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DEVELOPMENT OF WELL TESTING METHODS AT WAIRAKEI 1950-1980

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SUMMARY - This paper reviews some of the downhole and production testing equipment and methods that were developed and used at the Wairakei geothermal field over the last 40 years. Instruments to measure the downhole temperatures were developed and in use within a year of completing the first wells, and remained essentially unchanged as the preferred system for routine data collection for the next 20 years. Although separators were developed and available for permanent well test sites, for mobile exploration well testing, calorimeters were used until the James method became available in the early 1960's. This method remains as the preferred method for testing large geothermal well flows today.

1.0 INTRODUCTION

In many respects Wairakei was a fortunate choice for the fist large scale liquid geothemal development. Although the temperature and fluid properties at the time were considered to be quite severe, compared with many more recently developed resources, the Wairakei conditions are rather benign. This allowed the development problems to be overcome without recourse to exotic high-tech solutions and provided impetus for "political" acceptance for liquid geothermal as an economic energy source. Never-the-less, new ideas and methods for testing were required to make the measurements that allowed proper understanding and quantifying of the resource.

From the time that the first wells were completed, the essential elements of any geothermal well measurement programme were quickly established The importance of accurate, quality data, the need to interpret the measured information to obtain the "real" information, and the relationship of wellbore temperature-pressure data to the boiling point conditions were recognised (McKree and Banwell, 1951). The immediate need was for suitable measurement techniques that could give downhole temperature information and production flow data to determine the potential of the resource. Solutions to these problems were often developed from basic principles as off-the-shelf solutions were not available. There were other factors: New Zealand's isolation, post-war material shortages, restrictions on imports and the do-it-yourself tradition.

2.0 DOWNHOLE MEASUREMENTS

2.1 Temperature Logging

The first temperature logs were made using maximum recording thermometers. By insulating these to reduce the heat transfer rate, temperature reversals could be correctly measured, but the method was tedious and investigation of alternatives quickly led to the successful development of the "geothermograph". This was a mechanical instrument using a bimetal strip sensor,

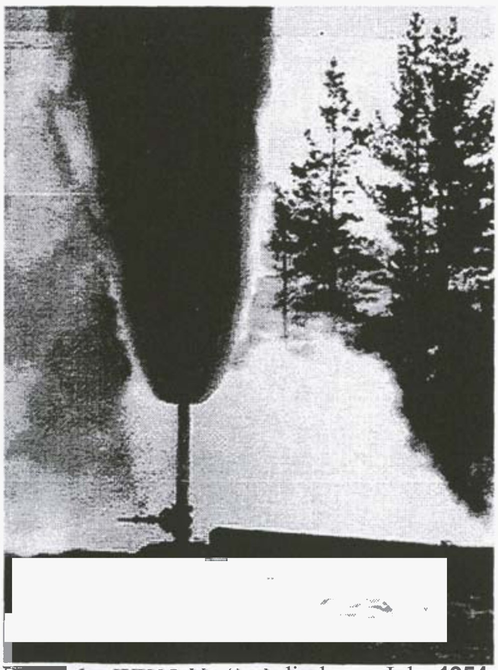

Figure 1: WK19 Vertical discharge July 1954. This photo appears to be soon after opening with the well producing a large proportion of rock.

developed from the bathythermograph used to measure underwater temperatures in oceanographic work. In the bathythermograph the temperature is recorded as a function of pressure, so a record of temperature versus depth could then be derived. The pressure input for the bathythermograph was substituted by a mechanical inertia drive mechanism, so by jerking the instrument suspension cable the recording plate could be moved past the temperature sensor. In the "geothermograph" the deflection of a bi-metal strip temperature sensor was recorded on a smoked glass plate. Initial results were good (McKree and Banwell, 1951) and the geothermograph was used up until mid 1970's for all routine downhole temperature data in New Zealand. Comparing results of many runs, the absolute accuracy of this instrument was about ±3°C. It had the advantage of a rapid stabilising time, of less than two minutes, so surveys could be completed rapidly, but only about 15 separate "indexes" could be recorded. This instrument was, in effect, custom made and required a lot of tender loving care to perform reliably. In the mid-70's the Kuster bi-metal sensor temperature recording instrument superseded the geothermograph.

At the same time as the geothermograph was being developed, other methods for measuring downhole temperatures were also investigated and trialled. In 1950 an attempt was made to use resistance thermometers, but this was unsuccessful as no cable suitable for repeated high temperature operation was available (McKree and Banwell, 1951).

Figure 2: Temperature logging using the copper-sheathed pyrotenax cable at WK23, October 1954. This is the "compleat" logging unit!

A metal-sheathed thermocouple ("Pyrotenax") cable was also trialled. This was a copper-constantan thermocouple enclosed in a copper jacket with mineral insulation. The problems of cable self support and stretch were partially overcome by enclosing the pyrotenax cable within a standard wire rope using a home-made device to insert the copper-jacketed pyrotenax thermocouple cable within the wire rope armour. This system was not successful for routine logs, but was used to measure temperatures in a flowing well where 2" tubing had been installed for measuring pressure by a gas purge system. It was also used in some wells to install permanent temperature monitors in the annulus of the cemented casing strings.

In 1966 a steel-axmoured, teflon-insulated, three-core logging cable was purchased. With this cable accurate temperature logs could be made with a platinum resistance sensor, although the surface "log" was obtained by manually balancing a Wheatstone bridge circuit. A spinner was also developed at this time to allow simultaneous temperature-spinner logs to be run. Continuing development of this system was curtailed when geothermal development activities in New Zealand were suspended in July 1971 - with the discovery of the Maui gas field. Activity was rejuvenated in 1974 after the "oil shock" and temperature-spinner tools were developed and used at Wairakei to confirm the severe downflows that were present in some of the wells that intercepted shallow and deep liquid aquifers (Syms and Syms, 1981).

2.2 Pressure Logging

During the initial field development the steam zone was not extensively developed and deep liquid pressures were calculated using the shut-in wellhead pressure or water level together with the fluid column density based on measured downhole temperature profiles in selected wells. In the mid-50's the Kawerau geothermal field was also being developed. Following the initial exploration by DSIR and Ministry of Works, the development drilling was carried out by Brown Brothers, an American drilling company who made some temperature-pressure surveys using Amerada RPG instruments. Development drilling at Kawerau was terminated with the loss of the rig at KA9 blowout in 1956. The company left a set of Amerada downhole gauges in New Zealand. These were modified to operate reliably in high temperature wells and were first used at Wairakei in 1960. In the early 1980's downhole logging Using quartz transducers was introduced, and in 1988 permanent pressure monitors using capillary tubing were installed in several wells.

2.3 Other Downhole Logs

Gamma Ray: The first deep wells drilled to more than 600 metres, in 1952, all had severe problems with broken/collapsed casing. The shallow casings for some of these wells were excavated and trapped water identified as the cause of the problems. To assist with obtaining better grout jobs it was proposed to dose the cement with a radioactive substance and subsequently check the effectiveness of the grout job by gamma ray logging. In fact this was never done in practice but tests with high temperature gamma ray logging were carried out for some time.

Casing Caliper: As a result of several casing collapses and joint failures an Otis casing caliper was purchased in 1958 and since that time has been used successfully to monitor changes in casing condition due to thermal effects, corrosion and ground subsidence. This tool is completely mechanical, and while recording only the maximum diameter measured by any one of its 16 arms, there is no temperature limitation.

Other "Oilfield" logs: A series of wells at Wairakei, Tauhara and Orakeikorako were logged in the early 1960's using the oilfield logging methods available at that time (gamma, sonic, resistivity). However no useful interpretation was obtained fiom these logs and for this reason and due to the temperature limitations of these tools no further logs of this type were run at Wairakei.

3.0 PRODUCTION TESTING

3.1 Flow Characteristics

Although a few of the Wairakei wells produce "dry" steam, the bulk of the wells produced fiom liquid/two-phase conditions. The first exploration wells were 150mm (6 inch) diameter and 2-300m deep. These were relatively small producers and the flows could be measured with a small calorimeter. The full magnitude of the flow measurement problem did not become evident until bigger diameter, deeper wells were completed into the "real" resource at about 600m depth. These wells could produce up to 450 t/h fiom liquid conditions at 250-260°C (Figure 7) often together with copious amounts of foxmation, as many of the early wells were completed without perforated liners. Over a period of months, with several intermediate workovers to clear blockages fiom the wellbore, WK25 deposited an estimated 800 cubic metres of rock on the surrounding area. Systems to control the foxmation, control the two-phase fluid at the wellhead and to measure the well flowrate and fluid quality were urgently required. Efficient steam-water separators were available fiom early in the field development (Bangma, 1961), but a more portable method capable of handling the large flows of up to 450 t/h was needed. The use of a liner with milled slots quickly cured the foxmation problem. A "horizontal silencer" had been used to control the surface discharge fiom most of the initial wells. This was superseded by the twin-stack "silencer", or atmospheric separator (Dench, 1961) in the mid-50's.

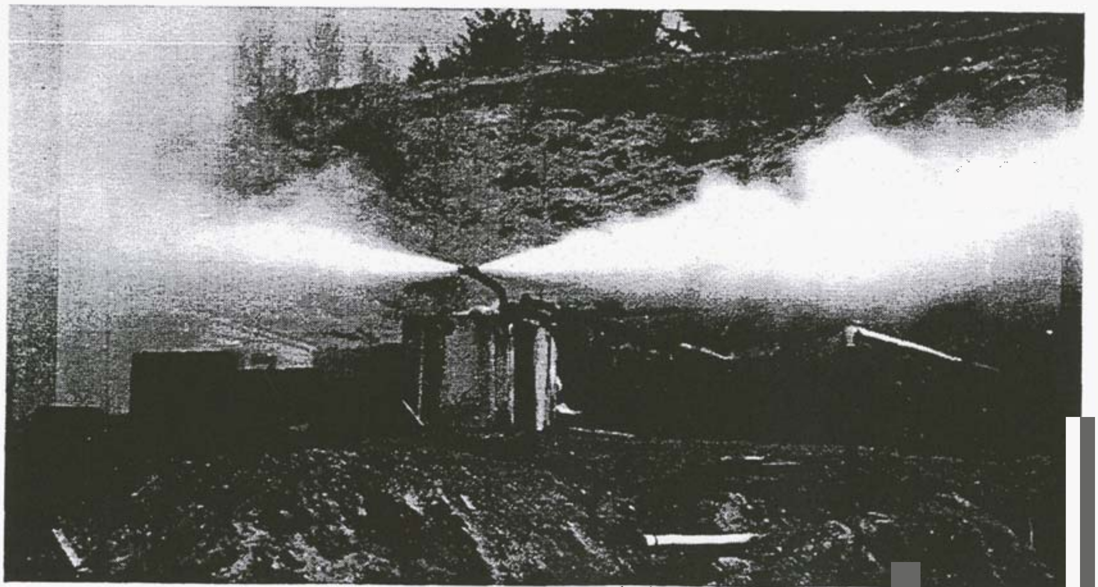

Figure 3: WK26 testing using a 4,500 litre swinging-arm calorimeter, July 1954. Flowrate is about 90 t/h .

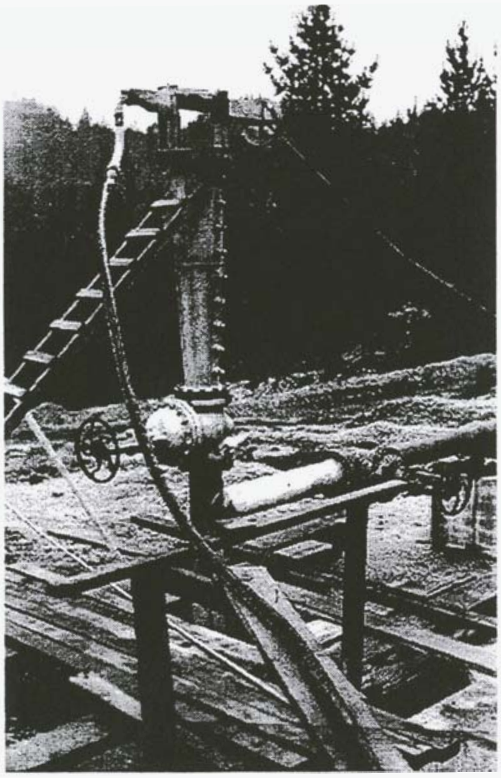

Figure 4: Mark 11 Steam Sampler at WK26 May 1954.

32 Calorimeters

After some experiments with different methods including on-line dryness determination (Belin, 1955), the calorimeter was chosen as the most practical method for testing exploration wells. Various types of total flow calorimeter were constructed, from 1000 to 15000 litre (Figure 3). These were suitable for "smaller" wells, but for the larger capacity wells the size became unwieldy, and unsafe due to the large flow being discharged direct to the atmosphere. The sampling calorimeter ("Steam Sampler") overcame many of the difficulties for measuring larger well flows with a reasonably portable test setup. The sampling calorimeter method was developed by DSIR in 1954 (Banwell, 1954) and from then until about 1964 was the preferred testing method for new development and exploration wells.

Initial tests for the Mark I "Steam Sampler" were with horizontal pipes, as most of the well testing at that time was done into the "horizontal silencer". These tests showed the flow distribution at the discharge of a horizontal two-phase flow was highly asymmetric. The "Mark II" Sampling Calorimeter (Figure 4) was developed for use with a vertically flowing well discharge to avoid this potential source of error.

At that time wells were frequently discharged vertically to the atmosphere to clear rock fiom the wellbore and for general testing.

The initial tests to develop the method were used to define the distriiution of heat and mass flow across a vertical two-phase flow (Figure 6). This information was then used to design a sampling and calculation procedure that could be used to determine the total heat and mass flowrates. The sampling calorimeter method required a 0.25 square inch nozzle to traverse across a 12" diameter two-phase fluid discharge (Figure 4) using a standard 44 gallon drum as the calorimeter (Figure 5).

The first field tests of the sampler must have been something of a trial, to judge from the preliminary test report Banwell (1954):

" The well was opened on 13/5/54, throwing out an appreciable amount of pieces of hard rock. The sampler nozzle was traversed out of the jet .... but erosion was very rapid ... and eventually the shroud disappeared."

" A set of point by point calorimeter runs ... was taken the next day ...the well having been closed overnight. During these trial runs, the following troubles were encountered:-

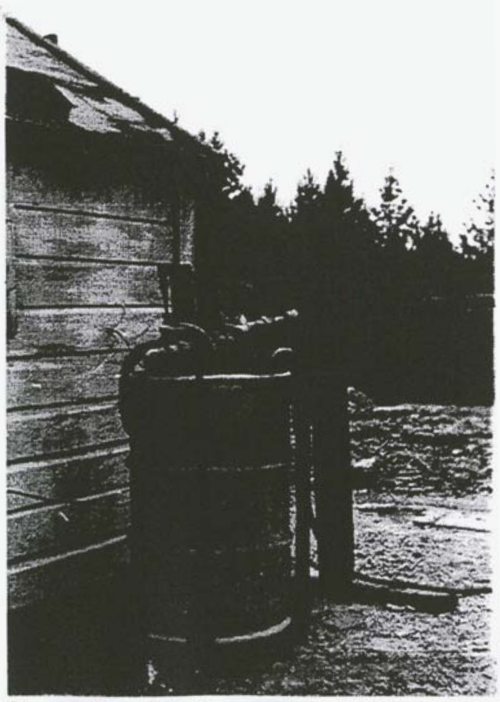

Figure 5: Calorimeter for Mark 11 Steam Sampler, WK26 May 1954.

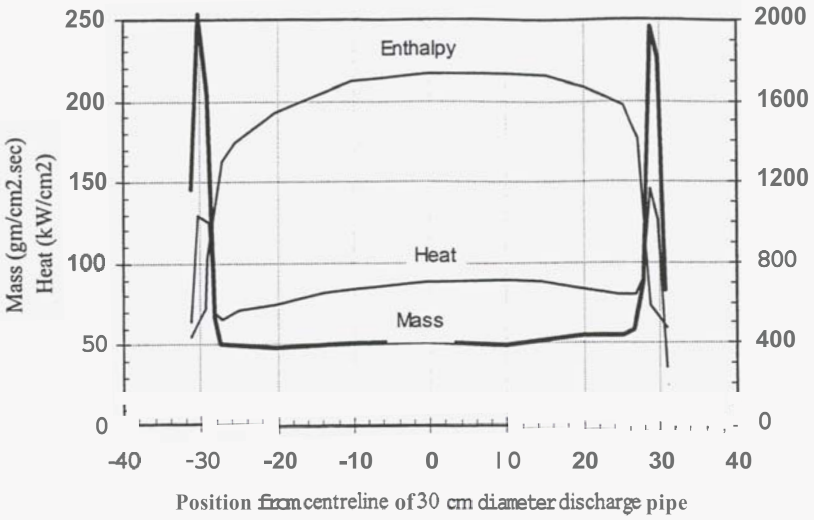

Figure 6: Mass and energy flow densities measured across a 300 mm diameter vertical two-phase discharge using the Mark 11 Steam Sampler - see Figure 4 (after Banwell, 1954)

"(1) The vibration of the hut caused by the high noise level made the zero of the potentiometer extremely unsteady, so that balancing operations were unduly slow and difficult, and accuracy was impaired somewhat.

"(2) The location of the calorimeter outside the hut was unsatisfactory, as both operator and calorimeter were showered with cold water from the bore in certain conditions..... Also the operator .... often became extremely wet, and had difficulty in adjusting the potentiometer, taking notes etc. afterwards."

"(3) The sampler diverted some of the steam and water from the jet in a downward direction. This came through the hut door in some wind conditions and filled the hut with steam, leading to frequent difficulties in reading the instruments *or finding* the hut [my italics].

"(4) The manual traverse drive [for the sampling nozzle] was unsatisfactory in a number of ways. It did not drive smoothly, and the operating point could not be placed near the other instruments, nor could it be readily placed where required to give different directions of traverse.

The sampling calorimeter had the disadvantages of any calorimeter-based method in that each measurement was a snapshot in time, with attendant environment and logistical problems. To check and maintain accuracy the sampler was frequently calibrated against measurements made at a well which had a permanent separator. However, as mentioned above, taking all the factors into account it still was the most appropriate method for testing large wells. Typical results are shown on Figure 7.

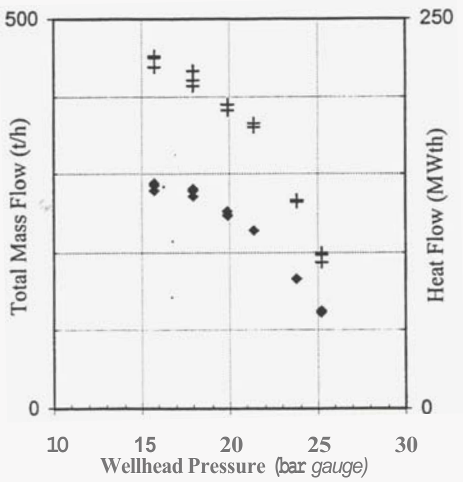

Figure 7: WK26 Productivity curve measured using the Mark 11 Steam Sampler - 1958

3 3 Steam-Water Separators

The very large flows of boiling water and flash steam produced by the deep, eight inch diameter wells required. pressure separation of the two phases to permit measurement by recognised engineering methods, using differential pressures across standard circular orifices. In the early tests, "primary" separation was obtained using inverted 180 degree U-bend pipe separators. These diverted only about half of the water, but when located upstream of the conventional top-outlet cyclones, allowed "dry" steam flow to be measured - albeit along with two water flows. To prevent the water boiling across the measurement orifices, the pipes were cooled in large tanks, making this type of test setup impressive, to say the least.

Concurrently with the adoption of two-stage separation for the wells being connected to the power station, Ministry of Works staff successfully tested a bottom outlet Webre-type cyclone without using an upstream U-bend to reduce the water ratio. Subsequently, a series of tests were made of various geometries to optimise separator performance, to the degree that the dimensions required for any well flow-enthalpy-pressure combination could be calculated (Bangma, 1961).

The alternative well output test methods were calibrated against orifice measurement of separated phases, to ensure acceptable accuracy.

3.4 James Method

Alternative methods for measuring well performance were being continually trialled by DSIR and by 1962 what is now known as the James or Lip Pressure method had been developed. Flow measurement for compressible single phase fluids using critical flow was already well known and inconclusive experiments had been made with two-phase fluids using relatively small pipes. A series of tests was carried out using typical geothermal conditions - fluid enthalpy 600-2800 kJ/kg, 3-8" pipe size and critical pressure up to 4.4 bar. These experiments showed that the critical pressure at the end of a pipe discharging two-phase fluid was related to the heat flow along the pipe by the equation below (James 1962, converted to metric units).

$$\frac{G \times h^{1.102}}{p^{0.96}} = 0.184$$

where:

G = mass flow velocity t/cm2/sec
h = flowing enthalpy kJ/kg
p = critical pressure bar absolute

This relationship was not of immediate application as there remained two unknowns, the flowing enthalpy and the total flow rate. However, as most of the Wairakei wells were discharged into an atmospheric separator (Dench, 1961) to avoid environmental problems, the separated water flow could be used together with the "James" equation to calculate the flowing enthalpy and then the mass flowrate (James, 1966). This simple method immediately resolved the geothermal two-phase flow measurement problem and has become the (almost) universal method for testing two-phase geothermal exploration wells.

4. ACKNOWLEDGEMENTS

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