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STORED HEAT AND RECOVERY FACTOR REVIEWED

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ABSTRACT

Recovery factor has been computed for a number of fields with long production history or well-supported reservoir simulation. The recovery factor is not a fixed constant but depends upon the definition of the reservoir volume and the reference temperature.

With a tight reservoir definition, and reference temperature at ambient, observed recovery factor is 13±5%. This case corresponds to the traditional USGS definition but the recovery factor is halved. When the reference temperature is at separation, the recovery factor is 27±15%. When a wide definition of reservoir volume is used, and ambient reference temperature, the recovery factor is found as 5±2%.

INTRODUCTION

The stored heat method was defined by White & Williams (1975) and Pálmason et al. (1985). In the following decades it became apparent that there had been significant overestimates and there were ongoing efforts to adjust the method. (Grant, 2000, 2015, Sanyal et al 2002, 2004, Williams 2004, 2007, Stefansson 2005, Garg & Combs 2010, 2011, Quinao & Zarrouk 2014). There is now sufficient data in the public domain to define actual recovery factor achieved in a number of fields. This paper summarizes those results.

METHOD

Calculation

The stored heat contained within a volume of rock is given by:

$$Q = \int \left[(1-\varphi)\rho_r C_r\left(T - T_{ref}\right) + \varphi\rho_w\left(h_w(T) - h_w\left(T_{ref}\right)\right)\right] dV$$

where the subscript *r* refers to the rock and *w* to water. The integral is over the entire volume, and the amount of heat is the total heat stored in that volume, above the reference temperature T_{ref}. In practice this expression is only weakly dependent on the porosity φ, and this expression can be simplified to

$$Q = \int \rho C\left(T - T_{ref}\right) dV$$

where ρC is the volumetric heat capacity of the saturated rock. This does not vary greatly between rock types and a value of 2.5×10^6 J/kg.K is representative. Often the reservoir is idealised as having a constant thickness, and a representative average temperature T_{av}, and the expression then becomes

$$Q = \rho C\, A\, h\, (T_{av} - T_{ref})$$

where *A* is the reservoir area and *h* the reservoir thickness. Finally, the recoverable heat is given by

$$E = \eta Q = \eta \rho C\, A\, h\, (T_{av} - T_{ref})$$

where η is the recovery factor, the proportion of the heat in the reservoir that can be recovered.

Reservoir volume

The thickness and area of the reservoir are usually difficult to define accurately. Williams (pers. comm.) has stressed the importance of a clear definition. At one extreme a tight definition takes an area and thickness around permeable zones found by drilling, usually with a margin such as 500m. An explicit method is given in the Appendix. This can be considered a high confidence estimate. At the other extreme a wide definition takes an area out to a geophysical or structural boundary, or all the area within a cut-off temperature, which is the minimum temperature at which wells can produce. This produces a low-confidence estimate since it will including undrilled areas.

Reference temperature

Several choices are possible for the reference temperature: ambient, reject temperature or separation temperature. The ambient temperature is the average surface temperature at the project, often taken as 20°C. The reject temperature is the exhaust temperature of the project. For a condensing turbine this will be ambient, for a binary system it is higher. For direct use it is the temperature of the waste water. The temperature of separation is used, on the basis that all the heat in the water, below this temperature, is discarded. Any of these choices are possible. However, whichever choice is made it must be applied consistently, and the recovery factor derived from observed field performance using the same definition.

FIELD CALCULATIONS

The fields reviewed are all volcanic (CV-1, CV-2 and CV-3) in the classification of Moeck et al. (2015), and so the results are applicable only to such volcanic fields.

Ngatamariki

The calculation method is described in the Appendix. Resource capacity was assessed by simulation (Clearwater et al. 2011, 2012, Grant & Bixley 2011). A major issue emerged. There is a highly permeable cold water aquifer overlying the field, and downflows of cold water could develop if reservoir pressure fell. For this reason a strategy of full injection to maintain pressures was adopted, and binary plant chosen rather than flash plant (Boseley et al. 2010b, Clearwater et al. 2015). Simulations showed that the planned development of 82MW (net) could be supported.

Sensitivity testing

Model sensitivity was tested (Moon et al. 2014, Quinao & Zarrouk, 2015). These provide a probability range over future performance for a defined project using the existing wells only, ie they do not test the field to depletion. Both demonstrate that the exising project can continue to perform for 50 years with relatively little change in well performance and total production. With a tight definition, reservoir area is 3.5 km^2., with a wide definition, 15.5.km^2. With the simulation history for 50 years, this gives a recovery factor of 14 and 3% respectively.

Brady Hot Springs

Production history for this field is provided by GeothermEx (2004) and Ormat (various). Reservoir area and cross section is reported by GeothermEx (2004) and Laboso & Davatzes (2016). Figure 1 shows the decline in production temperature. Recovery factor to date is estimated as 20%, but with very poor control due to uncertainty about definition of reservoir volume. This calculation uses ambient reference temperature and a tight area definition.

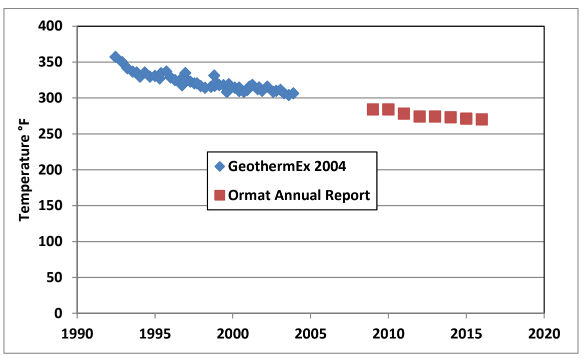

Figure 1. Brady production temperature.

Ohaaki

Ohaaki has installed capacity of 116MW but has produced below this for most of its history, as shown in Figure 2.

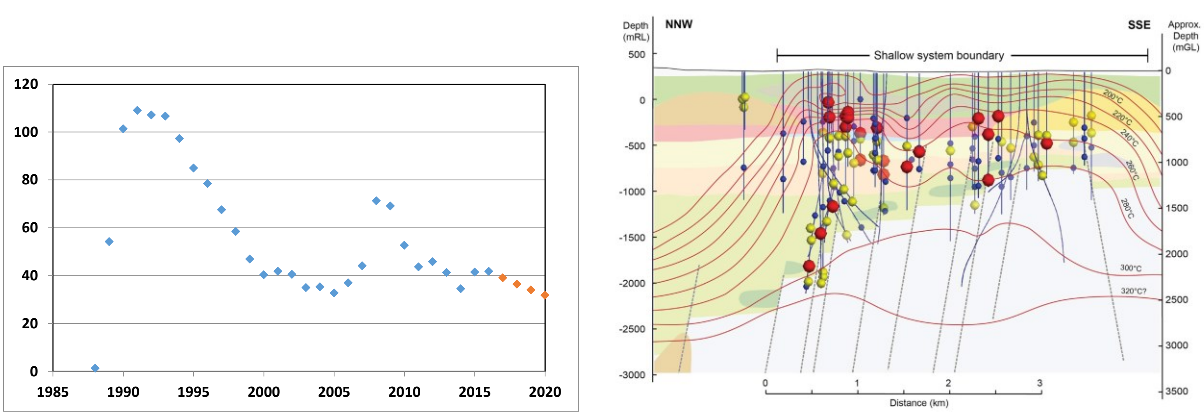

Figure 2. Left, Ohaaki production, MW. Extrapolated 2017-2020; Right cross-section of Ohaaki (Mroczek et al. 2016). Dots on wells indicate permeable zones.

Total heat produced 1988-2020 is $4.7x10^{17}$ J relative to 20°C (Contact, pers. comm.). Reservoir area is 4 km^2, on a tight definition. Figure 2 shows a cross section with permeable zones marked on wells. There is a well-defined top to the reservoir near sea level. Permeability extends to the greywacke and a short distance into it. Thickness of the permeability ranges from 800m in the east to 2000m in the west, giving an average of 1400m. Adding a margin of 500m below gives a thickness of 1900m. With reservoir temperature of 275°C, and volumetric heat capacity of $2.5x10^6$ J/m^3.K, total heat stored above 20°C is $4.8x10^{18}$ J. Actual recovery factor, relative to this tight definition of area, is 10%.

Rotokawa

There have been four simulations of Rotokawa, at various stages of development. These are catalogued in Hernandez et al. (2015a). Only two are published, and only for the last are forward projections published. Figure 3 shows one set of results.

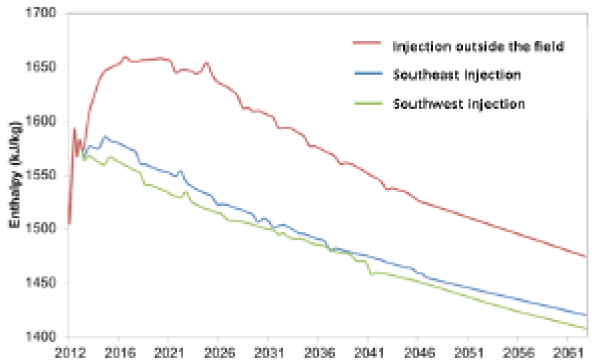

Figure 3 Simulated enthalpy, 2012-2061 (Hernandez et al. 2015b)

Using a tight definition of resource area, and stored heat relative to 20°C, recovery factor to the end of 2014 is 2%. Simulated recovery factor to 2061 is 16% but there must be considerable uncertainty about the simulation so far ahead

Kamojang

The actual production to 2008 is taken from Sofyan et al. (2010). Future production was estimated by decline analysis (Sanyal et al. 2000), who also give the field area of 14 km^2.

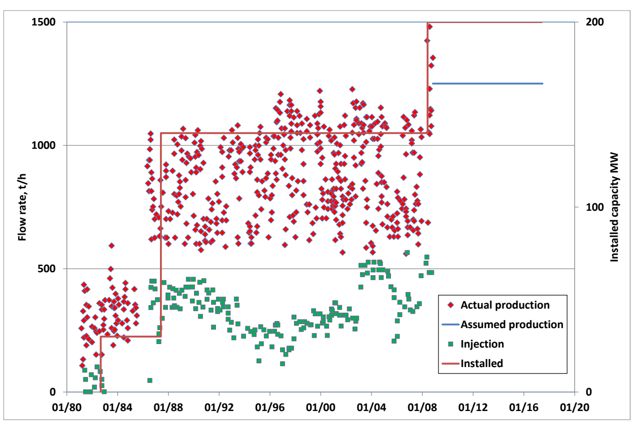

Figure 4. Kamojang installed capacity and production

Recovery factor is 8%, or 5.5% on a wider area.

The Geysers

Production history is given by DOGGR. The traditional (wide) field boundary encompasses 170 km^2, and reservoir thickness is 5000 ft (Khan, undated). This gives a recovery factor of 5.5%.

Momotombo

Figure 5 shows the production history, and the wellfield.

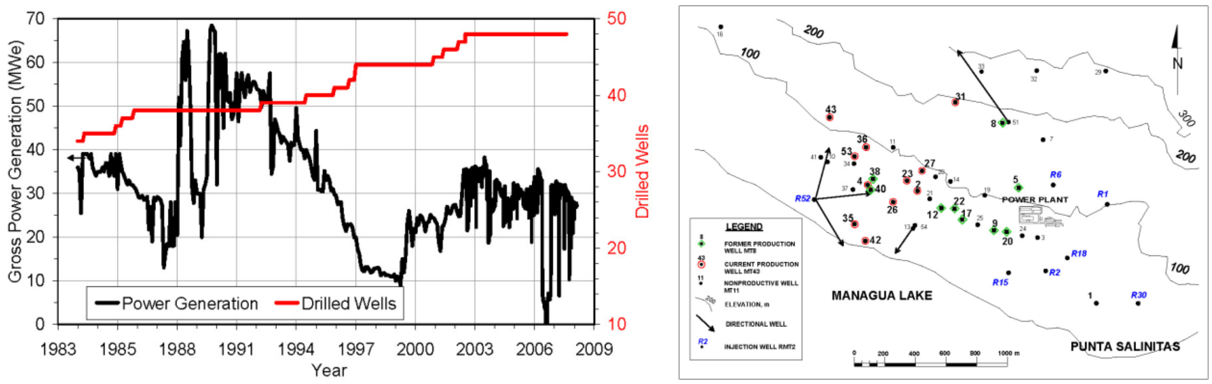

Figure 5. Momotombo production history and wellfield (Porras & Bjornsson 2010)

With a tight area of 2.2 km^2, and a thickness of 1100m, recovery factor is

- Using a tight volume definition and reference temperature at separation, the recovery factor is 32%.
- Using a tight volume definition and reference temperature at ambient (30°C), the recovery factor is 18%.
- Using a wide volume definition and reference temperature at ambient, the recovery factor is 3.4%.

Tiwi

The wellfield and production history, as steam flow, is shown in Figure 6. Reservoir thickness is 2km (Barker et al 1990). With these data, recovery factor is 8% using ambient reference and 18% using separation temperature.

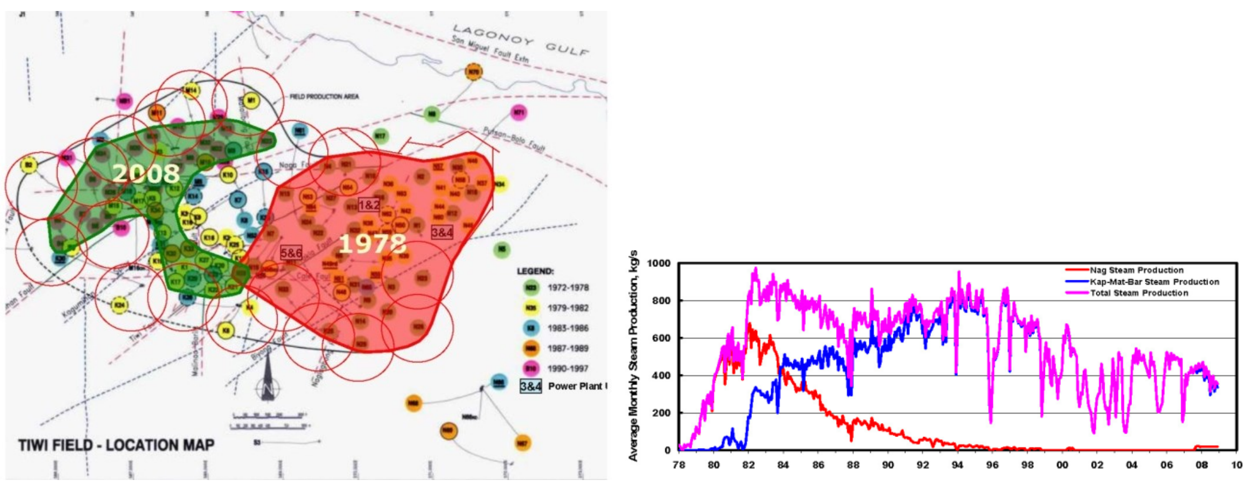

Figure 6 Left, Tiwi area delineated following Appendix (base map, Menzies 2008): Right Tiwi steam production (Menzies et al. 2010)

Mak-Ban

Figure 7 shows the steam flow from the field. Field area is traditionally taken as 7 km^2, and thickness as 2.5 km, (Clemente & Villadolid-Abrigo 1993, Menzies et al. 2007, Guevarra-Segura et al. 2015. This gives a recovery factor of 46% when the reference temperature is separation.

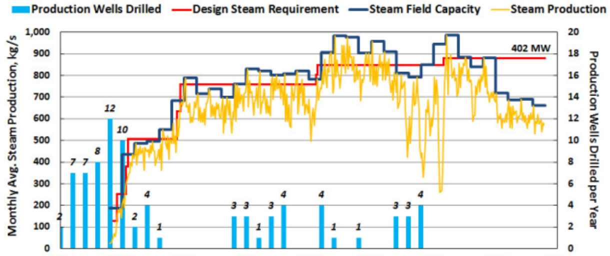

Figure 7. Mak-Ban steam flow (Sunio et al 2015)

Wairakei and Mammoth Hot Springs

Results were computed for these two fields. Very high recovery factors were obtained, and these results are not included in the final average. The reason is that both these fields are subject to large stimulated recharge, with large amounts of hot fluid flowing into the identified reservoir from greater depth. The stored heat method describes the exploitation of a specified volume, and the recovery factor is the fraction of heat within that volume that is finally recovered. The high recovery in these two fields comes from a different physical process and the results are not representative of what recovery is achieved by heat sweep through the defined volume. These fields are unusual, and should not be taken as indicative of a wide-spread pattern of behavior. The only other field identified with such stimulated recharge is Laugarnes in Iceland.

RESULTS

Table 1 lists all the results.

Table 1. Recovery factors

Area definition	Tight		Wide
Reference temp	Ambient	Separation	Ambient
Field			
Brady	20		
Ohaaki	10	14	3
Darajat^	9		6.8
Rotokawa	16		
Ngatamariki	14		3
Mak-Ban		46	
Kamojang	8		5.5
The Geysers			6
Momotombo	18	32	3.5
Tiwi	8	18	
The Geysers*	11		
Coso*	8		
Dixie Valley*	21		8
Wairakei#	*72*		*15*
Mammoth#	*100*		
AVERAGE	**13±5#**	**27±15**	**5±2#**

^ Ussher, pers. comm.

* Williams (2004)

Wairakei and Mammoth excluded from average

DISCUSSION

There are two important results from this tabulation:

- Values are lower than original USGS method
- Results depend strongly on definition of volume and reference temperature

That the values are lower is no surprise, this has been well established by previous reviews. What is striking is how strongly the method varies with definition of the reservoir volume and reference temperature. There is a five-fold variation in recovery factor between the different cases. It is critically important that any use of the stored heat method uses a clear set of definitions, and that the recovery factor used corresponds to actual results using the same definition.

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APPENDIX: RESERVOIR VOLUME DEFINITION

A1. Area

- The basic rule is that a successful production well defines a productive area within a circle of 500m radius around the well.
- A successful well is a well that is an economic producer by the project criteria
- If there are adjacent unsuccessful wells, a boundary is drawn halfway between the unsuccessful well and the successful well.
- If a productive well is planned to be used as injector, the boundary is drawn through the well, ie the resource beyond the injector is stranded

Error! Reference source not found. below illustrates this process for Ngatamariki. Circles are drawn around the productive wells, NM2, 3, 5, 6, 7. Two modifications are necessary: a small area is excluded in the NM2 circle because of the unproductive well NM1. Half the area of NM6 is excluded because it is intended that this well be used as an injector. This provides the tight (high confidence) estimate of productive area. Rule 1 may require modification for CV-3 fields (eg Basin & Range) to reflect the orientation of the reservoir along an inclined plane, rather than the delineation of a horizontal area. A wide area is defined as the entire area within the geophysical anomaly, excluding any areas proven unproductive by drilling. This wide area includes undrilled areas.

A2 Depth

To define the reservoir thickness, or reservoir top and bottom, several indicators can be used.

A2.1 Geology

It is sometimes the case that the reservoir is geologically defined, or at least the reservoir top is so defined. If permeability is confined to particular formations, these formations define the reservoir and the geological boundary is the reservoir boundary. This is often the case, for example, with a cap rock.

A2.2 Temperature

If there is a clearly-defined transition between conductive and convective temperature gradient, this transition defines the reservoir boundary. This often coincides with a cap rock. Note that in both these cases, there is no 500m margin added. The geological transition or the gradient transition is the precise boundary.

A2.3 Drilling results

When the first two methods do not define a boundary, the occurrence of permeability is used to define the reservoir thickness. This is often the case with the reservoir bottom, as the bottom may not have been reached, or there is no clear bottom, permeability just decreases steadily with depth.

If there is a major fluid entry, this is taken as identifying reservoir. A 500m margin is added below this occurrence. Note that a minor entry does not qualify, it is not sufficient to drill to greater depth and intersect increasing temperature and minor permeability. This condition is similar to the characterisation of successful wells in the preceding section. A well that is hot but with poor permeability does not add to the proven area, neither does additional depth in a well that has only poor permeability.

For the reservoir top, the occurrence of permeability defines the presence of reservoir but no margin is added above. In practice permeability, base of caprock and temperature gradient break often coincide at the reservoir top.

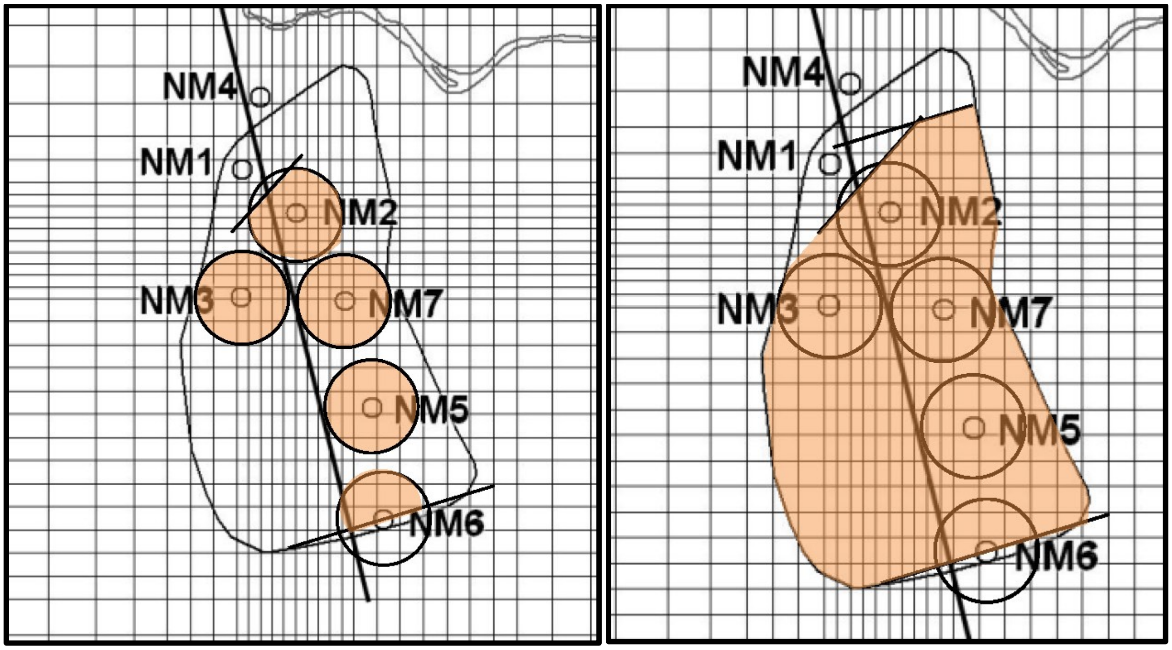

Figure 8. Ngatamariki, left tight definition; right, wide definition.

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