A Feast of Cycles – Different Geothermal Plants for Different Resources

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Abstract

In this paper, we present some of the technical and commercial considerations associated with selection of technologies for application to a geothermal generation resource, and note that geothermal power cycles are best customized to match the individual resource, so that no two design approaches are the same. We sketch out the major species of geothermal plants – dry steam, flash, and binary – and contrast some of the characteristics of their typical applications in practice. The paper covers recent developments in the binary plant technology marketplace, with TAS, Exergy, United Technology and Cryostar beginning to assert their positions alongside Ormat for rapidly expanding opportunities for low-temperature geothermal power generation. Finally we outline the commercial position and supply characteristics of providers of large, utility-scale flash plants and steam turbines.

Why is the geothermal plant design process so interesting?

The idea of a geothermal power plant can seem simple: drill a hole, stick in a pipe, and persuade whatever comes out of the pipe to spin a turbine-generator. Well, no. There are a number of technical and commercial vexations that need to be dispatched and dealt with before the developer and investors can sit back and watch the meter turn. By far, the area of most knuckle-nibbling concern in this odd energy sector is the up-front challenge, risk, and cost of identifying a worthy prospect – by using ridiculously long steel straws to poke blindly around in the earth far below and out of sight – exploring underground for temperature, hot groundwater, and suitably permeable formations. This is a stupendously challenging part of the business. We can fairly say that exploration, drilling and steamfield development may require around 20-30% of total project cost [1], and consume the focused attention of the relevant geotechnical experts. We are happy to have the privilege of not discussing it further here, since the resource specialists can cover it better than we can.

We are pleased to talk about cycle application and plant design, though, and that is the subject of this paper. Compared to the challenges facing the resource prospector, the task of the plant engineer – selecting a plant cycle, and designing the plant to realize it – is comparatively cheerful and straightforward, though areas of great engineering interest remain on the plant engineer's worktable. The selection of a geothermal power cycle is one of the more involved engineering tasks that we at POWER Engineers undertake. Sometimes this is so interesting that we almost regret having to charge the client for the work. But so far, we've managed to bite the bullet and send the invoices anyway.

So why is geothermal cycle selection interesting, you ask? Well, this task is appealing because geothermal fluids vary widely in temperature, energy content, and delivery conditions. Since the local resource helps drive the best technology selection, every site solution is necessarily different. Although these "supplied fuel specifications" are subject to uncertainty and evolution over time, there is usually no way to change suppliers, or order up a higher grade of fuel, or sue the supplier – the planet Earth would be the defendant, we suppose – at the deep end of the pipe. Thus every geothermal plant is different from all others, and the cycle design engineer is called upon to be fully engaged with the uncertainties and constraints of the project. People in our line of work seem to enjoy that.

Another source of unfailing interest to us is the magnificent variety of geothermal generation opportunities that we see. We get to do cycle selection and plant evaluations for exotic islanded projects sometimes smaller than a megawatt in capacity, as well as cycle design for monster utility and IPP geothermal plants that slug it out kWh to kWh with large fossil plants for power sales to large national markets. In our daily experience, "geothermal" is actually a singular term which stands for a plural: for many kinds of "geothermals" – big ones and small ones, adventurous research frontier ones and ones that are strictly business. Dealing with this generous application range is a great privilege for engineers who enjoy continually facing new challenges for a living.

Still another reason for a high level of design intensity in geothermal cycle selection is that these energy resources tend to be thermodynamically feeble, compared to the high temperatures and energy densities available from fossil resources. For this reason, a geothermal plant needs to be finely tuned and cleverly designed in order to harvest enough energy to pay for the project, bear the not inconsiderable costs of developing the reservoir, and keep the investors happy. So one of the chief tasks of the geothermal plant engineer – in addition to designing a wellfield and a piping system for production and injection – is to use an exceptionally sharp-pointed pencil to select a reliable and cost-effective technology optimally matched to the unique resource likely to emerge from the well.

Adding to this interest, there are sometimes some weird design challenges that arise because of the wild and changeable nature of fluids pumped from deep underground: scaling and corrosion, gas content, and mule-like behavior from wells, among others.

Why do people bother to use geothermal energy to make electrical power?

Though the challenges of geothermal resource development are significant, and the demands on design engineers require a high level of tuning in order to configure a top-performing plant, there are compelling arguments for maximizing development of geothermal resources for power generation. For one thing, the earth is a respectably hot ball of rocks and metal, and heat is everywhere underfoot if you go deep enough. This thermal energy is stored both in hot rock and in fluids, and is continually recharged from deeper, hotter layers of the earth. Furthermore, well-designed geothermal plants can make their owners look great. Geothermal plants typically offer their owners and off-takers spectacularly high reliability and availability (90+%) for bulletproof service, low CO_2-emission generation, and impressively low lifetime levelized costs for power. Unlike many other forms of renewable energy, geothermal power can, head to head, take on large fossil units such as combined cycle gas turbines and beat them on both a $/kwh and emissions basis, be insensitive to fuel price variations, and supply comparable availability and dispatchability [2].

Geothermal owns a distinct edge over many other renewable energy sources such as wind, solar, or wave power, since a geothermal plant is relatively indifferent to seasonal and diurnal atmospheric activities and thus is ideally configured for a baseload role in a utility generation portfolio. A geothermal generation plant is typically a good neighbor, offers jobs to its host community, and is a popular destination for school field trips for both their natural and engineered features.

In many national economies, the use of strictly situational resources such as geothermal energy can spare other portable energy resources for higher-markup export sale, and can release native capital that might otherwise be tied up in high-cost imported fuels such as oil and distillates, as well as offering other social and economic benefits [3]. The energy economies of Kenya, Iceland, El Salvador, Nicaragua, and México offer great examples of this strategy in action.

What is involved in a geothermal power plant? How does it work?

A geothermal power plant works by converting thermal energy into fluid kinetic energy to spin the rotor of a turbine-generator. There are several variants on the Rankine Cycle, the familiar configuration in which heat added in a boiler creates a vapor, which is then fed to a turbine and subsequently condensed at the exhaust. The most common embodiment of the Rankine Cycle is the regular old water/steam cycle dear to all who are familiar with conventional thermal generation, leading to the observation that the most typical geothermal power plant breed – a flash or dry steam plant – is basically a normal steam plant minus the dirty bits: the combustion, the ash piles, the boiler, the stack, etc. In the case of our geothermal flash and steam plants, the earth itself is the boiler, and condensed fluid is pumped back to the earth to repeat the cycle.

In every geothermal plant on planet earth, something is boiling that makes the turbine or expander wheel go around and around and do some work.

How can we get this stuff to boil?

In the Rankine Cycle, boiling is the business. So the principal objective of a geothermal power plant is to arrange for some fluid to boil vigorously enough so that the vapor can do some useful work along its journey. So the first task our cycle selection engineer performs is to look at the temperature of the geothermal resource – the stuff that comes out of the wells and arrives at the plant site – to see what the working fluid in the Rankine Cycle contraption should optimally be.

In many happy geothermal cases, the fluid that comes out of the well is water hot enough on its own – roughly at 300-330 °F or above [4] – to boil at a useful pressure. In these cases, the resource fluid itself can be the working fluid. In a few exceptional areas – the famous sites of the Geysers and Lardarello – the fluid that comes out of the wells is power-plant-quality steam that can be used directly by the turbine. This highly prized species of geothermal plant is called a “dry steam plant.”

If resource temperatures are lower than that required to provide dry steam, a liquid or two-phase mixture may emerge from the wells. This fluid can be throttled to a lower pressure within a separator vessel; there, a portion of the liquid instantly "flashes" into steam. This steam – along with steam from other lower pressure flash stages, if additional flash stages are practical – drives a turbine on the way to being condensed in the plant's condenser. This species is called a "flash plant."

But what happens if the resource temperature is below 330 °F or so?

That's a very good question. Many geothermal resources – probably most of the readily tappable geothermal resources out there in the world – contain what engineers consider "low-temperature" geofluids that aren't energetic enough for direct admission into the turbine. They just don't boil vigorously enough (or at all) in the pressure regimes useful to the plant's designer.

So in the case of available geothermal resource temperatures below 330 °F or so in most places, the engineer making the cycle selection looks at fluids that boil vigorously at a lower temperatures – Butane? Ammonia? Industrial refrigerants? – and designs a system to transfer the heat from the geothermal resource fluid to the selected lower-boiling-point fluid which can then be boiled and condensed in a closed loop, spinning the turbine along the way. This species of geothermal plant, in which the resource fluid transfers heat energy to a separate and isolated loop filled with lower-boiling-point working fluid, is called a "binary plant."

Beg pardon? What were those plant species again?

Let's review, shall we?

- **Dry Steam Plants:** A few prodigious high-energy geothermal resources supply pressurized steam that, with a little cleaning to remove impurities such as chlorides, can be used to drive a turbine directly. Condensate is typically partly consumed by the operation of evaporative (wet) cooling towers, with the rest of the condensate reinjected to the reservoir.
- **Flash Plants:** Flash plants, which separate two-phase resource streams from liquid-dominated reservoirs and use the steam to drive the turbine directly, are used for higher-temperature resources. The fraction of the resource fluid that is flashed and then condensed is typically used in a wet cooling tower, and the remaining resource fluids are reinjected.

- **Binary Plants:** Binary plants – often packaged energy conversion modules along with auxiliaries – are typically applied to low to moderate temperature resources. The working fluid is a low-boiling-point fluid that cycles in a closed Rankine Cycle circuit. Binary plants which use hydrocarbon working fluids are commonly nicknamed ORC (Organic Rankine Cycle) plants. Typically most or all of the resource fluid used in a binary plant is reinjected.

There are also a number of permutations and variants of these species: multiple flash cycles, "combined cycle" flash plants with binary cycle bottoming plants, mixed and variable working fluid binary plants, "cogeneration" plants that supply both power generation and district heating, and others.

Do these plant types differ in the ways they're used?

These plant species tend to be applied differently all around the world because they are technically best matched to particular ranges of resource conditions and plant sizes, and, for reasons sometimes independent of strict technical merit, they seem to find expression in particular kinds of commercial and ownership arrangements. For example, binary plants are most often developed around highly pre-engineered and often pre-packaged and skid-mounted energy conversion modules supplied by their manufacturers. This readiness for modular supply is made more feasible due to the smaller size of typical binary plants, and can lead to easier and faster installation, especially in remote locations. By contrast, flash and steam plants tend to be open-sourced and independently engineered around a particular geothermal steam turbine. Flash and steam plants, since they are applied to more energetic resources, tend to be larger than binary plants.

I hear a lot about new binary plant activity. Is that happening?

Oh, yes. In the past couple of years, we at POWER Engineers have seen a dramatic spike in interest in binary geothermal plant development, here in the U.S. and abroad. This is partly trackable to increased interest in developing clean, renewable energy resources for all the prominent reasons, but also a product of pepped-up competition among manufacturers and suppliers of proprietary binary energy conversion technology. In our view, the binary geothermal industry has gone kind of bonkers lately, with a totally new level of product offerings and competition for development and supply of these interesting plants. Since this technology can also be used for power generation from other sources such as industrial waste heat, new horizons are continually opening.

This activity was not always so lively. For years, the binary geothermal field was the undisputed domain of one of the great historic franchises in the geothermal power industry – Ormat. Ormat is an Israel-based company with vigorous representation throughout the world, including the U.S., and even more intensely in geothermal-rich Nevada. The protean, vertically integrated company does it all: develop, design, manufacture, construct, operate, and finance. Their plants can be found on all the power-producing continents on Earth, and they continue to expand their product lines and projects.

Ormat plants are universally based on the company's own family of binary energy conversion modules using hydrocarbon working fluids such as isobutane or isopentane, though these binary modules are sometimes combined in Ormat-developed geothermal plants with topping steam subunits, resulting in a characteristic Ormat "hybrid" or "combined cycle" approach.

Recent years have seen the entry of new forces into the binary energy recovery market, including a large U.S. technology company, United Technology (UTC), another U.S. firm called Turbine Air Systems, and a highly regarded French company, Cryostar. Another U.S. company, Raser, has developed an interesting binary project in Utah using many dozens of fractional-MW UTC energy conversion units, and has plans for more at other sites. These forces have created a lively bidding and plant development climate, particularly in the U.S. The approach by United Technology is instructive, since the company (the parent of Pratt & Whitney and Carrier Corporation) brings to the geothermal business formidable chops in power plant understanding, and in manufacturing, adapting and applying standard HVAC solutions to low-temperature energy conversion. United Technology is now marketing its binary geothermal technology through its Pratt & Whitney subsidiary. The move is a signature development in this heretofore small and low-key industry, because it may apply a highly evolved style of Fortune 500 corporate R&D commitment, manufacturing expertise and production scale to geothermal technology use and project development.

With Ormat, TAS, United Technology, Exergy, Cryostar, Electratherm, and others on the binary scene, we see the growth in activity in this sector as a thrilling development in what has been a fairly sleepy technical scene for a long time.

What is the future for the big flash and dry steam plants?

The largest constraint on adding large flash or dry steam plants is the fact that many of the highest grade resources were the first utilized. However, many appropriate untapped resources still exist in promising areas such as Indonesia, Kenya, Turkey, Kamchatka and the Philippines. Some continents such as South America have had no development, despite potential resources spotted in Chile, Bolivia, and Argentina. The potential widespread applicability of Enhanced Geothermal Systems [5], combined with deep drilling [6], may unleash high-temperature reservoirs in many more locations and may lead to a second boom for these kinds of plants.

The supply part of the business of developing new utility and IPP-scale flash plants has been dominated, over the past several decades, by the giant Japanese turbine manufacturers Mitsubishi and Fuji, who have engineered sturdy turbines for the wet, saturated steam conditions encountered at flash resources, and have also brought their corporate financial and EPC horsepower to bear to realize formidably efficient new plants throughout the world.

The recent boom in geothermal plant development, as well as the high conventional steam turbine demand from China, may strain the manufacturing capacities of these specialized shops for a good stretch of the future, so it remains to be seen if other large turbine manufacturers will increase their offerings to the customized geothermal turbine supply world.

What keeps geothermal plant design engineers awake at night?

Good question. As we noted earlier, geothermal power plants always need to be finely designed in order to get high-value results – satisfactory return on investment, efficiency, and high reliability – from what is viewed as a low-value resource: hot groundwater. So what keeps geothermal plant engineers up at night are questions that may seem absurdly fussy in comparison to the apparent simplicity of the workings of a geothermal generation project. Here are some principal technical and cycle selection considerations that engineers such as us take into account for the projects that come in our door.

- **Tailoring Resource Production – Is That a Sucking Sound We Hear?** The canny geothermal plant engineer optimizes extraction for sustainable use and maximum economic return, develops strategies for managing variability in produced fluid enthalpies and non-condensible gas content, and considers effects of injection and possible supplementary injection. All these require close cooperation among engineers and geoscientists, with appropriate respect for the inherent uncertainties of intelligently designing a power plant built in faith, to draw upon a resource far underground that will never be visited, surely tested, or perfectly understood.

- **Cooling Systems:** A geothermal plant extracts energy from the difference between the resource temperature and the heat sink temperature available at the plant. So the geothermal plant cycle engineer pays extravagant attention to the plant's cooling system performance. (This attention sometimes strikes spectators as obsessive.) The usual design choice is either air-cooled condensers, limited by dry bulb temperatures, or a wet cooling system that takes advantage of wet bulb temperatures and can therefore achieve a lower heat sink temperature. Cooling system design is often complicated by other considerations: Is an external source of cooling water available? Should the cycle be chosen to allow the use of condensate for cooling tower makeup? What are the incremental costs of more effective cooling or water conservation, versus revenue for generation? What cooling water chemical treatment strategies are best suited to the local conditions? There are never easy answers in the geothermal plant cooling system business.
- **Plant Sizing to Best Match the Power Sales Price Profile:** This is a complex question. Installed costs invariably increase with size, of course, but cost per MW or MWh generally decrease with size. Production profiles may vary with time due to annual climatic variations, power sales patterns, or long-term resource changes. The geothermal cycle engineer wants to size and design the plant just right, so that the plant is no bigger than it needs to be for optimal return on investment, but still generates particularly efficiently and strongly when power sales rates are advantageous – perhaps in mid-day and afternoon in an arid Southwest-area power sales market, for example. This consideration also affects – or is just as often affected by – the cooling system choices available for implementation at the plant, since a wet tower can deliver a significant output edge in hot dry conditions. It is never simple.

For all these reasons, we enjoy the challenge of geothermal system selection and plant design. We are privileged to have the opportunity to think about these magnificent power generation machines, and encourage the clients, developers, manufacturers, drillers, explorers, stockholders, ratepayers and others in this field who make it possible for us to step in and contribute our part in this meaningful and fast growing industry. ■

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