The ~~10~~ ~~25~~ 55 (And Counting) Most Common Mistakes in Geothermal Development

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ABSTRACT

Although geothermal development worldwide is a success story, there have also been sub-optimal results. A number of common themes have been observed. The most important over-arching reason for failure (other than simply poor quality resources) appear to be: (1) lack of communication between scientific disciplines and between the resource and engineering design teams, (2) failure to maintain flexibility, updating and changing working assumptions as the project progresses, (3) lack of recognition of the requirements of long term operation of a successful project such as operability and steam quality, and (4) lack of recognition that geothermal development is fundamentally an economic activity and the project must make financial sense both initially and into the future.

1. INTRODUCTION

The authors have jointly about 130 years of accumulated international geothermal development experience, much of it collaborative but also each has worked separately, often in lead technical or advisory roles to developers, investors, regulators and international development banks. We have also collaborated in teaching courses, including at the Geothermal Institute. Two of us (JVL & PJW) are geoscientists, and one (JBR) an engineer. Two of us are nearing complete retirement. During our careers we have observed several common themes of less than optimum development strategies, and in some case outright failures which could have been avoided. The objective of this paper is to document some of the more significant recurring themes and pitfalls to be avoided, in the hope of seeing better outcomes in future.

One of the commonest mistakes has been a lack of communication between the geoscientific or resource team and the engineering design and operational teams. That is why we consider it particularly important to produce a joint paper on the topic. Space does not permit a full exposition of each item considered, but a number of examples will be presented, some of which will be anonymized to allow the use of data or experience which is not fully in the public domain. For this reason, not all examples are fully referenced. Issues are grouped where they illustrate a common theme

2. ISSUES DURING EXPLORATION AND WELL TARGETING

2.1 Use of inappropriate geohydrological concept models

Conceptual models developed in "continental" or "rift/basin" geological settings such as New Zealand and the USA did not translate well during the early stages of exploration in island-arc settings such as Indonesia and the Philippines. Fundamentally, this was a lack of appreciation of the models developed by Henley and Ellis (1983). This was exacerbated by the widespread use of DC Schlumberger resistivity surveys (which were all that was available at the time) with their lack of penetration, meaning that low resistivity zones were identified only on outflows, not over the upflow of the system under a stratovolcano. The significance of kaipohans as forming over the upflow zone in such settings (Bogie et al. 1987) was not initially appreciated, nor was the fact that large chloride springs can be found on distal outflows. That can be exemplified by the Tongonan project, where it was not until the tenth well that commercial production was achieved – though to be fair, the depth and design of the initial wells would probably be regarded as slimholes today. This example also illustrates the importance of persistence, since it is now part of the very successful 770 MW Greater Leyte development.

Hopefully with greater use of MT surveys this lack of understanding is now a thing of the past, although there is still a tendency to **target exploration wells under the largest thermal features.** That will not be successful where thermal features occur on distal outflows, nor where there is such strongly localised vertical permeability on geological structures that they effectively act as a well, conducting fluid directly from depth without forming a widespread hot reservoir near surface.

Another error that we still see today is **inappropriate use of cation geothermometry on immature or acid fluids**. It ignores the fact that these estimates are based on feldspar equilibria, so cannot be applied to fluids that are not feldspar-stable, and **failure to recognize that silica geothermometry rapidly re-equilibrates**. This is particularly common where springs at low elevation are outflowing neutralized condensates. More generally, the **failure to distinguish the latter situation from a mature island arc system with a neutral upflow** can lead to wells being targeted to an acid magmatic core (as was seen at Alto Peak in the Leyte project) (compare Figure 1 and Figure 2). Such systems can have a neutral(ised) hot zone surrounding the acid core, but they may not. Hochstein (2015) went so far as to say that the producible island arc model system as illustrated in Figure 4 was rarely or never found, based largely on experience in Indonesia. We agree that magmatic-cored systems with advective condensate outflows are common in Indonesia (as in Figure 5), but the alternative type as in Figure 4 do also exist and have been successfully developed.

A more fundamental error is **to assume that all hot springs within an active volcanic terrane are sourced from a high temperature geothermal system** with a magmatic heat source. Hot springs with a tectonic origin can occur in volcanic areas with elevated terrain. There are several examples in Sumatra along the main Sumatran Fault Zone of moderate temperature, high flow rate springs with a high

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bicarbonate, low chloride content and often extensive travertine deposits, that are clearly unrelated to magmatic activity (e.g., Sipoholon). Interpreting these as part of high temperature volcanic systems has led to over-estimates of the region's geothermal energy potential. It is likely that many of the thermal occurrences along the western branch of the East Africa Rift Zone are likewise of purely tectonic origin, leading to unrealistic estimates of the potential and probably unnecessary exploration drilling (e.g., in Rwanda, Hochstein 2015).

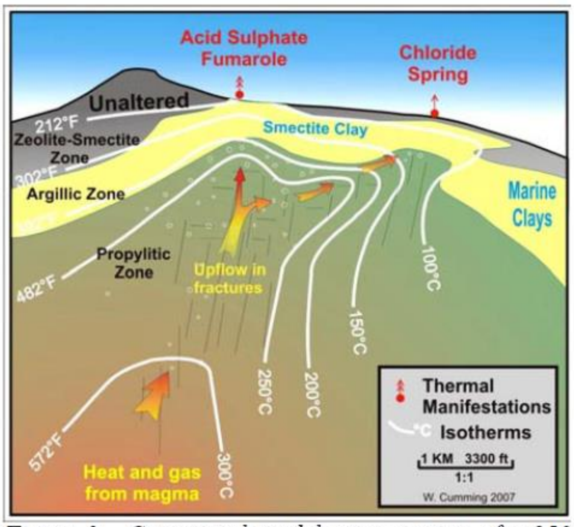

Figure 1: Conceptual model cross-section of a 250 to 300°C geothermal reservoir with isotherms, alteration zones, and structures

After Cumming (2009)

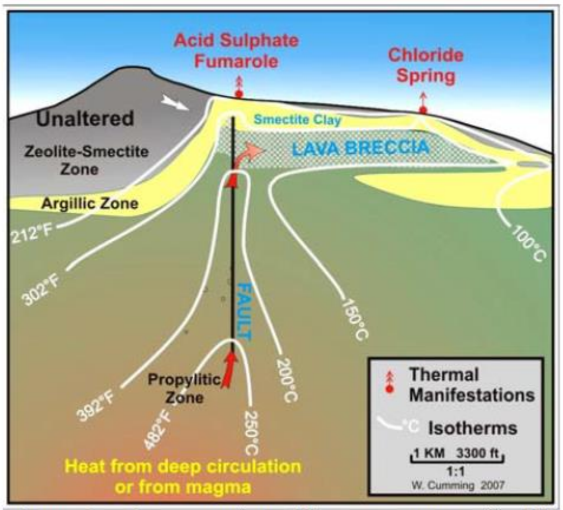

Figure 2: Conceptual model cross-section of a 150 to 200°C geothermal reservoir with isotherms, alteration zones, and structures

After Cumming (2009)

2.2 Insufficient constraint of models by geological realities.

MT resistivity surveys have become the default means of predicting the sub-surface structure of volcanic-hosted geothermal systems. They rely on the basic principle that rocks containing clay minerals formed by hydrothermal alteration are also highly conductive. The fundamental assumption, which in many cases is true, is therefore that zones of low resistivity are an indication of current hot conditions, and that, due to the fact that increasing illite substitution within smectitic clays causes resistivity to vary in a systematic fashion, the presence of a hot upflow can be indicated by a zone of slightly greater resistivity at depth.

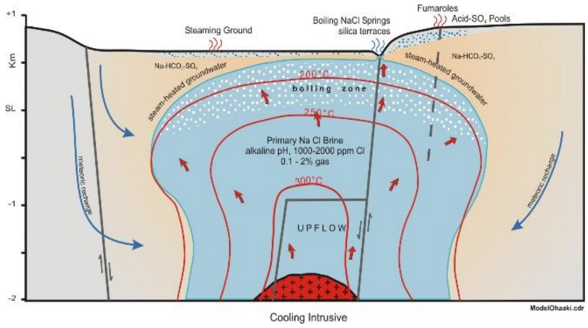

Figure 3: Idealised Basinal or Continental type Geothermal system.

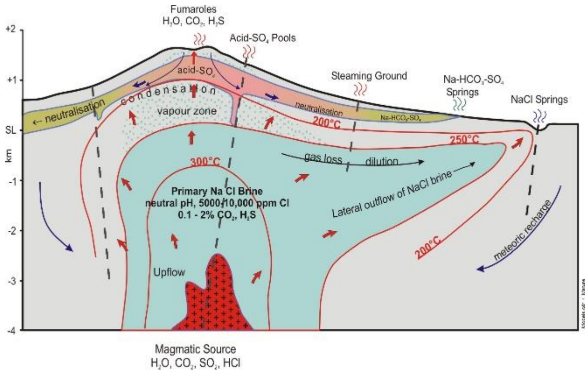

Figure 4: Idealised Mature Island Arc type geothermal system.

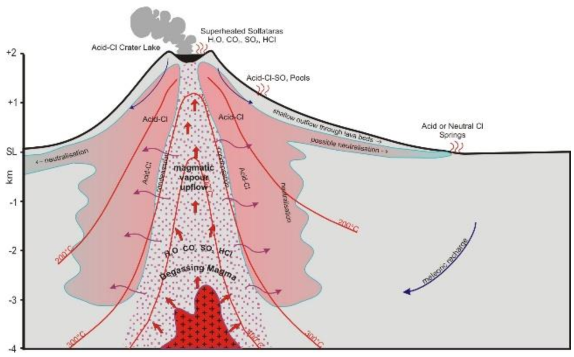

Figure 5: Idealised Juvenile Island Arc type geothermal system.

The problem with this assumption is that all that the resistivity is really telling us is that smectite clays were formed *by some mechanism at some time*. They can persist long after cooling (and in some cases after heating in zones of low permeability leading to significant drilling problems with swelling clays). **Thus, the presence of "fossil" alteration must always be considered when interpreting resistivity surveys** – but often is not. The best clue is from petrological analysis of surface samples, which, if they indicate the presence of minerals such as epidote that cannot form under surface conditions, must therefore demonstrate a degree of erosion and the presence of relict alteration. The lack of correlation with the resistivity data can be compounded by **use of automated XRD interpretation, and a failure to recognize dis-equilibrium assemblages.** If these are real, they are very significant, but more often the apparent situation is caused by the XRD software trying to match all minor peaks.

Conductive clays can also be present with origins other than recent hydrothermal alteration. Clay-rich marine or lake sediments can be conductive, which can be a particular problem in areas such as Sumatra, with numerous pull-apart basins in the vicinity of hydrothermal systems along the main Sumatran Fault. In New Zealand, older ignimbrite sheets form extensive zones of moderately low resistivity with no current hydrothermal significance.

More generally, the above issues show the dangers of **compartmentalisation of technical work** and the lack of on-going critical review of the conceptual models. We consider it is no coincidence that both New Zealand and the Philippines had a great deal of successful early geothermal development, where in both cases a single technical organisation took the lead (DSIR plus MWD for drilling/well testing, and PNOC-EDC plus KRTA as consultants respectively), thus building up invaluable institutional knowledge and retaining key individuals through many projects. In contrast, where individual packages of work are carried out under separate contracts, no matter how competently, there is no such continuity nor back-checking.

A common failure is **not re-mapping the surface geology after civil works are carried out, and/or not encouraging rig geologists to look at the surface exposures when road cuts are available.** As well as faults we have seen steam vents, alteration zones, and previously unidentified geological units (e.g., rhyolite lava flows) that were uncovered (and ignored) in access road cuts.

Not re-interpreting surface geology in terms of later well geology is a similar issue. Geological prognoses should always be revisited after drilling, but this is not easy if they are carried out as discrete contractual packages.

Assuming all surface geo-lineations are faults without considering the geomorphological and volcanic history. There is no doubt that in some cases faults provide potentially productive permeability and targeting wells to intersect faults can be successful. But not all faults are permeable, and not all surface lineations are faults. Identifying lineations on the surface is a useful geological exercise but it is only the start of a structural geological interpretation. We have seen far too many examples of criss-crossing "faults" on geological maps, with no consideration of the fact that faults should generally not cross without offset except in very specific circumstances. Unfortunately, it is much easier to add faults to maps than to remove them, even when they are not proven by drilling or where other explanations for lineations such as margins of lava flows exist. It is vital to remove discredited "faults" from geological maps. While there is some point in preserving older versions of maps for historical reasons, at some stage an "official" version must be produced which contains only the structures where there is some good evidence for supposing they exist. If this is not done, there is a danger of ending up with maps with so many "faults" shown that it is impossible to target wells with any reliability, or conversely to site surface facilities to avoid supposedly hazardous structures.

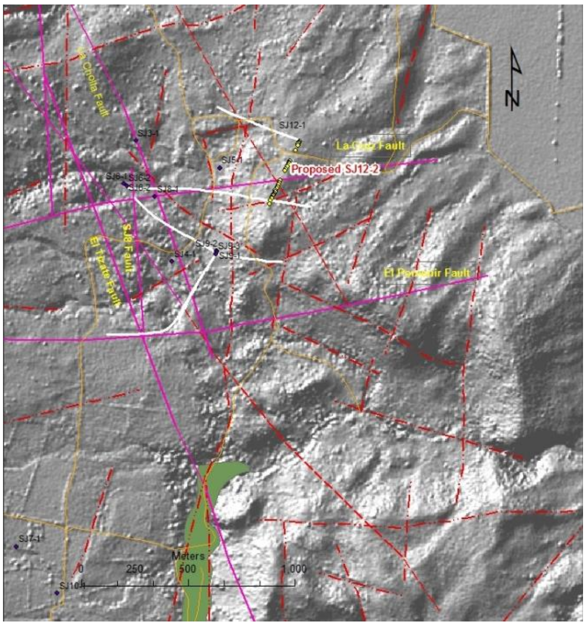

Figure 6: Example of too many conflicting "fault" interpretations.

Field checking of supposed faults is always advisable, but may not be possible where the surface is draped in young pyroclastics, deep weathering or alteration or heavy vegetation, and can be misleading if **features such as strongly oriented cooling joints in lavas are mis-identified as fault fractures.** Without direct evidence such as sheared or slickensided outcrops, inconsistent juxtaposition of lithologies, or strong lineation of thermal activity and alteration, a fault should only be inferred if other explanations can be discounted.

Nor are all sub-circular features "calderas". Such structures do occur in volcanic areas, although it has not been clearly demonstrated that they necessarily constitute good permeable targets for geothermal exploration. Sector collapse amphitheatres and sub-circular stream courses around the margins of stratovolcanoes have frequently been mis-interpreted in this way – and neither will have any major significance to sub-surface hydrology. While not always identifiable, the presence of voluminous extra-caldera pyroclastics is a good clue to their true origin, while high-temperature alteration and marine sediments should not occur within a caldera, as any such occurrences will have been down-faulted.

Assuming "deeper and hotter is better" when targeting wells. This ignores the facts that there is an optimum temperature range for brittle fracturing of rock, meaning permeability will reduce with depth, and that very deep wells may be impossible to discharge, or produce very poorly even if hot at the bottom.

2.3 Allowing short term expediency to override exploration strategy.

Deep (say, 2500m), full diameter geothermal wells today cost about US$8M. Multi-well pads are unlikely to cost more than $0.5M each, and access roads more than $0.5M per kilometre even in difficult terrain. Yet we have frequently seen unpromising targets drilled for reasons of false economy such as:

"*We drilled where the end of the road was when the rig arrived*."

"*We didn't have another pad available and it was too expensive to put the rig on standby*."

One way to ensure that the programme retains flexibility is to always have at least two alternative sites ready for the rig to occupy at the end of drilling each well. This requires some pre-investment in civil works, but minimises the chance of unproductive rig down-time.

Or, a related issue, sometimes referred to as the **"Concorde syndrome":**

"*We have already spent so much money that we can't stop now and admit failure*".

The Rwanda example earlier mentioned could be seen as in this category given that there were plans to drill a second deep well even after less than 100°C had been achieved at 3000m in the first one. (Hochstein, ibid).

Or, "*We know the well is going to be a failure but the budget is already approved*".

It should not be thought that even delineation drilling will achieve a 100 % success rate. **Nor should it be assumed that the success ratio in drilling will necessarily continue to improve with time** (e.g., Lawless et al. 2011). Each well adds more useful information about targeting future wells, but contrariwise, the most probable targets will hopefully have been drilled first. Since the objective is to determine the extent of the productive resource, sooner or later one or more unproductive wells may be drilled.

3. ISSUES RELATING TO DRILLING

3.1 Drilling contracts

A related issue is a **failure to recognise that the drilling contractor's objectives** (completing wells as easily as possible with minimal risk, or simply avoiding the possibility of getting stuck) **can be in direct conflict with those of the project developer** (obtaining production or reinjection capacity with as few wells as possible) or the developer's geological team (obtain more data). A simple example is the use of mud in the production section of the well.

Generally speaking, **trying to load too much risk on to the drilling contractor** is a mistake. The problem can be exacerbated by using inappropriate drilling contract structures. Early geothermal drilling contracting followed oil & gas industry practices, with typically 30 separate contracts for services and materials. The introduction of project specific Independent Power Production (IPP) companies, which often had limited contracting experience and limited staff to administer so many contracts, resulted in a trend towards Integrated Service Contracts (ISC), where services and materials were bundled to bring the number of contracts down to perhaps 3 or 4, or even less.

Experienced developers expressed concern about costs rising as the lead contractors took on sub-contract risks, but there is very little evidence to show that that really was a problem. Drilling continued on basically the well-established and successful pattern of contractors providing services and materials, and the actual drilling operations remaining under the control of the developer, who mobilised a team of exploration geologists, drilling engineers, company men, reservoir engineers and rig geologists. However, there has been a push in recent years for drilling contractors to offer a complete service under an Integrated Project Management (IPM) contract form, whereby the drilling contractor takes responsibility for the entire drilling operation including providing the well design (i.e,. drilling engineering) and day to day management of drilling (i.e. company men). We actually see this as a regressive step in drilling operations, especially in the geothermal environment where sub-surface risks are often unidentified and generally higher than in oil & gas infill drilling, where IPM can be made to work. Care has to be taken in particular because of the trend for lenders to push for turnkey or Engineer, Procure, Construct (EPC) type contracts for drilling because they do not understand the nature of drilling and its risk environment but think that they are pushing all risks onto the contractor and will get a firm price. This simply is not the case. The drilling contractor has different commercial drivers from the project developer (and his lenders), and the end result will very likely be inflated costs, early well terminations and increased problems.

3.2 Overly-tight specification of drilling targets

This can also cause problems. During one phase of drilling at San Jacinto for example, directional targets were specified to such a high degree of precision that mud motors were used extensively in the production section of the holes, leading to poor hole clearing, loss of equipment (fish in the hole) and failure to complete wells (Lawless et al. 2011). The reality was that the sub-surface geology was not well enough known to justify such tight specification. Similarly, **insistence on constructing well pads in a specific location without consideration of likely active faults** at relatively shallow depths can lead to major problems and even lost wells because of very shallow steam presence (San Jacinto and Sarulla).

Avoidable delays, caused by poor logistics and poor decision-making or a lack of decision-making, for example **not having the equipment on site for a side-track** when there is a real possibility that it might be needed. On the Mutnovsky project in Russia, decisions such as production casing setting depth had to be referred back to a committee in Moscow, 9 time zones away, who did not meet outside office hours.

4. ISSUES RELATING TO WELL TESTING AND PHYSICAL INTERPRETATION THEREOF

4.1 Well completion and discharge testing

A common mistake is to discharge wells too soon after drilling, often because of commercial pressure to demonstrate success. While that desire is understandable, it must be resisted as there is much valuable information on temperatures, pressures and permeability that can be obtained during the heat-up period and in some cases that can never be repeated later: Heat- up may take months.

A similar issue is to use wells for reinjection of well test fluids too soon after drilling. There can be strong pressure to do so, in cases where reinjection of test discharges is mandatory, but it may mean that the true temperature profile in the well is never determined, and the well used for reinjection of well test fluids **may take many months to re-heat to the point where it can be discharged.** Failure to do a full, multi-stage injection test **at well completion is in a similar category.**

4.2 Safety Issues

An issue which is fortunately not too common (though we know of at least 3 examples) but which can have serious and even fatal consequences is **allowing high partial pressures of Non-Condensable Gasses (NCG) to accumulate within wellheads, and then inappropriate well discharge procedures**. This is inevitable prior to the first discharge, but high partial pressure of cold H_2S and CO_2 can lead to serious corrosion of casing leading to well failure, and for that reason alone keeping wells on bleed is better. More serious are the effects of allowing such accumulations of gas to discharge at too low a velocity, in some case through large vessels. The lack of upwards velocity, and extreme cooling due to pressure release, hence no thermal buoyancy, can lead to lateral flow across the wellpad of a "wave" of CO_2.

In at least one case, it is likely the pressure drop was sufficient to allow the accumulation of frozen CO_2 in the pipework, which then became mobilised as a large volume of gaseous CO_2 as the well started to discharge steam.

A related issue **is lack of adequate safety protection of well ponds,** most particularly *after* drilling. Fatalities have resulted due to drowning in abandoned well ponds, but it is very rare that pond drains are installed or that the other safety features in place during drilling are actually retained. Similarly, gravity drainage using large diameter pipes of both water and gases from well cellars must be maintained.

4.3 Interpretation of well measurements

Over-reliance on Horner plots during heat-up, to extrapolate to stable temperatures, is no substitute for waiting and actually measuring the temperatures. The reality is that few wells meet the strict criteria for meaningful Horner plots, such as a lack of fluid losses below the measurement point while drilling.

Similarly, **extrapolation of temperature gradients from shallow wells to significantly greater depth can lead to erroneous predictions**. Although this method can be useful in areas where hot dry rock prospects occur, such as Australia, as soon as any fluid is present and there is a chance of convective rather than conductive heat transfer, the results become meaningless – and will tend to predict over-estimated temperatures at depth. An example is the Soultz project on the border of France and Germany, where production drilling was eventually extended more than a kilometre deeper than had been predicted on the basis of extrapolation of shallow temperatures (Genter 2010). In this context it is important to note that whether or not convection occurs depends on the size of the system. In other words, the bigger the connected hydraulic volume, such as a deep sedimentary basin, the more likely it is to convect, albeit slowly.

5. ISSUES RELATING TO RESOURCE CAPACITY AND RISK ESTIMATION

The basic reason for geothermal development is energy generation at an economic cost. **If a project is not economic, the thermal occurrence is not a resource**. Such is widely appreciated in the petroleum and mining industries, and spelled out in the UNFC approach to geothermal resources (e.g., Grant and Ussher 2015), but it is not always apparent that this is recognised at a conceptual level in resource estimation and financial models (e.g., including make up drilling in the last few years of a project's economic life).

The two most widely used methods for resource capacity estimation are stored heat and numerical reservoir models. Both have their place: but both can be misleading if used inappropriately.

5.1 Stored heat estimation

Stored heat is more useful at an early stage, **provided that the inherent uncertainties are recognised**. To some extent that can be alleviated by probabilistic methods, but it is unlikely that any individual stored heat estimate is more accurate than ±50% (Australian Geothermal Energy Group 2015). Thus, excessive emphasis or debate on anything but the first one or two significant figures of such an estimate are a waste of time. Yet we have seen resource assessments produced *prior to drilling* which are expressed to three significant figures.

The most common errors in stored heat studies are:

- **Use of inappropriate recovery factors**, including over 100% in some cases. While stimulation of the upflow under production has been observed in some cases such as Wairakei, that is better addressed by numerical modelling.
- **Use of ambient base temperatures as the base temperature for stored heat,** implying 100% thermodynamic efficiency of the power plant. That was the case in the original USGS method (Muffler 1978) which became an industry standard, leading to significant over-estimates.
- **Failure to distinguish base-** (ex-power plant or separator) **and cut-off-** (minimum to include in the resource volume) **temperatures**.
- **Inclusion of reservoir volumes that are impossible to economically develop,** because of issues such as access or acidity or permeability.

5.2 Numerical reservoir models

A common problem with numerical reservoir models is that they are **applied too early in exploration**, before there is sufficient data to constrain them. While that is not necessarily technically inaccurate, it leads to a spurious degree of precision. We recommend using numerical simulation at an early stage only to address specific questions, for example, *"Can we use shallow injection to mitigate the risk of hydrothermal eruptions?"*, or *"What minimum separation between production and injection wells should we plan on initially?"*. Other issues are:

- **Lack of correspondence of the model to the actual development strategy.** It may seem fundamental that the model should have the production and reinjection wells in the correct locations, with appropriate-sized flows and temperatures, but it is surprising how often reservoir models are not updated as the development plan changes, nor **re-calibrated once the reservoir response to production become apparent**.
- **Assuming that the "steady state" models have physical reality.** This is not so much an error as a conceptual issue, and it is hard to see what else

reservoir modellers can practically do, but it is unlikely that any real geothermal reservoir remains at a physically steady state for tens or hundreds of thousands of years (Lawless 1988). There is good evidence that they are more dynamic than that.

6. ISSUES RELATING TO SURFACE PIPEWORK, SEPARATORS AND PUMPS (SAGS) AND PLANT DESIGN

6.1 Not optimising for reservoir characteristics

As well as the fallacies mentioned above in assuming "deeper and hotter is better" when targeting wells, there is also the issue of what to do with the fluids on the surface. The amorphous silica vs. quartz solubility curves are such that **very hot fluids may create very serious issues of silica deposition**. Indeed, at one stage Hochstein, in an unpublished inventory of geothermal resources in Indonesia, made the somewhat controversial (but logical) suggestion that parts of reservoirs over 300°C should not be considered part of the resource for that reason.

More generally, there is an issue of designers **not taking geoscience into account early in the power scheme design process,** e.g., incorrect gas content or enthalpy, resulting in being locked into something expensive or inefficient, too large or too small, or simply using a "boilerplate" approach to specifications. The gas content in steam from fumaroles can be measured, but this will not be the same as the gas content at depth. Nor can it simply be taken as a maximum or minimum, since there are two conflicting processes at work: an increase in gas due to condensation, and a decrease in gas along outflows. Only by an appreciation of the setting of the thermal features within the hydrology of the system and specific geochemical modelling can a reliable estimate be made.

Trying to optimize the process design from the well head to the power plant, rather than from the deep resource to the power plant - because the process engineers do not talk to the geoscientists and hence do not consider the original deep production fluid chemical and thermodynamic properties – leads to problems with silica scaling and/or inefficient use of thermodynamic cycle. Design engineers also need to be aware of **the limitations of geoscientific data.** For example, testing a well too early may lead to an over-estimation of NCG content as the gasses have been concentrated by steam condensation by drilling fluids. That can lead to over-sizing of the gas extraction system, or even in one case to specification of a totally unnecessary H_2S absorption process. The use of the term "dry steam reservoir" by geoscientists can also mislead the engineers, since there is always some liquid water present, and wells in certain zones or to greater depth can produce such (e.g., The Geysers, Wayang Windu, Kamojang) which will be very detrimental if not allowed for.

6.2 Failure to fit the design to the topography

One of us (JVL) had the interesting experience of providing geotechnical support to Unocal during their exploration of the Sarulla block on Sumatra (Gunderson et al. 2000). Given that some of the terrain was challenging including the moderate-sized Batang Toru river, they took the far-sighted step of **considering possible pipeline routes and power plant locations before drilling the first exploration wells,** and adjusted the exploration drilling targets accordingly. Unfortunately, that is not always the case, leading to stranded wells that can never be economically connected to a logical SAG system.

After drilling, good topographic data is essential – LIDAR surveys are relatively cheap and very useful today, **and topography needs to be taken into account**. It seems that sometimes SAGS designers sit in head office preparing the layout as a series of north-south, east-west and occasional northeast-southwest lines on paper, rather than getting out into the field. Aside from requiring excessive bulk earthworks to form pipeline corridors, resulting in 15 m or 20 m back slopes and traffic jams of earth moving equipment and trucks (as seen by another of our team) they also then miss the opportunity to use the flexibility inherent in looping the pipelines around natural features and in some cases being able to reinject under gravity rather than pumping.

6.3 Appropriate plant size and staging

Staging a development because of concerns over load demand or reservoir capacity is one thing, but installing yet another small scale **"pilot plant" to "prove the technology**" is another. The technology is already well proven, so further "pilot plants" are a waste of money unless for specific purposes such as understanding silica or sulphide precipitation or in fact providing generation into an isolated, very small grid (e.g., small island developments). In New Zealand, concern over sustainability could lead to excessive caution in terms of staged development.

However, care needs to be taken in selecting unit size in small grids because of potential network stability issues. The grid operator will usually want to avoid unit sizes greater than its existing diesel generators, but they need to be encouraged to think ahead to recognize potential load growth and the ability to absorb larger unit sizes.

A related issue is the **automatic use of multiple relatively small units** even when connected to a large grid e.g., Java and Sumatra in Indonesia. The use of topping and bottoming cycle plant at Leyte was an example of the correct approach to subsequently optimising the process after initial design proved too conservative.

6.4 Optimising SAGS for through-life steam quality

The turbine is the most expensive part of a geothermal project and it is essential it be **protected by good steam quality in all operating conditions.** We have seen a turbine destroyed in three weeks in Mexico through inappropriate SAGS design or operation.

Ball check valves used to be installed to protect the turbine from water slugs coming from an unstable separator, but actually cause further instability because of sudden drop in pressure in remaining separators. Generally, water slugs are not actually a problem, but brine mist and spray carry-over due to poor separator design or unstable separator pressure (leading to foaming and even reverse flow in the brine system) is a greater potential problem due to silica scaling. More recent designs have resulted in a vast improvement. A number of older plants required extensive annual shut downs to clean and descale the turbines, whereas using suitably large size separators with loop seals to isolate the brine system from pressure fluctuations, plus a larger diameter steam pipe with adequate drain pots to remove any mist or droplet carry-over now results in plants that are able to operate well for 5 years, with shutdowns not being required for loss of performance, but rather for pressure vessel code and insurance requirements.

Engineering conservatism has also shown itself in some piping designs, where local designers have been reluctant to adopt more efficient designs simply because they seem to be concerned that they will somehow be blamed for previously using older, less efficient and hence more expensive design details.

6.5 Designing for ease of operability

Not considering operability when positioning pipeline vents and drains, to ensure accessibility and hence easy operability, thus avoiding silica build up in shut-down lines. This includes **excessive use of vertical loops in brine lines,** resulting in silica scaling when shut down and difficulties with venting etc. when re-starting. It is better to properly route the pipeline to allow for horizontal loops where possible, also saving cost on support structures.

Designers insisting on providing full Piping and Instrumentation Drawings (P&ID) to operators rather than customized Process Control schematics. P&IDs contain too much information (piping size and material, control loop details) that is of very little value to the operator and usually are spread over a large number of separate sheets. They are good for the construction team and of limited value to the maintenance team, but the operators need something like the famous London Underground map, contained in a single sheet, preferably in colour, that can be fitted into their pocket. It with have all the important information (schematic relationship between components including all valves, indications of what parameter eventually controls what piece of equipment). Also, designers, please follow a logical valve and equipment numbering system, generally following the energy flow, with duplicate items being consistently numbered (e.g., odd numbers to the right, even numbers to the left – i.e., starboard and port - many good steam plant operators actually qualified initially as marine engineers, so try to make them feel at home!).

Designers issue pipe alignment adjustment data only by reference to an overall geographic grid system, rather than by reference to the actual pipeline (distances along and across the pipe route). The later makes it much easier for the field engineers to quickly review and adjust without bringing in surveyor teams, and to issue accurate adjustment data back to the designers.

7. SOCIAL AND ENVIRONMENTAL ISSUES

Social and environmental issues are important throughout all stages of all geothermal projects, and if not handled correctly and sensitively can cause major delays and in some instances halt a project.

Almost anyone in the most remote villages can now read stories on the internet, not all of which are entirely (or even vaguely) true. More insidious is where true statements are taken out of context e.g. "That geothermal development causes earthquakes". In addition, there are people who do not trust government organisations or large corporates. Being first on the scene, one of the responsibilities of the geoscience team is to listen to the locals and understand their fears, gently refute any misinformation, and communicate both the risks and rewards of geothermal development.

The rest of the project team then need to build on the early local relationships, by talking to local people, hiring them as unskilled labour for site maintenance etc., getting involved in supporting the local schools and clinics, using locals to help with re-planting (and let them have some of the young trees for their own use).

8. CONCLUSIONS

Geothermal development worldwide is undoubtedly a success story, but there have also been sub-optimal results. A number of common themes have been observed. The most important over-arching themes for success appear to be:

- Communication between disciplines. This cannot be over-emphasised.
- Maintaining flexibility, being prepared to continually collect and review data, update and change working assumptions as the project progresses.
- Recognition of the requirements of long-term operation of a successful project.
- Recognition that geothermal development is fundamentally an economic activity. Regardless of the funding source, anything which does not contribute to financial success is unhelpful.

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