SMALL GEOTHERMAL POWER PLANT DEVELOPMENTS

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SUMMARY - The paper discusses small power plant developments. Examples have been drawn from world-wide geothermal developments, presenting different views on how a geothermal resource can be developed, and the equipment required. Each field has specific problems in terms of the economics and thermodynamics of operation.

Alternative options for the equipment of power generation are also discussed; for example, condensing and back pressure machines, binary, biphase, etc. Thermodynamics performance parameters are presented, demonstrating where the inefficiencies occur in geothermal plant and highlighting that thermodynamic as well as economic parameters must be considered when planning the development of a geothermal resource. The discussion draws on New Zealand experience and published studies both in New Zealand and world wide in the utilisation of large and small scale plant.

INTRODUCTION

There are no hard and fast rules about the employment of small power plant units in geothermal development. Each geothermal field is likely to be different, and each country may have different requirements. The final choice of steam field power plant system has to be made after consideration of a wide range of factors which should include utilization efficiency of resource and plant as well as the economics of producing the electricity. For example, a number of studies have been made which compare resource development using large (greater than about 30MW(e)), plant and small wellhead units (about 5MW(e)). It is often claimed that by choosing to develop a resource using small plant enables (i) an early return to be made on invested capital, since the installation and commissioning of small plant requires less time than for a large plant sizes; and (ii) information to be obtained, particularly of the reservoir characteristics, for the future use of the resource. Most studies are based on economics, with little emphasis on plant efficiency and efficient use of the resource

Dobbie (1987) looked at the influence of plant capacity on the economics of geothermal development and concluded that there was no evidence to support the claim that small-scale developments enjoy any economic advantage over larger-scale plant. This study was based on an engineering study commissioned by the World Bank for Kenya, a country whose electrical generation system has similarities with the New Zealand system. Dobbie (1987) lists these similarities as (i) a major dependence on hydroelectric power with a mixture of old and new plant; (ii) considerable explored geothermal resource capacity with geothermal generation being a small but significant component of the base load generation capacity; and (iii) a high marginal cost for peak power which is based on thermal plant, mainly gas turbines.

Hiriart (1986) made a comparison between a single 110MW plant working at maximum efficiency using a number of wells connected to steam header with condensers, gas extractors, etc., designed to achieve optimum performance, and a system using 22 atmospheric discharge units, each with a capacity of 5MW(e). He concluded that this second alternative is very attractive and should be analysed in detail for each proposed development. Costs used in the comparison were based on Mexican experience at both Cerro Prieto and Los Azufres.

However, the final result and conclusions of any study which involves economics, usually expressed in terms of the unit price of electricity, depends on the economic model being analysed and the assumptions used in that analysis. The significance of the Dobbie (1987) and Hiriart (1986) studies is in the comparative values and not in the absolute values of the unit price Both studies have different economic models and a general conclusion cannot be justified from either, since Mexican fields have been developed with 5MW(e) atmospheric units whilst the current trend in Kenya is to use larger units in a central power station.

Economics is not the only criterion that should be used in deciding a particular development strategy. Hiriart (1986) lists a number of points which often cannot be quantified in economic terms and which will influence the decision, and it is important to note that these criteria are presented in favour of the installation of small wellhead units. These points are:

(i) the level of national involvement in the manufacture of equipment.

(ii) Reliability of the system; he suggests that 22 units of 5MW(e) are more reliable than a system based on one 110MW(e) unit.

(iii) A plant trip is more costly for the larger plant.

(iv) Reservoir gas content and its variation with time can affect a central plant.

(v) Installation of wellhead units allows staged development and also allows income to be generated immediately a well becomes available during exploration of the field.

(vi) In areas where the topography is complex it is better to avoid piping the steam, and to use wellhead plants.

(vii) If there is drawdown in the field sooner than expected, it is possible to modify the turbine to operate at a lower pressure and maintain the same generated power, although at a lower efficiency.

(viii) The analysis can be affected if it is not possible to combine wells adequately to generate the required 5MW(e) and the units have to be derated.

It should be noted that the use of the small, inefficient atmospheric discharge turbines results in use of considerably more geothermal fluid and probably will give an earlier run down of reservoir pressure than would result if condensing sets were used. This is an important factor which should be built into the economic model. The conclusion reached by Hiriart (1986) is that when the production of steam and the generation of electricity are considered as a single project the use of cheap atmospheric wellhead sets is attractive, but the economic advantages of the wellhead units disappear when the company generating electricity has to buy steam from a third party.

PERFORMANCE PARAMETERS FOR GEOTHERMAL PLANT

The concept of available work (Exergy) was proposed in the 1930s by Keenan (1935) and others as a means of assessing the performance of thermodynamic plant. However, only recently has it become acceptable as a technique for highlighting the inefficiencies in the thermodynamic processes employed in the plant (see Szargut (1988)). Whilst application of second law analysis is beneficial to the study of conventional fossil and nuclear power plant as a means of determining the irreversibilities of the processes involved, it is not essential in obtaining an overall plant efficiency since, as is shown in Table 1, the plant efficiencies for first and second law analysis are similar. However, its use for analysing a geothermal plant is essential to rigorously assess the plant thermodynamically. It also allows valid direct comparisons to be made with conventional or non-conventional energy systems.

Irrespective of the particular processes (i.e., dry steam, flash or binary) involved in a geothermal plant, the fluid at the wellhead of a geothermal well has a capacity to do work and it can be taken through a series of processes designed to extract, within economic and thermodynamic limits, as much energy from that fluid as is feasible. Heat is exchanged between the fluid and the surroundings and is finally discharged to the surroundings in a state influenced by the ambient conditions. The geofluid does not experience a cycle: it goes through a series of processes from an initial to a final state. A simplified exergy analysis of a system and its application to geothermal plant is presented in DiPippo (1984). The expressions and method of analysis are presented in Appendix 1.

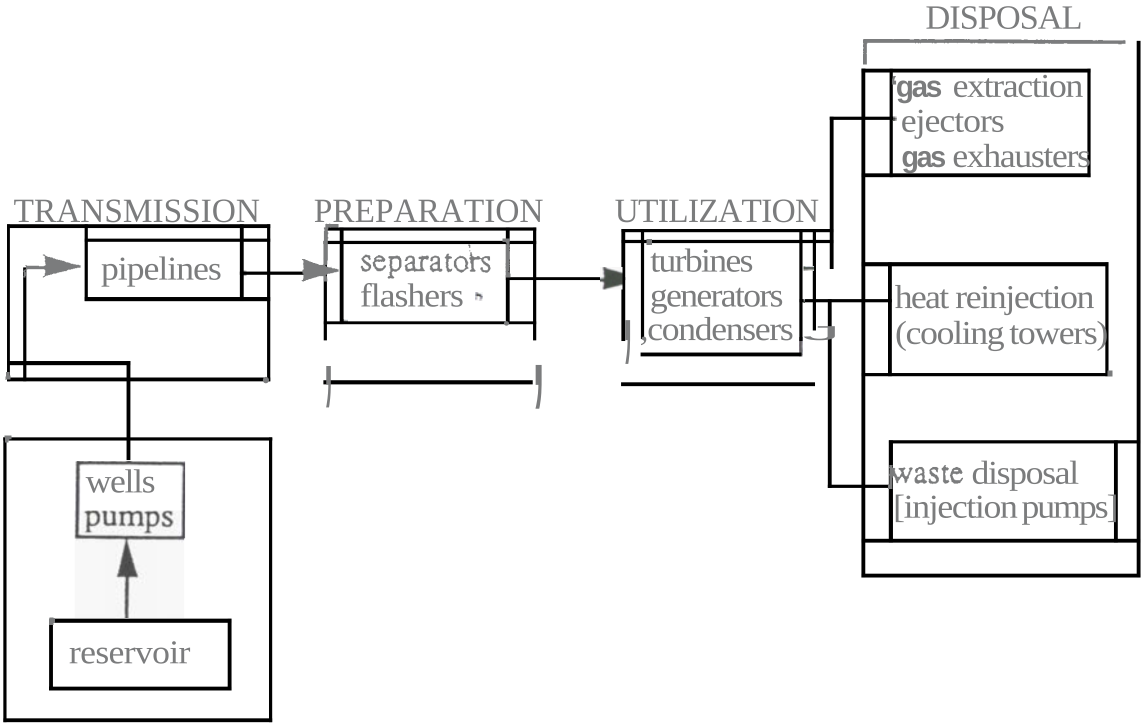

Figure 1: Block diagram of a geothermal plant (from DiPippo, 1984)

Unlike energy, exergy is not conserved. Exergy losses occur when processes are not reversible and therefore reduce the potential of the fluid to produce useful work. As the level of exergy through the plant reduces, less is available relative to the ambient or dead state, to do work. Figure 1 gives a block diagram of a geothermal plant, and any plant component can be analysed on a second law basis by applying the basic equation of:

(exergy in) - (exergy out) = (exergy lost)

DiPippo (1984) discusses the relative merits of basing the inlet exergy on reservoir or well head conditions. He concludes that for comparison of one geothermal plant with another, inlet exergy should be calculated on a reservoir basis whilst for comparison with conventional plant an exergy based on wellhead conditions is more appropriate, since the geothermal plant is not then burdened with the losses of exergy in the well. Table 1 shows a comparison of first and second law efficiencies for three different designs of geothermal plant and for some large coal-fired steam turbine plant. Note, as mentioned earlier, that the first and second law efficiencies for the fossil-fuelled plant are similar whereas, for geothermal plant, a second law analysis gives a more realistic and comparable value.

A first law analysis for a simple steam plant shows that about 70% of the total heat added to the system is rejected to the condenser, giving the impression that the main cause of inefficiency lies in the condenser. However, the second law analysis shows that the exergy destruction, or irreversibility, in the condenser is only about 4% of the input exergy. The main cause of the thermodynamic inefficiencies is the exergy destruction in the heat addition process, which is about 50% of the total exergy input to the system. The designer has to find ways to reduce this amount, and conventionally this can be done by introducing feed heaters. However, the improvement in thermodynamic performance is obtained at the expense of a more complicated arrangement and higher capital cost A balance is therefore required between savings in energy costs and the additional investment involved.

The exergy distribution through a small (1.3MW) unit is compared for a single flash steam and Binary plant, Appendix 2. The calculations are based on a 176°C geothermal fluid as utilized at Kawerau, New Zealand. The Ormat plant graphic output (Figure 3) shows the components, and the mass, temperature and pressure distribution through the binary plant, and the cycle is plotted on the pressure enthalpy chart for isopentane (Figure 4). This plant has an air cooled condenser. Using these data a number of calculations can be made, giving a thermodynamic comparison of the utilization of the fluid by the two cycles. For example, based on the inlet exergy for the 176° C geofluid and a gross turbine output of 1.3MW second law efficiencies of 23% for the flash and 22% for this binary plant are given, with first law efficiencies of 4.5% and 4.2 % respectively. Turbine second law internal efficiencies are 30.7% for the flash and 33.9% for the binary plant. For this case, with the numbers and the thermodynamic parameters calculated, there is little to choose between the two types of plant. The analysis presented here is not rigorous; its purpose is to demonstrate that in any study of the utilization of a resource it is important to look at the thermodynamic options, not just the economic ones. If the resource is used inefficiently, its life will be reduced and it will, in the long term, cost money. It could be argued that this flash plant would be uneconomical because it would be very large for the low density steam and the problems of extracting non-condensables; however, it has become fashionable, particularly for binary plant, to construct power stations using small modules of the order of size used above, and the author believes that the thermodynamics of the processes involved must be studied, as well as the economics, before deciding on the type of plant to be used.

OVERVIEW OF SMALL PLANT

Conventional Plant

Modern small steam turbogenerator modules (<10 MW(e)), suitable for use in geothermal fields, are generally constructed at the factory on a single skid giving the advantage of a preassembled unit, factory-tested after manufacture, which shortens the time needed for commissioning in the field. Wellhead units require only short pipelines to connect them to the well; although this has a major cost advantage over the larger central unit it may lead to problems such as carry-over of dissolved solids, resulting in deposition on surface equipment, turbine blades, etc., as has occurred in Italy and on some units in Mexico. This problem has necessitated the installation of steam scrubbers and final stage separators to take out the solids, which increases costs. Modular units are available with either atmospheric or condensing exhaust. Atmospheric (backpressure) turbines are the simplest and, in capital cost, the cheapest of all geothermal machines. However, they are wasteful of steam, consuming about twice as much, for the same inlet pressure, as condensing turbines per kilowatt of output, and are therefore wasteful of energy and costly to run, particularly in terms of the increased number of wells required. But they are useful as pilot or standby plant and for generating electricity during field development, as used in Mexico. Other advantages include the ease of location and, because of the lack of auxiliaries, relocation to a new site in the same field is generally of the order of two months; they can also be started without the need for an external power supply. Non-condensing machines are used if the geothermal resource has a high gas content (>12% by weight) because of the high power required to extract these gases from a condenser.

Steam consumption of the standard units offered by Mitsubishi is quoted in Hudson (1988); the steam consumption from alternative suppliers are similar to these. The curves are for the rated design point and also for zero non-condensable gases in the steam. Hudson (1988) suggests the effect of gas content can be corrected by the following:-

$W_g = W_o(1-G.0.0059)$, where

W_g = Gross power with G% non-condensable gas by mass.

W_o = Gross power with zero non - condensable gas.

G = % non condensable gas content by mass in total steam plus non- condensable gas flow.

Hudson (1988) makes a comparison of the specific steam output for atmospheric exhaust and condensing units for a range of pressures and power output (Table 2) and makes the point that it is not appropriate to compare these two at the same inlet pressure since the optimum separation pressure, and hence the turbine inlet pressure, for an atmospheric set is higher than that for a condensing set. For example, for a fluid enthalpy of 1200kJ/kg, the optimum pressure is 6.5bar for a machine exhausting to a condenser pressure of 0.12 bar and 12 bar for an atmospheric unit.

Hudson (1988) gives some typical costs, at 1988, for condensing and atmospheric sets, ranging from US$ 775/kW net for atmospheric to US$ 1250/kW net for a condensing 5 MW turboalternator. A 10MW condensing unit would be cheaper, at US$1175 net. These figures exclude the cost of wells, and assume short pipelines and power transmission lines. Hudson also quotes a total time from order date to commissioning for these units of 14, 16, and 19 months respectively. These numbers show that cost of the turbine equipment is a function of size and type. It is not possible to carry out a generalized economic study because, as was discovered in attempting such an analysis for New Zealand, the model for the analysis is site-specific.

Binary plant

As with the conventional plant above, the operation of binary plant is based on the Rankine cycle; however, it uses an organic working fluid instead of water, and the cycle is closed. This requires an additional component, a heat exchanger in the plant, giving a typical installed cost of US$1500 (Hudson (1988)). Generally, because of the lower boiling point of these organic fluids, an Organic Rankine Cycle (ORC) or Binary plant has the capability of utilizing lower temperature (85°-150°C) geothermal fluids for the generation of electricity. Binary plant is also used when it is inadvisable to allow the geofluid to come in contact with turbines, etc., because of concerns about scaling, corrosion or large gas content in the primary fluid. Ormat Turbines Ltd have pioneered the application of small ORC plant, in sizes of 300-1300kW, factory tested and in modular form for application on geothermal low temperature resources. These units utilize a subcritical cycle and can be cascaded to produce increased outputs. Up to December 1989, more than 120 geothermal Ormat energy convertors (OEC) have been installed, representing about 120 MW of base load, and to that date have accumulated over 1.8 million hours of operation. At East Mesa, California, USA, 30MW are installed, with 26 OEC units utilizing 152°C geothermal water. The largest binary plant constructed is the Heber demonstration plant of 65MW (gross), 45MW (net). Apart from the use of basic units, as described above, this type of plant has potential for increasing conventional plant overall efficiency by utilizing the waste water to generate electricity, as is done at Kawerau, New Zealand, and has been proposed for waste water at Wairakei. This type of application is described as a "bottoming" cycle.

Much research has been done on basic Binary cycles and their variations. The bottoming cycle, as used at Kawerau, New Zealand, is one such variation. Earlier work centred on selection of working fluids for particular some temperatures (summary in Milora and Tester (1976)); however, recent research has been carried out on advanced binary power plants and the limits that can be expected of their performance (Bleim and Mines, 1991). Since the basic binary cycle can have a low second law or utilization efficiency because of the parasitic power requirements, there is an incentive to seek more efficient binary cycles. The dual-pressure binary cycle uses a dual admission turbine accepting the fluid at two pressures. The working fluid is returned by the condensate pump to a preheater where it is heated to the saturation point. The fluid is divided into two streams, one of which enters the low pressure evaporator and the other is pumped to a higher pressure before entering the high pressure preheater/evaporator. Usually both evaporators operate at sub-critical pressures. Such plant can have 15-25 per cent higher brine utilization efficiencies than the basic binary plant for fluids in the range 95-150°C (DiPippo, 1990).

The dual fluid binary plant at East Mesa California, USA (the Magmamax Unit which was the foreninner of the present B.C.McCabe Unit 1) has the capability of further improvement provided optimum performance is achieved by correct choice of working fluids matching the heat source. The improvements are the result of better heat exchanger design. It is well known that the smaller the average temperature difference in a heat exchanger, the higher the thermodynamic efficiency of the heat transfer process. It is therefore easier to design a high efficiency liquid-to-liquid heat exchanger, where the temperature difference between the two fluids is reasonably uniform thus diminishing the adverse effects of the pinch point, than a higher efficiency evaporator (boiler), where there is a large temperature difference between the heating fluid (geofluid) and the boiling working fluid. The geofluid cools at variable temperature whilst the working fluid first heats up at variable temperature and then boils at constant temperature. The dual fluid binary plant utilizes two binary loops, each with a particular working fluid chosen to match the temperature range of the primary fluid. The loops are coupled by a heat recuperator in which the energy normally rejected to the surroundings from the upper loop is transferred to the lower loop to provide heat of vaporization of a second binary unit.

The Kalina cycle incorporates several features leading to higher efficiency compared to a basic binary cycle (Kalina & Leibowitz, 1989; Leibowitz & Markus, 1990). It uses a mixture of water and ammonia as the working fluid to exploit the variable temperature evaporation and condensation that occurs with mixtures, thereby reducing the irreversibilities of heat transfer. It also uses recuperators to reduce external heating requirements and, because of the thermodynamic properties of the mixture, does not require vacuum pumps as the working fluid operates at atmospheric pressure. Further conventional steam turbines can be used since the fluid, water and ammonia have similar molecular weights.

Bliem and Mines (1991) point out the practical limit to plant performance to be expected from these developments; it is summarized in Figure 4. The results of their study indicate that all these advanced technologies have the potential to improve on current technology and each system has advantages and disadvantages which have to be considered, together with the economic criteria, to select the power system which best meets the requirements of that application.

Other Power Systems

Two other developments have taken place in recent years, namely, the Biphase Rotary Separator Turboalternator and the Helical Screw Expander. Both these units take two phase fluid from the wellhead and use it without first separating the water and steam; that is, they are total flow machines. In the case of the biphase machine, a separation process is part of the cycle. The thermodynamics of this cycle and its performance are discussed in Hudson (1988). He compares a 10MW/15MW biphase topping plant with optimised single flash plant and shows that for fluid enthalpies over the range 929 kJ/kg to 1402 kJ/kg the power output ratio, biphase/flash, varies from 1.08 to 1.24 depending on biphase inlet pressure. These plants seem to be designed for a higher temperature range, 170°-300°C, rather than the binary and flash units discussed above; however, at the low end of the temperature range where enthalpies are low, flash plants are likely to be uneconomic and the biphase flasher gives a better thermodynamic return than conventional flash. Hudson quotes costs in the range US$1375/kW installed for a biphase machine exhausting to atmosphere to US$ 1175/kW for a biphase topping unit with a condensing turbine. There are commercially operating plant at Desert Peak, Nevada, USA (9MW) and Roosevelt Hot Springs in Utah, USA, (14MW). The author has no information about their performance and reliability.

A 1MW experimental Helical Screw Expander (HSE) was built and tested in a number of geothermal fields worldwide as part of an International Energy Agency project (DOE, 1985). The unit is a positive displacement machine incorporating a Lysholm or Helical screw which enables it to handle scaling fluids from liquid-dominated geothermal resources. As the fluid flows through the machine it flashes continuously down to the exit pressure. At entry to the machine the fluid gains kinetic energy which produces an impulsive torque on the rotor, the central region is for positive displacement and the contribution to overall energy of the exit is dependent on the exhaust conditions fixed by an atmospheric or condenser pressure. Based on thermodynamic principles, total flow machines, of which the HSE is one type, have the potential to convert the greatest fraction of the available energy. However, as a class, positive displacement machines are limited in volume flow capacity because internal losses become great as the fluid nears sonic velocity when it travels through the machine. This, in turn, means that these expanders are large in size to produce significant power. The demonstration unit used between 1980 and 1983 in Mexico, Italy and New Zealand was tested over a wide range of conditions and demonstrated its viability particularly using highly scaling fluids. The machine was deliberately designed to have high internal clearances in the expectation that scale would form during operation. Improvements in efficiency of 3.5 to 4 percentage points were recorded over some best periods where scale deposition occurred. Typical machine isentropic efficiencies of 40 to *50%* were calculated and, for most operations, efficiency increased logarithmically with shaft power while inlet quality and rotor speed had only small effect . A comparison with a 1MW back-pressure turbine showed that the HSE can compete favourably under certain conditions (DOE, 1985; Carey, 1983). However, although the machine tested was found to be rugged, some of the components, e.g., shaft seals (Carey, 1983) need to be improved.

SMALL POWER PLANT IN NEW ZEALAND

Currently, there are only two small geothermal units operating as stand-alone power units in New Zealand, apart from the small units used in the major power stations at Wairakei and Ohaaki. One of these is at Kawerau, where a 10MW backpressure unit uses the excess geothermal steam not required in the Pulp and Paper plant as process steam, and the 2.6MW Ormat installation uses separated water from a flash plant. The 10MW unit has been installed and operating for some time; it is understood to have good reliability but the author has no details. The Tarawera Ormat Installation (TOI) was commissioned in late 1989 and officially opened in February 1990 after a record short construction time of 15 months from purchase award day, according to Tilson et al. 1990, who reported on the first 6 months performance and operational characteristics of the units. The binary cycle installation of two Ormat energy convertors (OEC) receives waste water from Kawerau 21 flash plant at about 172°C and 8 bar. Heat rejection from the plant is by a forced draught air condenser situated above the OEC units. Each unit has a gross output of 1250kW, a total of 2.5MW, of which about 13% is used by the auxiliaries, pumps fans, etc., giving approximately 2.2MW available for the Bay of Plenty Power Board grid. As air coolers are used, the output is a function of the ambient air temperature. Figure 2 gives a graphic display of data of the flows, pressure and output of the machines at any time. This sophisticated monitoring system for an unattended plant ensures that unscheduled outages can be picked up quickly. In addition, plant performance is monitored directly by the manufacturers in Israel, who provide weekly reports direct to the BOP offices in Whakatane. Tilson et al. (1990) report no deposition in the heat exchangers and, with little maintenance required, load factors for the first six months of operation were over 90%, with 96.6% availability. Ormat have supplied some later availability data for the year 1990/91: the total for both units was 16,915 available hours giving *96.55%* machine availability; 456hrs of the total unscheduled downtime of 605 hours were due to an unusual generator bearing failure. As a comparison, the Ormesa E (10MW) and Ormesa H (13.2MW) plant at the Imperial Valley and East Mesa in the USA have an overall availability for 1991 of 97.9%.

This power plant's performance and simplicity in operation and maintenance is impressive. The TOI units are only two of over 120 geothermal OEC's installed by Ormat around the world, giving mainly geothermal base load electricity. These are the only commercially available units with this kind of proven experience, and as such have been shown to be cost effective.

In 1984, the then Ministry of Works and Development and the Ministry of Energy carried out a study on small scale (2 to 15MW) geothermal power development in five geothermal fields including Ngawha in Northland, and Mokai and Tauhara, in the Taupo Volcanic Zone, which were considered to be the priority fields for study (MWD, 1984). These fields were selected for study since investigation drilling had proven a source of steam and it was proposed to use these wells for production. A generalized evaluation of small plant was considered initially, but as work progressed it became clear that the economics of power generation were site-specific. Apart from looking at power developments, one objective of the study was to report on the potential geothermal energy for non-electric use in conjunction with power plant development. The arguments for and against small scale development have already been expressed in this paper; these were again quoted in this report; however, to achieve its objectives, the study group laid down the criteria that any small scale development must be economically viable by its own electricity production . The guideline set was that the production costs should be less that the marginal unit cost for new generation which at that time, March 1983, was seven cents/kWh for new thermal plant. It was also agreed that only proven technology would be considered, and therefore binary plant was not considered. For each field a range of factors was considered: atmospheric or condensing sets for the plant, various steam and two phase pipe line systems, reinjection options, environmental constraints. Optimisation of pressures, etc., was undertaken, with all power plant designed to fail safe, and remote supervision considered where appropriate. The direct heat alternatives for each field were also considered and a strategy for field development worked out. The economics were based on standard techniques using December 1982 costs. Sunk costs were excluded and a 10% discount factor was used. Realistic costings and delivery times were obtained and commissioning dates fixed at two years for atmospheric and three years for condensing sets. Costs and analysis were broken down into steamfield and power generation which enables the operation of the steamfield to be managed as a separate entity and provides a readily identified base cost of steam for industrial uses. The recommendations of the study were:-

Mokai: A 15.9MW net condensing set connected to a 120t/h steam supply generating at 4.3c/kWh.

Tauhara: A 4.4 MW back pressure plant connected to a 90 t/h steam supply . For this a 6.5MW unit ex-Wairakei was used. Power generation would be at 5.4c/kWh.

Ngawha: A 4.8 MW backpressure power plant connected to a 100t/h steam supply generating at 6.4c/kWh.

On the economic and environmental criteria evaluated, **Mokai** is the most attractive field to develop in this way, with Tauhara second, offering developments which could use direct heat. Whilst this study is now history (it is now nearly 10 years old, and probably does not relate very much to the present day situation) it does illustrate a number of points. Firstly, the economics (which the authors reported had about a 20% tolerance) showed that such developments were below the marginal cost of electricity at that date (7.0c/kWh) and that they were close to the planned costs of both Ohaaki geothermal (6.4c/kWh) and Clyde Hydro (3.0c/kWh), both of which have since been constructed. Secondly, despite using the same criteria for the development strategy, the study showed that the final options are site specific, a point not always appreciated by developers.

Because of a number of decisions at Government level and the fact that, currently, New Zealand has an over-capacity of power plant, none of the developments discussed above has taken place. There has been continual dialogue over the years between potential developers, Government, the power suppliers and the utilities distributing the electricity, concerning development of these fields and others in New Zealand, but no hardware has been installed. However, following the success of the TOI plant at Kawerau, it has been announced that the Bay of Islands power board are interested in developing Ngawha with similar plant. It has also been reported that a 10MW plant is proposed to be developed by developers other than Electricorp, on the Wairakei field.

CONCLUDING REMARKS

This paper discusses small power plant. It is not intended to be a recommendation for any particular type of development. World-wide examples have been given representing different views of how and with what equipment a geothermal resource can be developed. The author wishes to stress the point that each field has specific needs both in terms of the economics and the thermodynamics of operation. Using energy and exergy principles, it is possible to match a development to a resource to make the best use of that resource and to ensure that the installation is cost effective..

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Table 1: Comparison between first and second law efficiencies in geothermal and oil-fired plant

Geothermal''

	Efficiency(%) First Law	Second Law Res.	Second Law Wellhead
Geysers, California, USA - *Dry* Steam (100MW(e))	16.0	43.2	52.8
Krafla, Iceland, - Double Flash (30MW(e))	9.8	33.3	36.3
Nigorikawa, Japan, - Binary (1MW(e))	9.6		20.0

Note : For this binary plant a second law efficiency of **33.5%** is achieved, based *on* the exergy drop between production and injection wells.

Coal Fired(Large Capacity)+

Steam Pressure/temperature (MPa)/(°C)	First Law	Second Law
12.61538	31.9	30.6
34.5/649	**40.1**	38.8

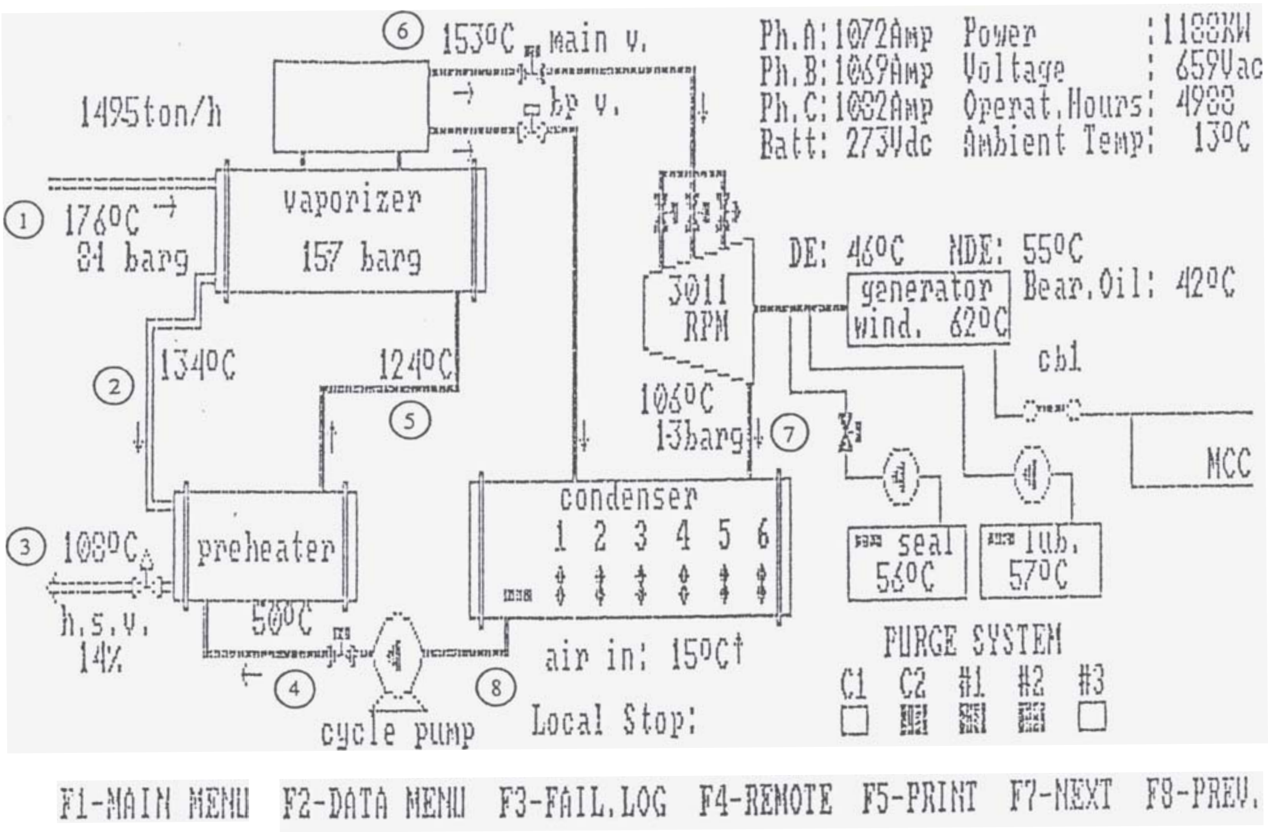
*DiPippo, Marcille, (1984)

+Szargut et al. (1988)

Table 2: Specific steam consumption at selected inlet pressures for atmospheric and condensing miniturbines

Inlet Pressure (bar a)	Atmospheric Exhaust (t/kWh)		Condensing (t/kWh)	
	2Mw	5Mw	4Mw	10MW
5	21.1	20.4	9.7	9.5
7	18.2	17.3	8.6	**8.4**
9	16.5	15.8	7.8	7.7

Atmospheric Pressure 1 bar
Condenser pressure 0.14bar
Gas content < 2%



Ph.A:1072Amp Power :1188KW
Ph.B:1069Amp Voltage : 659Vac
Ph.C:1082Amp Operat.Hours: 4988
Batt: 273Vdc Ambient Temp: 13°C

DE: 46°C NDE: 55°C
Bear.Oil: 42°C

Fig. 2: OEC 1 Graphic Display, Kawerau

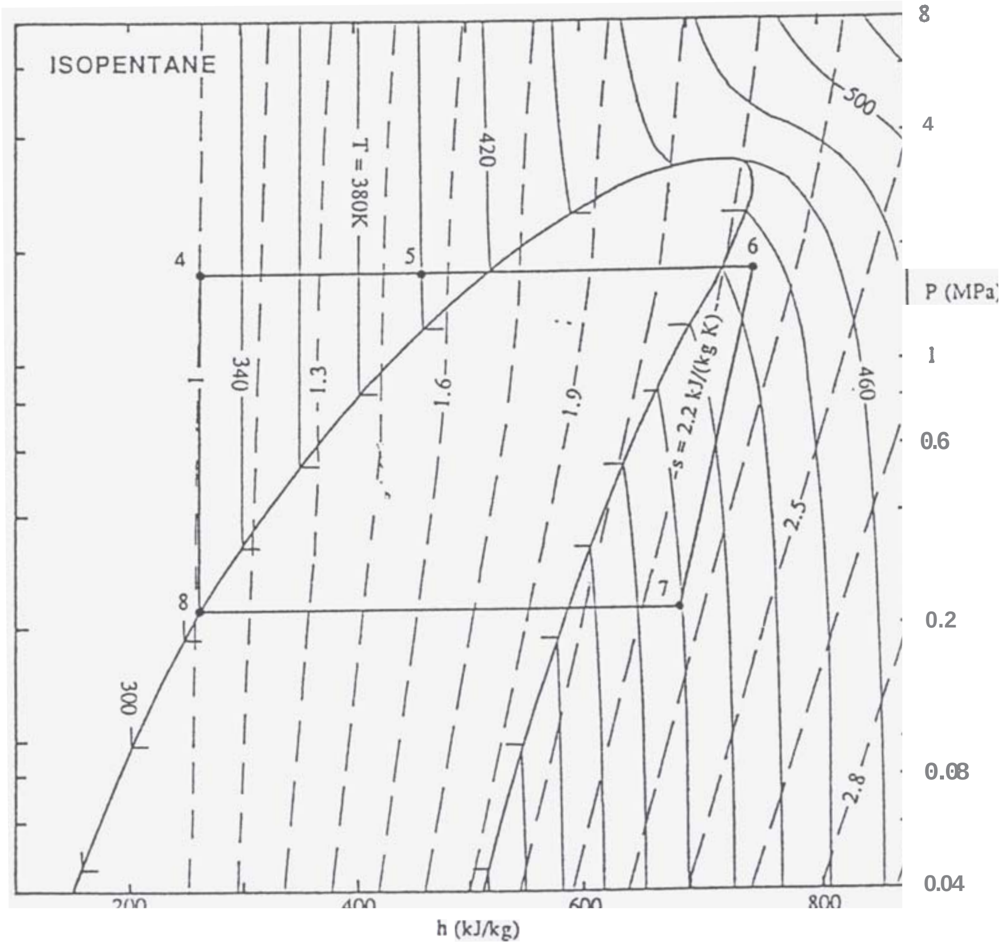


Fig. 3: Thermodynamic Cycle - Kawerau Binary Plant

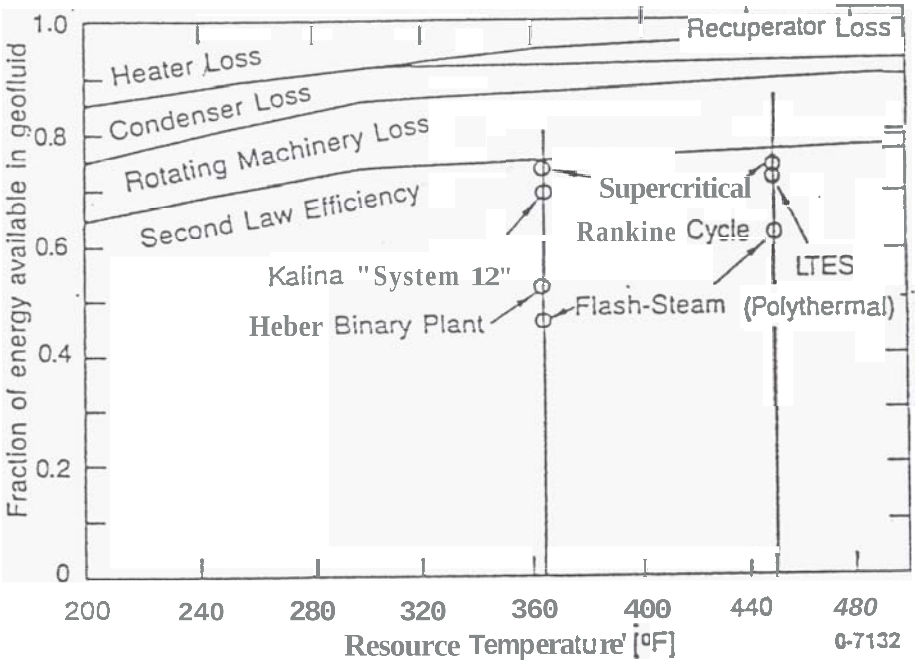
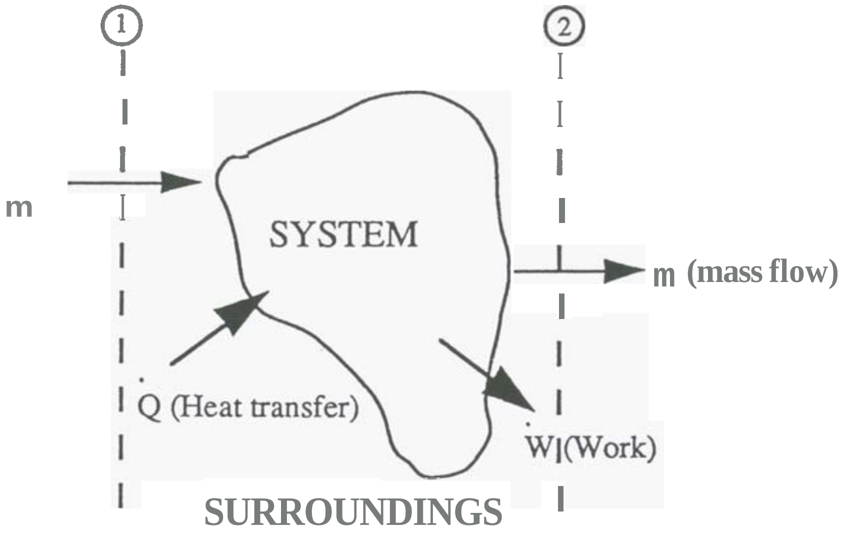


Fig. 4: Results for advanced systems (Bliem and Mines, 1991).

Appendix 1

Exergy Analysis



First Law

$$\dot{Q} - \dot{W} = \dot{m}\left\{(h_2 - h_1) + \frac{1}{2}(v_2^2 - v_1^2) + g(z_2 - z_1)\right\} \quad . \qquad 1$$

or neglecting change of kinetic and potential energy terms

$$\dot{Q} - \dot{W} = \dot{m}\,(h_2 - h_1) \qquad 2$$

Second law for system and surroundings

Entropy production $Q = \dot{m}\,(s_2 - s_1) - \frac{\dot{Q}}{T_0}$ 3

A reversible process gives $Q = 0$ which is the upper limit for given initial and final state then:

$$Q = \dot{m}\,T_0(s_2 - s_1) \quad . \quad . \qquad 4$$

combining equations 2 and 4 maximum termodynamic work

$$\dot{W}_{max} = \dot{m}\,\{(h_2 - h_1) - T_0(s_1 - s_2)\} \quad . \qquad 5$$

If the system is designed so that the final state of the geofluid is at the 'state' of the surroundings, the maximum possible work will be extracted from the geofluid for a given initial state. This ultimate work is called the **EXERGY**

i.e. $$\dot{E} = \dot{m}\,\{(h_1 - h_0) - T_0(s_1 - s_0)\} \qquad 6$$

or specific exergy $\left(\frac{\dot{E}}{\dot{m}}\right)$

$$e = (h_1 - h_0) - T_0(s_1 - s_0)) \quad . \qquad 7$$

For binary plants, or in cases where the geofluid is utilised as a liquid then

$$(s_1 - s_0) = c \ln\left(\frac{T_1}{T_0}\right) \qquad 8$$

$$(h_1 - h_0) = c\left(\frac{T_1}{T_0}\right) \quad . \qquad 9$$

where c is the specific heat, the exergy of a liquid with constant specific heat is

$$e_{eia} = c\left[T_1 - T_0 - T_0 \ln \frac{T_1}{T_0}\right] \quad . \qquad 10$$

The maximum power that can be obtained from a liquid being cooled from a temperature T_1 to a temperature T_2 is given by

$$\dot{W}_{max}\,(\text{liquid}) = \dot{m}\,c\left[T_1 - T_2 - T_0 \ln \frac{T_1}{T_2}\right] \qquad 11$$

Comparing the actual power developed by a system with the maximum possible power gives a Second Law Efficiency

$$\eta_2 = \frac{\dot{W}}{\dot{E}_1} \qquad 12$$

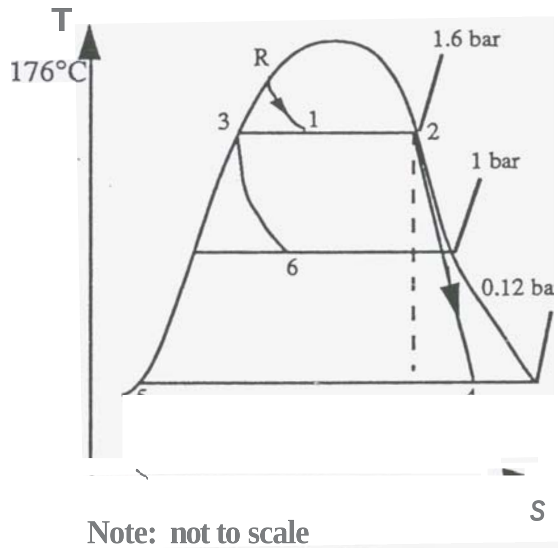
Note that if the K.E. or potential energy is important (h_1) should be replaced by

$$\left(h_1 + \frac{1}{2} v_2^1 + gz\right)$$

Also if the state 1 is at the bottom of the well the (gz) term *can* be included to refer the efficiency to reservoir conditions.

Appendix 2

Flash Plant



Note: not to scale

Assumptions

1) Saturated liquid source at 176°C
2) No pressure losses between wellhead - separator - turbine.
3) Optimum flashing pressure.
4) Turbine isentropic efficiency is 70%
5) Dead state at $T_0 = 288K$
6) 1.3 MW gross output - no allowance for auxillaries (ejector, etc.).

Position	t	h	s	e	m	E
	℃	kJ/kg	kJ/kgK	kJ/kg	kg/s	MW
R	176	745	2.0984	142.2	38.9	5.53
1	113.3	745	2.1561	125.7	38.9	4.89
2	113.3	2696	7.202	623.4	4.7	2.96
3	113.3	475	1.455	57.6	34.1	1.96
4	49.4	2422	7.5678	2244.1	4.7	1.16
5	49.4	207	0.696	141.9	4.7	0.67
6	99.6	475	1.4586	56.5	34.1	1.93
0	15.0	62.9	0.224			

Binary Plant

Assumptions:

1) Saturated liquid source at 176°C
2) No pressure losses between components.
3) Dead state at $T_0 = 288K$
4) 1.3 MW gross output.

Positions are as shown on Isopentane chart and graphic display Figures 2 and 3.

	t	h	s	e	m	E
	℃	kJ/kg	kJ/kgK	kJ/kg	kg/s	MW
1	176	745	2.0984	142.2	41.52	5.9
2	134	561	1.672	81.1	41.52	3.4
3	108	454	1.400	52.4	41.52	2.2
4	50	257	0.984	5.1	23.70	0.12
5	124	452	1.516	46.8	23.7	1.1
6	153	761	2.292	132.4	23.7	3.1
7	106	694	2.302	62.5	23.7	1.5
8	50	258	0.984	6.1	23.7	0.15
0	15	62.9	0.224	-	-	-
0^i	15	175	0.717	-	-	-

Note: 0 is deadstate water
0^i is deadstate isobutane