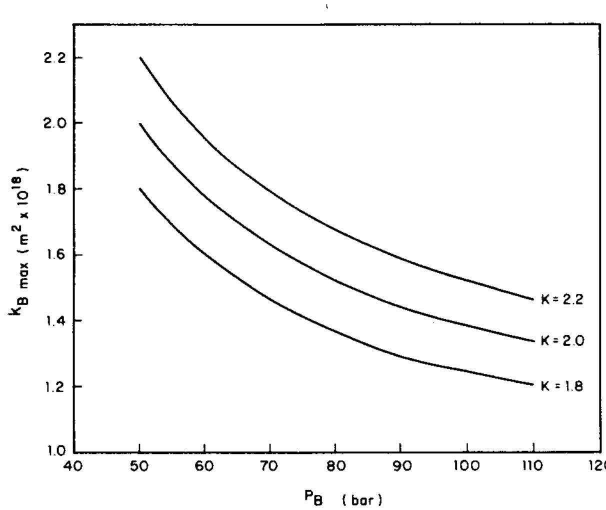

Fig. 4. Typical values of k_{Bmax}.

Q_{min} and k_{Bmax} for the systems, from (9) and (11). The thermal conductivity of the andesites (the predominant rocks) in Los Azufres ranges between 1.0 and 2.4 $Wm^{-1o}C^{-1}$, with a mean equal to 1.72 $Wm^{-1o}C^{-1}$ (Iglesias et al., 1987). The mean effective porosity of these rocks is about 10 % (Iglesias et al., 1987), and therefore the effects of the fluid conductivity on K are negligible. Taking the extreme measured value of K we find.

$$Q_{min} \sim 0.06\text{-}0.14 \text{ W m}^{-2}, \qquad (12)$$

$$k_{Bmax} \sim (0.74\text{-}1.76) \times 10^{-18} \text{ m}^2, \qquad (13)$$

The values estimated for k_B in (13) lie within the typical range of matrix permeabilities (smaller than 2.3×10^{-18} m^2) found for the Los Azufres andesites (Iglesias et al., 1987). This suggests that near the boiling point of the system the vertical flow proceeds predominantly through the rock matrix, not through fractures. More information about the vertical permeability at Los Azufres can be obtained from the profile in Fig. 1. One way to do this is to rearrange (1) and (4) to obtain

$$kk_L = \mu_L \ (Q+K\gamma\nabla p-h_V F)/[h_{LV}\rho_L(\nabla p+\rho_L g)] \qquad (14)$$

$$kk_V = -\mu_V \ (Q+K\gamma\nabla p-h_L F)/[h_{LV}\rho_V(\nabla p+\rho_V g)] \qquad (15)$$

In the liquid-dominated zone the pressure gradient is negative, and its absolute value is very close to hydrostatic (i.e., $\rho_L g$). Thus, even small errors in ∇p translate into great uncertainties for estimates of the effective vertical permeability. This approach is therefore impractical for liquid-dominated zones. In vapor-dominated zones the differences between ∇p and the vaporstatic term tends to be much greater, and practical estimates of effective permeability are possible. To apply this method we estimated Q via temperature gradients from stabilized temperatures in the caprock, obtained while drilling. Data from wells Az-9 , Az-23 and Az-28 (Alfonso Aragón, personnal communication) indicate $0.045<Q<0.380$ Wm^{-2}, with a mean value equal to 0.180 Wm^{-2}. Having estimates of Q, p_B, k_{Bmax} and K (and therefore of F), and considering the constraints

$$0 \le k_V \le 1.0 \le k_L \le 1 \qquad (16)$$

we obtain

$$k_{V\text{-}dom} > 1.5\times10^{-17} \quad m^2 \qquad (17)$$

for the vertical permeability in the vapor-dominated zone at Los Azufres.

A second approach to obtain permeability information from the profile in Fig. 1 is based on an expression for the pressure gradient

$$\frac{dp}{dz} = -g\left[\frac{k_V\,\rho_V^2\,\mu_L + k_L\,\rho_L^2\,\mu_V + F\,\frac{\mu_L\,\mu_V}{k\,g}}{k_V\,\rho_V\,\mu_L + k_L\,\rho_L\,\mu_V}\right] \qquad (18)$$

and a constitutive constraints equation

$$k_V\left[\left[\frac{Q}{k\,g}\right]\left[\frac{\mu_L}{\rho_L^2\,h_V}\right] - \left[\frac{F}{k\,g}\right]\left[\frac{\mu_L}{\rho_L^2}\right] - \left[\frac{k}{k}\right]\left[\frac{\gamma\,\rho_V\,\mu_L}{\rho_L^2\,h_V}\right]\right] + k_L\left[\left[\frac{Q}{k\,g}\right]\left[\frac{\mu_V}{\rho_L\,\rho_V\,h_V}\right] - \left[\frac{F}{k\,g}\right]\left[\frac{\mu_V\,h_L}{\rho_L\,\rho_V\,h_V}\right] - \left[\frac{k}{k}\right]\left[\frac{\gamma\,\mu_V}{\rho_V\,h_V}\right]\right] - k_L\,k_V\left[1-\frac{\rho_V}{\rho_L}\right]\left[1-\frac{h_L}{h_V}\right] = \left[\frac{F}{k\,g}\right]\left[\frac{k}{k}\right]\left[\frac{\mu_L}{\rho_L^2}\right]\left[\frac{\gamma\,\mu_V}{\rho_V\,h_V}\right] \qquad (19)$$

obtained manipulating equations (1)-(6) (e.g., Pritchett, 1979). In this approach one integrates (18) subject to the constraints (16) and (19), assuming values for Q, F, the vertical distributions of permeability and thermal conductivity, and relative permeability functions in terms of liquid or vapor saturations. One advantage of this approach is that, given p_B and z_B, it provides self-consistent estimates of Q, F, K, k_B and $k_{V\text{-}dom}$.

We first tried a simple model in which k and K were constant. Numerous integrations were performed for reasonable values of K and trial functions for the relative permeabilities, including Corey-type curves, "fracture permeabilities" ($k_L+k_B=1$), and others. The synthetic pressure profiles so generated could not satisfactorily fit the observed profile. The greatest discrepancy was in the profile's "knee" marking the transition between the liquid- and vapor-dominated regimes. To obtain acceptable fits it was necessary to adopt permeability values drastically greater than the estimates of k_{Bmax}, for the vapor-dominated zone. The two-permeability model ($k=k_B$ in the liquid-dominated zone, $k=k_{V\text{-}dom}=$ constant in the vapor-dominated zone) was able to generate acceptable fits. More complex models, with permeability monotonically increasing from k_B to $k_{V\text{-}dom}$ in a variety of ways, resulted unsatisfactory.

Our best fit is shown in Fig. 5. its parameters are $Q=0.0128$ Wm^{-2}, $F=8.26\times10^{-10}$ $kgm^{-2}s^{-1}$, $k_B=1.5\times10^{-19}$ m^2, $k_{V\text{-}dom}=1.0\times10^{-16}$ m^2 and $K=2$ Wm^{-1}. The value indicated for Q is consistent with that inferred from stabilized temperatures. The value obtained for k_B lies in the typical range found for matrix permeability in andesites from Los Azufres. The value indicated for K is close to the mean thermal conductivity found from measurements in drill cores for these rocks.

The two approachs indicate that in Los Azufres there is a vertical permeability contrast between the liquid dominated- and the vapor-dominated zone, with the deeper zone significantly less permeable. The permeability contrast is 1-3 orders of magnitude. These results suggest that similar permeability contrasts may underlie the characteristics pressure profiles of other vapliq systems.

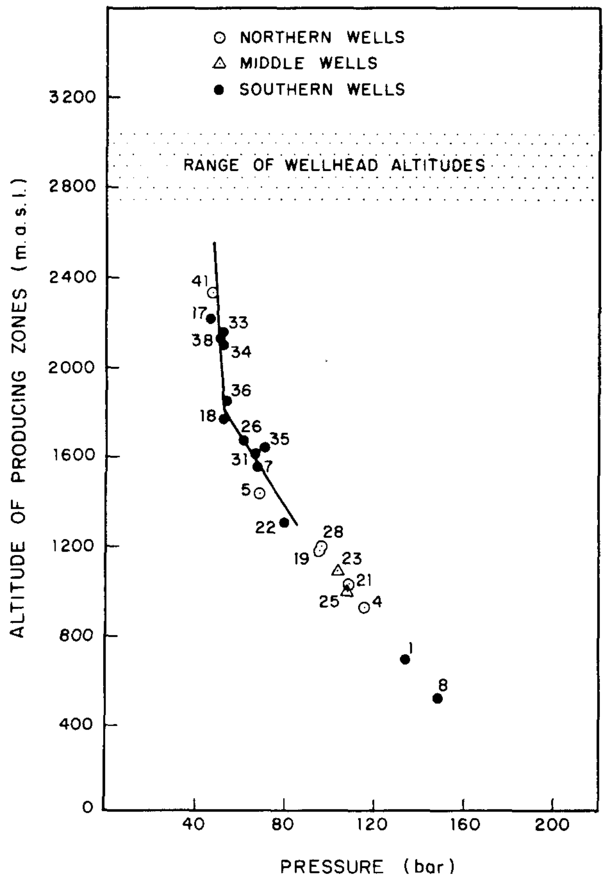

Fig. 5. Best fit to the observed profile.

CONCLUSIONS

We identified a new *category* of hydrothermal systems, that we call vapliq, which are intermediate between the traditionally recognized liquid- and vapor-dominated systems. Vapliq systems are characterized by a composite pressure profile which is nearly vaporstatic in the shallower zone, and nearly boiling-point-for-depth at depth.

A necessary condition for the existence of 2-phase hydrothermal systems is that the vertical thermal flux must exceed Q_{min}, a parameter that only depends on the values of the pressure and of the thermal conductivity at the boiling point of the system. Typical values of Q_{min} are 1-4 times the average terrestrial flux.

Our results indicate that the existence of hydrothermal systems with vapor-liquid counterflow is conditioned to having low (e.g., < 3×10^{-18} m^2) boiling-point permeabilities. This is consistent with the observation that all vapor-dominated and vapliq systems are associated with low matrix permeability formations.

Finally, in Los Azufres there is a vertical permeability contrast between the liquid dominated- and the vapor-dominated zone, with the deeper zone significantly less permeable. The permeability contrast is 1-3 orders of magnitud. These results suggest that similar permeability contrasts may underlie the characteristic pressure profiles of other vapliq systems.

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