WAIRAKEI - A FRESH LOOK AT REJECTED TECHNOLOGIES

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SUMMARY - 1998 marks the 40* anniversary of the commissioning of the first units at Wairakei Geothermal Power Station, New Zealand. While precedents for geothermal power development had already been set in Italy with the harnessing of vapour-dominated fields, and in Japan on a small scale, it was Wairakei that led the way for large-scale development of water-dominated fields for power generation. At this 40* anniversary it is interesting to look back at some technologies that were considered for Wairakei and rejected, either prior to commissioning or shortly after, and then to see where these rejected technologies have gone since. Amongst these were binary cycle technology, a heavy water distillation plant, mechanical gas extraction, centralised multiflash systems and simple methods for phase separation.

1. BINARY CYCLE GENERATION

In the late 1940's and early 1950's water-dominated steamfields had not been developed commercially for power generation. There was an expectation that fluid conditions could be more arduous than those found at Lardarello. (Later materials studies showed that Wairakei fluids were quite benign). New Zealand engineers had studied the facilities at Lardarello but that technology could not be directly applied to New Zealand fields. Either phases had to be separated to allow steam to be used, or an alternative technology had to be developed that could handle wet steam.

One solution trialled at Lardarello for handling the difficult fluid conditions (particularly the high gas content) was to install heat exchangers for the generation of clean steam. However, right at the outset of consideration of power generation at Wairakei, the question was asked whether a water-based working fluid was the most appropriate to use. The New Zealand Dominion Laboratory was commissioned to investigate the use of Organic Rankine or Binary Cycle technology with a view to direct use of 2-phase fluids.

The brief reports on this concept have proved elusive, but minutes of a geothermal meeting involving staff fiom the Department of Scientific and Industrial Research and from the Ministry of Works in September 1950 make reference to the "ethyl chloride" plant as an alternative generation means. It is thought that the study did not proceed far beyond a consideration of a working fluid and the associated data, supply and cost problems. However, it is significant that a geothermal application for this technology was being considered at such an early date. At that time, the Organic Rankine Cycle was almost unheard of.

There had been some early consideration of organic fluids as working fluids for high temperature applications, but research papers tended to discount such use (Alcock et al, 1953). Bronicki (1984) records that development of Organic Rankine Cycle turbines began in the late 1950's with a view to solar applications (Tabor, 1961). Another research paper (Aronson, 1961) records the existence of vapour turbines at that time, while suggesting the apparently novel use of organic fluids (renamed refrigerants) in power cycles. However, a slightly later paper (Luchter, 1967) reviewed the status of technology, referencing some demonstration plants and concluded that the technology could seriously be considered for "near term application". Hence, it appears that technology to implement the Wairakei binary concept did not exist for another one or two decades after the initial concept.

The first known implementation of binary technology for a geothermal application was in the USSR at Paratunka in 1967 (output was less than 0.5MW), nearly two decades after the Wairakei binary concept (DiPippo, 1980). China followed with a number of small scale plants in 1970 (Zhou, 1983). The plant at Wentang, commissioned in 1971 is notable for also using ethyl chloride (or R160) as the working fluid.

Acceptance of binary technology was slow, with the focus in the geothermal world being on continued use of high temperature fields and flash technology applications. However, general interest was accelerated by the energy crisis in the 1970's, which significantly altered energy costs. Developments occurred in the areas of solar power, geothermal power and waste heat recovery (Angelino et al, 1984). A rapid boost came with the establishment in the US of renewable energy incentives and the establishment of Ormat Energy Systems Inc in the early 1980's.

Amongst a number of designers and manufacturers, Ben Holt and Ormat became the dominant players in the geothermal binary cycle market. Ben Holt designs were based on super-critical cycles using iso-butane as a working fluid while Ormat designs are based on sub-critical cycles using pentane as the working fluid.

Ormat have continued to expand applications of binary cycle technologies with the use of hybrid systems (Figure 1). These use phase separation with the steam phase being passed through a steam turbine to almost atmospheric pressure. Binary cycle units then replace the condenser. The liquid phase is usually passed through dedicated binary units to generate additional power. These hybrid plants have similar costs and performances to conventional plants. The first was installed in 1992 at Puna, Hawaii. The largest has been installed at Upper Mahiao, Leyte, Philippines. In New Zealand, this hybrid design has been used at the recently commissioned Rotokawa plant and is being used in the design and construction of the first stage of the Mokai plant.

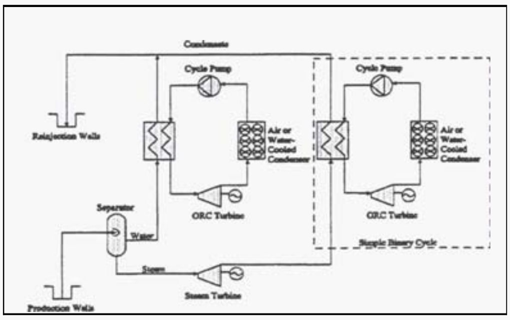

Figure 1: Typical Hybrid Binary Cycle Schematic

Contact Energy Ltd has recently applied for consents for a simple binary plant (not the hybrid type) to be installed at Wairakei to take advantage of the hot fluid now being piped to the vicinity of the existing power station for reinjection purposes.

Binary cycle technology has moved fiom a vague idea to established technology since the initial Wairakei concept. It is now routinely considered as a geothermal power generation option for lower temperature resources, and in its hybrid form for high temperature resources. Its acceptance in connection with g e o t h e d applications appears to be better than for non-geothermal applications, where limited use is found for waste heat recovery.

2. HEAVY WATER DISTILLATION PLANT

The New Zealand government was committed to a Wairakei development fiom the early 1950's, with Wairakei firmly established as a project effective fkom 30 July 1952 (Bolton, 1998). However, the government's resolve to develop the Wairakei geothermal field was helped by the interest of the United Kingdom Atomic Energy Authority (UKAEA) in the production of heavy water for it's nuclear programme. New Zealand Government approval, in principle, was given in May 1953. In 1954, the Government formally announced that a joint venture had been established between the New Zealand Government and the UKAEA to develop a plant producing 40MW of electric power and 6t/year of heavy water. The British firm of Merz and McLellan was appointed to undertake the design of the power station while Head Wrightson was appointed to design 'the heavy water production facility (Love and Bolton, 1980).

Details of the heavy water plant are not known. However, the Wairakei location was chosen partly because of the availability of large quantities of inexpensive heat. The process of large-scale production of heavy water at that time required much hydrogen gas and electricity. A hydrogen-water exchange reaction was employed in which hydrogen gas and steam were passed upward through a tower containing a catalyst, while liquid water flowed downward. An isotopic exchange reaction took place resulting in deuterium concentrating in the steam which then condensed, and was passed out of the bottom of the tower with the rest of the water. Consequently, this water was enriched in D_2O. A cascade arrangement lead to further concentration, with the final concentration being achieved by electrolysis (Glasstone, 1967).

It may be significant that all correspondence related to the heavy water plant refers to the "distillation plant" only. There is no mention of hydrogen or electrolysis. A demonstration plant and corrosion test facility was established on WK9. This was essentially just a distillation plant incorporating corrosion coupons within the design. The plant was apparently successful in demonstrating the principle of distillation and showed that ordinary materials such as mild steel were adequate for geothermal applications. Effort went into ensuring that the corrosion data was retained no matter what the fbture of the heavy water plant was.

The pioneering nature of the designs presented problems, and there are some verbal reports that simple arithmetical errors affected the initial concept. The initial design of the power station/heavy water plant required two separation pressures in the field, one high pressure system at 13.5barg and a second intermediate pressure system at 5.5barg. This in turn was associated with station pressures of 12barg and 3.5barg. The high pressure was for electricity generation while the second pressure was dedicated to the heavy water plant (Bolton, 1977). The heavy water plant was designed to take 450t/h of steam. It was designed to produce 6t/year of heavy water. Preliminary design concepts developed in 1954 were refined in the detailed design phase. By the end of 1955 detailed engineering costings of the respective plants had doubled the cost of the heavy water plant and increased by one-third the cost of the power plant (although it's output had increased fiom 40 to 47MW). As a consequence, the UKAEA announced it's decision not to proceed with the heavy water project in January 1956 (AJHR, 1956).

Design and procurement had reached an advanced stage when the heavy water plant was abandoned, so station steam pressures were retained. A decision was made to replace the heavy water plant with steam turbines. The pressure drop and flow available lead to the selection of two 11MW sets. This enabled the use of identical alternators to those of the LP sets. A comparison between the simple layout of "B" Station with the contrasting layout of "A" Station indicates the extent to which this abandoned heavy water plant affected the design of the initial station.

The heavy-water distillation plant also dictated the LP manifold pressure as it was going to reject steam at 0.1barg. It was decided to install condensing turbines to take this atmospheric steam for additional generation. These atmospheric pressure turbines have successfully operated at Wairakei to the present without difficulties. Atmospheric turbines represent an opportunity for additional generation, which could be transferred to other stations or fields around the world.

A later development for large scale production of heavy water, possibly after the Wairakei trials, utilised hydrogen sulphide gas and electricity. At the first stage of production, there is an isotopic exchange reaction between liquid water and H_2S gas. A "dual-temperature process" is used whereby hydrogen sulphide acts as a carrier for deuterium giving it up to water at the lower temperature (ambient) and regaining it at a higher temperature (100°C). Depleted water is discarded while enriched water is passed through a cascade system to enrich it further. After a certain concentration is reached, the dual-temperature chemical exchange process is no longer economic, so the product is transferred to a distillation plant for further enrichment by fractional distillation. Finally, the production of 99.75% pure heavy water (D_2O) is achieved through electrolysis (Glasstone, 1967). If the potential role of H_2S gas in the production of heavy water had been recognised at the time of design, then it is possible that the Wairakei heavy water plant could have proceeded.

Heavy water reactors for power production were slow to develop, largely because of the cost of production of heavy water. The UKAEA had its own reactors at Harwell, but these were gas cooled and graphite moderated. They were used for research and for space heating. The UKAEA were probably spurred on in their power research by the announcement from the National Reactor Testing Station, Idaho, USA that they had generated the first electricity (60kW) fiom nuclear power on 21 December 1951. Despite wanting to develop heavy water reactors, the cost and availability of heavy water forced development of gas-cooled reactors with graphite as the moderator. Heavy water plants were advanced in Canada, which had indigenous uranium resources but did not have the capability to construct and operate a fuel enrichment plant. With a heavy water reactor, a critical assembly can be achieved using natural uranium as the fuel. The first prototype CANDU power reactor (the type developed in Canada) was commissioned in 1962 generating 22 MW (Glasstone, 1967). The UKAEA eventually developed its own version of the heavy water reactor known as the Steam Generating Heavy Water Reactor *(SGHWR)* The only one of its type in existence was the Winfrith 100MW prototype commissioned in 1967. Now the "favoured" reactor design is of the light water type, and principally the Pressurised Water Reactor (PWR) which is derived from nuclear plant for marine propulsion (Crossland et al,1992).

3. MULTI-PHASE TRANSMISSION AND SEPARATION

Wairakei Power Station originally operated at 3 different manifold pressures: HP of 12barg, IP of 3.5barg and LP of 0.1barg. As a result, one possible misconception today might be that the steamfield was originally based on multi-phase separation. This is not correct. Initially, wells were tested then designated for use as HP or IP wells. The steam was separated at the wellhead, and separated water from all wells was fed directly to the silencers and steamfield drains.

However, in the initial independent concepts associated with both the heavy water plant and the power generation plant, the residual value of the hot water was recognised. The heavy water proposal by Head Wrightson included transmission of hot water to the station for flashing and provision of additional steam for the turbines. The power generation proposal by Merz and McLellan included the provision for flashing of additional steam at the wellhead.

At the time of power station commissioning in 1958 a Pilot Hot Water Scheme was implemented and was commissioned by July 1963, increasing power output by 5MW (Smith, 1970 and 1973). This involved piping hot water fiom the field to the station for secondary and tertiary separation (Figure 2). The designers however were wary of steam formation and to prevent boiling in the pipeline, the high pressure water was both pumped and attemperated with IP water. An elevated header tank in the steamfield was used to maintain and control pressure within the water line. Water was flashed at the station to provide additional IP and LP steam. Effectively this was the first flash plant. The plant operated for several months but was abandoned because of the characteristics of the wells connected to it. Field pressures were dropping rapidly in the first few years of production, reducing the water output of the connected wells.

Another significant feature of the pilot hot water scheme was the provision of scrubber vessels after each flash stage. Near pure condensate was used to scrub solids fiom the water carryover to reduce the saline content of the IP and LP steam to less than 10ppm (Haldane and Armstead, 1962). Although such scrubbers did not feature in subsequent flash steam developments at Wairakei (the long steam pipelines effectively fulfilling that function), scrubber vessels have become an integral part of other geothermal developments especially where steam separation is in close proximity to the power station.

The Pilot Hot Water Scheme was eventually cannibalised. The hot water line was converted to a steam line (H line). The separators were later used in flash plants located in the steamfield. Although the Pilot Hot Water scheme had a short life, the feasibility of secondary or tertiary flashing had been established.

A review of geothermal plants around the world indicates a good proportion are dual flash systems. Hence, although the technology was temporarily abandoned at Wairakei, multi-flash systems had been proven there and were later re-

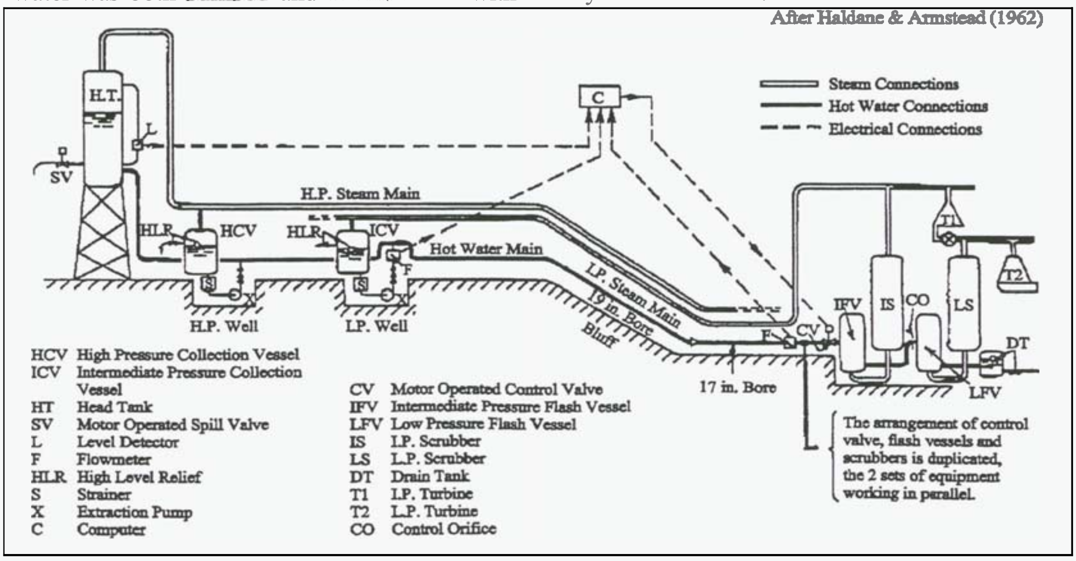

Figure 2: Diagram of Pilot Hot Water Scheme

implemented at Wairakei and many other fields world-wide.

4. U-BEND AND T SEPARATORS

As part of the initial efforts to separate the geothermal fluid phases, some very simple separators were tried. The New Zealand Dominion Laboratory and the New Zealand Ministry of Works separately undertook laboratory and field tests on the separation efficiency of simple Tees and U-bends with inside offtakes (Figure 3). As with the cyclone separators that eventually replaced them, these took advantage of momentum principles. The heavier liquid phase was less inclined to go around sharp bends.

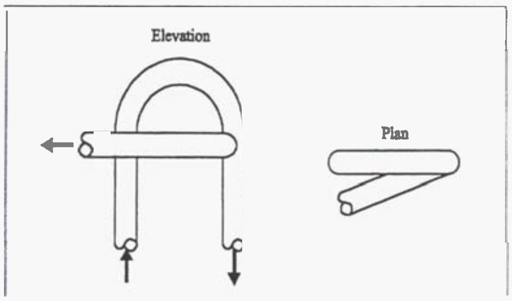

Figure 3: U-Bend Separator

The U-bend separator was originally used to separate phases to conduct simple well tests. It was then applied upstream of the early cyclone separators in order to prevent fragments of rock reaching the separator as well as assist with separation. In such a role, the pressure drop through the U-bend was of more interest than the actual separation efficiency. And so, while some initial performance testing was done, there was little development work done on understanding and improving efficiency. The U-bend "pre-separator" was soon made redundant with the introduction of high efficiency bottom outlet separators. The U-bend was quite effective and could be refined further with our current understanding of the two phase flow regimes within pipes.

The U-bend reportedly removed 80-90% of water, with the outlet steam about 50% dry. However, test results were quite variable. This was thought to be due to the water leg operating in a flooded condition. This meant that little steam passed down the water leg, and slugs of water had nowhere else to go than down the steam leg. A larger vertical pipe or chamber with water level control would avoid this problem today. In which case, separation efficiencies greater than 90% could be expected in the steam line. While this is not adequate for conventional developments, there are some situations where this could be adequate.

Performance testing was conducted in the late 1950's when techniques for sampling and measurement were still being developed. At the time, measurement error was recognised as being a limitation to understanding the separator performance.

Following preliminary tests at Wairakei, the U-bend separators were relegated to use as a pre-separator on some of the early wellheads. However it is worth considering their perfoxmance again, particularly with a view to binary cycle or process heat applications. If steam is required for a heat exchanger rather than a steam turbine, then the requirements for dryness can be relaxed. Steam dryness must be high for admission to a steam turbine, both to reduce exhaust wetness and to reduce the concentration of dissolved solids which could eventually foul the machine. However, dryness can be much less for a heat exchanger, with the dominant criterion being to avoid damaging flow regimes at the inlet to the exchanger. This can allow the relaxation of separator efficiency requirements by 3 or 4 orders of magnitude. Large separator vessels could be replaced with U-bend separators where flow regime allows, with a potential saving of millions of dollars for large developments. Consideration could also be given to the use of these in conjunction with downstream demisters for steam turbine use.

5. MECHANICAL GAS EXTRACTORS

Wairakei steam, as with all geothexmal steam contains a certain amount of gas which has to be extracted in order to maintain condenser vacuum. Plant in Italy utilised mechanical gas extractors of centrifugal design to handle gas percentages up to 500 times greater than in conventional thermal plant. Wairakei's initial concentration was up to 50 times greater than for conventional plant (Haldane and Armstead, 1962). Conventional thexmal plant utilised steam jet ejectors to extract the gas principally sourced fiom dissolved oxygen in the makeup water.

Mechanical gas extractors, with backup steam jet ejectors were initially selected for the "A" Station at Wairakei. Unfortunately the principle of relying on well-tried designs was difficult to follow. The design was atypical, partly forced by the low gas concentration and an apparent leaning by the designers towards the use of mechanical exhausters, because of their common use in Italy. The Wairakei mechanical gas extractors operated at relatively high rpm (14,500rpm), as a consequence of the atypical flowrates compared to the Italian conditions. Each LP condensing set had a 10-stage, high speed, motor-driven exhauster in four separate series casings. During commissioning, these units had problems with noise and excessive vibration (Bolton, 1977). Careful balancing and alignment was required. They proved very unreliable, mechanically, suffering fiom bearing and coupling failures. In addition, several designs of motor rotor were tried out before a design that could withstand the tough starting conditions was found (Haldane and Armstead, 1962). They were eventually abandoned, with the last unit taken out of service in 1970 (Stacey and Thain, 1983) and replaced with an all-steam jet ejector system still in use today (with modifications). Although mechanical gas exhausters were considered for "B" Station, they were ruled out at the tender stage for commercial reasons (Haldane and Armstead, 1962).

The design of the mechanical gas exhausters selected for Wairakei is unusual by today's standards. The 10 stages and high speed imply that the pressure ratio achieved for each stage was low, which may be explained by limitations in technology, particularly the lack of inlet inducers on the impellers, as well as the low inlet flowrate.

Today's mechanical gas exhausters are more reliable, simpler and run at slower speeds. Inducer impellers are used where the blades extend down around the hub radius so that the gas first encounters the blade while flowing axially. This allows increased head output and higher stage pressure ratios. The use of three or four stages is more typical nowadays. The configuration might consist of two LP stages on a rotor running at 3,000 to 5,000 rpm, and two HP stages on a smaller, shorter rotor running at 4,000 to 11,000 rpm.

Mechanical gas extractors were presumably chosen at Wairakei because the extra steam required to generate the electricity to drive them is approximately one quarter of the steam needed to drive the equivalent capacity steam jet ejectors. However, this figure exaggerates the benefit of mechanical gas extractors, as the value of the steam to drive the ejectors is much less than the displaced electricity generation inherent in a mechanical gas exhauster. This is because geothermal power generation economics is largely capital cost driven, and the steam generation (steamfield) costs are typically less than half' of the capital cost of the entire project.

However, at high gas contents the steam consumption of steam jet ejectors gets to be so large that mechanical gas exhausters become much more common. For example, Ohaaki, which has a gas content of approximately 4%, selected mechanical gas exhausters. These consume about 2 MW of a 40 MW gross turbine output, compared to steam jet ejectors which would have consumed about 8 MW equivalent of steam.

Although steam jet ejectors and mechanical gas extractors are both very inflexible with respect to gas flow, steam jet ejectors gain flexibility through their relatively low capital cost. This allows installation of 2x100% or 3x50% systems to give 50%, 100% and 150% capacity for example. Ejectors are simply turned on or off as required. The high capital cost of mechanical gas extractors tends to promote 1x100% or 2x50% designs. Less than 100% flows can be accommodated using recirculation, but at greatly reduced efficiencies – typically very little drive power reduction is achieved even with only 25% of design flow. Although it has not been used in geothermal applications to date, variable speed drives are used in other industries on compressors to give efficient turndown to the surge limit (about 50% of design flow). Newer modular compressor designs allow flexibility for a particular casing configuration at the selection stage, but post-installation capacity changes would still require impeller replacement as well as piping reconfiguration. As the modem inducer impeller requires a 3 dimensional design, they form a significant part of the exhauster cost, and therefore re-rating is expensive.

Outcomes from typical project economic evaluations for a modem application produce the following rules of thumb. Steam jet ejectors (typically 3-stage for maximum efficiency) are usually preferred for a non-condensable gas (NCG) content up to 1.5%. Hybrid systems consisting of steam jet ejectors for the initial stages and liquid ring vacuum pumps (positive displacement) for the final stage are preferred for a NCG content between 1 and 3%. Mechanical gas exhausters are preferred for a NCG content greater than 3%. On this basis, steam jet ejectors would probably be selected for a new application at Wairakei because of the low gas content. Where gas contents are higher, mechanical gas extractors based on successful

Italian experience, continue to be used with relatively little trouble.

6. CONCLUSIONS AND RECOMMENDATIONS

Wherever possible, the original designers of the Wairakei Power Project tried to employ established technology with some specific refinements. A number of the technologies rejected prior to or shortly after commissioning of the Wairakei Power Station in 1958 have been looked at again for this paper. Some, such as the heavy water plant have limited potential. Others, such as centralised multi-flash systems, binary cycle plant and mechanical gas extraction systems have achieved common usage in applicable situations. Simple technology such as the U-bend separator has been overlooked but has the potential for capital savings particularly in relation to binary cycle or process heat applications, with a little more research.

While a reasonably conservative approach to design is needed to aid funding of geothermal projects, there is an obligation on designers to keep an open mind on potential technologies. Old ideas should be reviewed to see if they could work in today's context. Other industries should be watched to allow cross-fertilisation of ideas. Wairakei Power Project was a soundly based project, but future developments will have a different blueprint.

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REFERENCES

AJHR (1956). Annual Report, Engineer-in-Chief, MOW. In: ***Appendix to the Journal of the House of Representatives, 1956,*** Section D1. pp45-46.

Angelino, G., Gaia, M. and Macchi, E. (1984). A Review of Italian Activity in the Field of Organic Rankine Cycles. ***Proceedings of the International VDI – Seminar held in Zurich 10-12 September, 1984,*** 465-482.

Aronson, D. (1961). Binary Cycle for Power Generation. ***Proc. Of Amer. Power Conference,23 1961.***

Bolton, R.S. (1977). Geothermal Energy in New Zealand. In: ***Energy Technology Handbook,*** Considine (Ed.), McGraw-Hill, pp7-14 to 7-31

Bolton, RS. (1998). Notes on the Early History of Wairakei. ***Proceedings 20th New Zealand Geothermal Workshop 1998.***

Bronicki, L.Y. (1984). Twenty Five Years Experience With Organic Working Fluids in Turbomachinery. ***Proceedings of the International VDI-Seminar held in Zurich 10-12 September, 1984,*** 685-696.

Crossland, I.G., Myerscough, P.B., Palmer, J.E., Pugh, A.R., Simpson, K.A. and Streatfield, R.E. (1992). Nuclear Physics and Basic Technology. In: ***Modern Power Station Practice, Volume J, Nuclear Power Generation,*** P. B. Myerscough (Ed)., Third Edition, Pergamon Press.

DiPippo, R (1980). Geothermal Power Plants Around the World. In: ***Sourcebook on the Production of Electricity fiom Geothermal Energy,*** J. Kestin (Ed)., USDOE.

Glasstone, S. (1967). ***Sourcebook on Atomic Energy.*** Third Edition, Van Nostrand, Princeton.

Haldane, T.G.N. and Armstead, H.C.H. (1962). The Geothermal Power Development at Wairakei, New Zealand. ***Proc Instn Mech Engrs, Vol 176 No 23 1962,*** 603-649.

Love, R.N and Bolton, R. (1980) Wairakei Geothermal Power Project: New Zealand. In: ***Geothermal Energy Projects Planning and Management,*** L.J. Goodman and R.N. Love (Ed)., Pergamon Press.

Luchter, S. (1967). Current Status of the Technology of "Organic" Rankine Cycle Power Plants. ***Proc. Intersociety Energy Conversion Engineering Conference- "Advances in energy conversion engineering" – Miami, FL, 13-17 August 1967,*** 117-121

Smith, J.H. and McKenzie, G.R. (1970). Wairakei Power Station New Zealand – Economic Factors of Development and Operation. ***Geothennics (1970) – Special Issue,*** 1717-1723.

Smith, J.H.(1973). Collection and Transmission of Geothermal Fluids. *Unesco, 1973. Geothermal Energy (Earth Sciences, 12.)*, 97-*106.*

Stacey, R.E. and I.A. Thain (1983). *Twenty-Five Years of Operation at Wairakei Geothermal Power Station.* Unpublished Draft Report for Electricity Division – Ministry of Energy.

Tabor, H. (1961). Large Area Solar Collectors (Solar Ponds) For Power Production. *UN Conference, New Sources of Energy Rome 1961.*

Zhou, Hong-Yi (1983). Binary Cycles in China. *Proc 5th NZ Geothermal Workshop 1983*, 275-279