HEAT TRANSFER OF THE KARAPITI FUMAROLE FIELD (1946-2000)

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SUMMARY: Improvements in heat transfer calculations for the Karapiti fumarole field are described. Heat loss from conduction, evaporation and direct steam discharge can be assessed using air-photos and infrared surveys. Analyses of 22 air-photos since 1946, and 5 infrared surveys since 1989, are used to map changes in steam discharge, areas of hot ground and areas of thermally tolerant vegetation. The linear relationship between heat loss and normalized steam cloud area observed in recent studies has been applied to older fumarole studies and air-photos. Large changes in heat flux occurred at Karapiti during the first 25 years (from 1950), but changes have been more gradual since 1975. The source of deeper vapour flux has apparently migrated southwards over this period. The heat output of all fumaroles is assessed to have increased from about 30 MW (1950) to 235 MW (1960) then decreased gradually to c. 100 MW (2000). The total heat loss for Karapiti in 2000 is assessed to be c. 200 MW, 50% from conductive losses and 50% from steam discharges.

1. INTRODUCTION

Recent improvements in reservoir simulation allow for more accurate matching of calculated to observed changes in heat transfer from thermal areas. This, along with increasing public expectation of more rigorous environmental monitoring, provides the motivation for our recent efforts to improve the accuracy of such heat transfer calculations.

Concentrated heat discharge occurs in the Karapiti fumarole field ('Craters of the Moon'), located c. 3 km south of the Wairakei bore field (New Zealand). This is one of the largest fumarole fields associated with a liquid dominated geothermal system. A shallow layer of lake sediments, which restricts vapour flux elsewhere in the Wairakei field, is thin or absent beneath the Karapiti area. This explains why so much steam is discharged in this rather small area of c. 0.45 km^2 (see Fig.1). Heat is transferred to the surface by conduction, evaporation and direct discharge of steam through numerous small and large vents. Vapour ascends close to the surface and condenses at shallow depth, this raises the surface temperature and inhibits plant growth. Conductive heat transfer through 'hot ground' is enhanced by a large temperature gradient in the upper few centimeters. In the hottest ground some minor steam is also discharged directly. 'Steaming ground' is surrounded by 'warm ground', with soil temperatures < 40°C at 15-cm depth, populated by thermally tolerant vegetation. Numerous surveys were made in the past to assess the magnitude of the heat discharged at Karapiti; these studies are listed in a summary report by Allis (1979).

Most of the steam, however, is discharged by large fumaroles. The steam output of fumaroles increased by about one order of magnitude from c. 30 MW in 1950, to over 200 MW by 1965. This increase in steam flux was caused by formation of mobile steam from flashing of deep hot water, induced by the pressure drop in the reservoir from 1954 onwards (Allis, 1981).

During our recent studies of the characteristics of harole clouds (Hochstein and Bromley, in press), we collected and scanned a total of 22 vertical air photos of the Karapiti area which were taken between 1946 and 2000. These photos contain importaut information about the major changes in heat transfer of the area. Changes in steam output and locality of fumaroles, and changes in areas of hot ground, are readily detectable. Since 1989, the extent and intensity of thermal ground has also been monitored using aerial infrared surveys to capture high-resolution thermal imagery on videotape.

2. CHANGES OF FUMAROLE PATTERNS

The major changes in harole patterns as they occurred during the last 50 years are immediately apparent in the air-photos; these patterns are shown in Fig.1. Allis (1979) and Mongillo (1988) have previously described some of the changes.

Fumarole activity in 1946, representative for the undisturbed state of this field prior to exploitation, was not restricted to the activity of the 'Karapiti Blowhole', since some steam discharge also occurred at the SW margin of the field (area "I", Fig.1). In addition, bare ground, usually indicative of thermal ground, covered about half of the area shown in Fig.1. In 1946, the Karapiti area was already a large thermal area, containing several inactive craters (area D1 and E). It has not expanded significantly in area since then.

There is a gap in the air photo collection between 1946 to 1958. From earlier reports (cited in Allis,

1979) it is known that large changes in fumarole activity occurred between 1954 and 1958. These were caused by fluid abstraction from the bore field, which started in 1954. By 1958, the resulting increase in vapour flux beneath the Karapiti area had caused numerous 'steam eruptions' whose craters became the centres for large fumaroles (areas C, D1, and E). The activity of D1 in an older, previously inactive, crater was short lived and lasted only from 1958 to 1965. The activity at centre C lasted until 1970.

Most of the presently active fumarole centres started with steam eruptions during the period fiom 1960 to 1970, namely centres B, D2, F, and G (see Fig.1). Steam eruptions have continued in some of the craters, mainly in areas E and F. New centres have not developed since 1970.

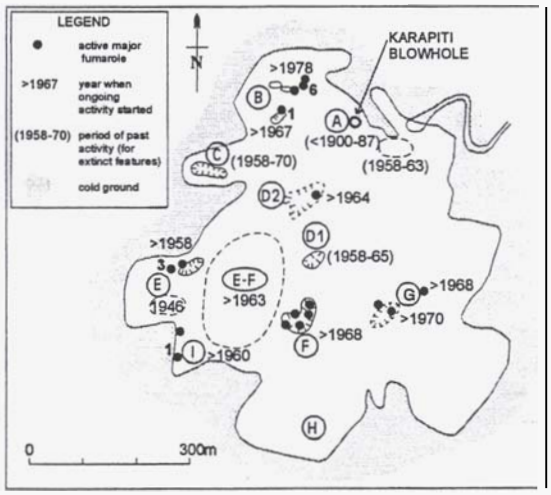


Figure 1: Map of the Karapiti Fumarole field

2.1 Relative changes in the output of fumaroles:

The heat transfer of fumarole plumes depends linearly on the total area of their steam clouds, since heat transfer by evaporation and air entrainment is proportional to the cloud area (Hochstein and Bromley, in press). These clouds consist of opaque and semi-opaque portions. The effects of differences in evaporation can be reduced by appropriate weighting factors (W=0.5 for semi-opaque portions and W=1 for opaque portions).

The cloud area of a single fumarole (Ai), as seen in vertical air-photos, depends upon various time-variable meteorological parameters. Wind speed is the most important. Others include ambient temperature, humidity and rainfall history. Although most air photos of the Karapiti area in our collection were taken in calm and cloudless conditions, the total area (A_{tot}) of all fumarole clouds over the field show large variations (Fig. 2). The value A_{tot} depends in part on the actual total steam (ie heat) output of all fumaroles (as shown by the rather small A_{tot} area in the 1946 photo). It also depends on the meteorological factors listed above. Thus, rather small areas A_i in the photo of March 1994 reflect a *dry*, calm day, whereas large cloud areas in June 1982 are caused by local winds.

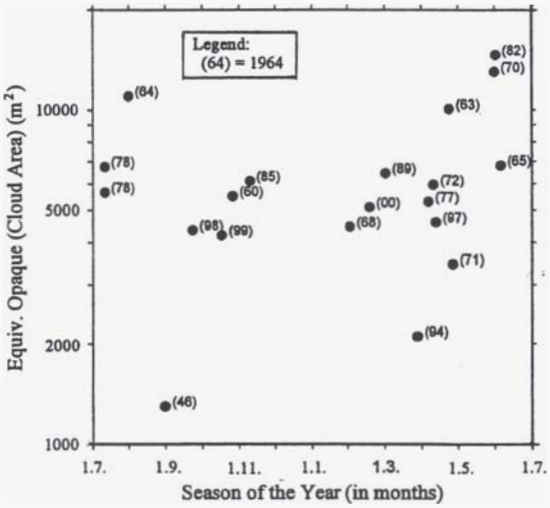


Figure 2: Total area (A_{tot}) of harole clouds visible in air photos of the Karapiti area taken between 1946 and 2000, plotted against season (1st of July '1.7.' to 30* of June).

The meteorological effects upon the cloud area A_i can be reduced by normalizing it with respect to A_{tot}; changes with time in (A_i / A_{tot}) for the same fumarole in different air photos reflect, therefore, changes in heat output of that fumarole. The cumulative values (A_i/A_{tot}) of all fumarole areas in the Karapiti field between 1946 and 2000 are shown in the form of a bar diagram in Fig.3. The horizontal axis represents elapsed time in years; the number at the base of each column lists month and year when the photo was taken (0658 stands for June 1958). The fumarole centres are identified by the capitals A to I, as located in Fig. 1. Each half in Fig.3 represents a time span of about 25 years: 1946 to 1972 (upper) and 1976 to 2000 (lower).

The bar diagram clearly shows the development in time of each fumarole centre. Large and irregular changes occurred between 1946 and 1972, whereas more gradual changes are indicated in the lower section for the second period (1976-2000). The most significant changes are associated with major steam eruptions, such as at Karapiti Blowhole (area A) before June 1958. The effect of the steam explosion creating the first haroles of centre B is still visible in their anomalous steam cloud area in the 0268 air photo. The short life span of centres C and D1 and the long life span of centres E and F can also be seen, together with other important trends. The dashed line, for example, joining the columns in each section separates haroles in the northern half from

those in the southern'halfof the Karapiti field. The position of this line with respect to the accumulated A_i/A_{tot} values shows that most of the heat discharged by steam originated fiom fumaroles in the northern half between 1946 and 1972. This changed between 1972 and 1976, when more heat was discharged by fumaroles in the southern sector. The pattern indicates that sources of deeper vapour flux have migrated southward. Since 1976, areas E and F show a possible inverse relationship in relative heat discharge. This is probably caused by pressure connection through a common underlying steam zone.

2.2 Assessment of the magnitude of heat output of the Karapiti fumarole field:

Our studies of fumarole outputs during the last two years have shown that the total heat output (Q_{tot}) of all fumaroles with visible steam clouds can be assessed fiom the measured output (Q_i) of haroles whose relative steam cloud area (A_i/A_{tot}) is known (Hochstein and Bromley, 1999, 2000). Since there is a clear linear relationship between Q_i and A_i/A_{tot} for all data fiom our last two Karapiti surveys, made in 1999 and 2000, an order of magnitude estimate of the total heat output (Q_{tot}) can also be obtained fiom other data sets of Q_i and A_i/A_{tot} (Hochstein and Bromley, in press).

This finding can be applied to older fumarole studies of the Karapiti area made between 1950 and 1979 since most of the original data are still kept in the IGNS data archive at Wairakei. Many of the early heat flow assessments contain systematic errors since the effects of air entrainment, which increases the total mass flow rate, were not recognised. Air entrainment, however, causes a typical turbulent flow pattern which can be recognised from the temperature of the steam-air mixture, and this effect can be reduced (Hochstein and Bromley, 2000). A linear relation between Q_i and A_i of haroles had already been postulated by Dickinson (1968) but no proof could be given, partly because of the problems in the earlier interpretations of fumarole measurements.

Out of the total of eight heat flow measurements of large fumaroles made between 1950 and 1979, four could be re-interpreted. The revised Q_i data together with reduced A_i/A_{tot} values are listed in Table 1. The resultant uncertainty in Q_{tot} is greater than that of the Q_i values because of the difference between the date of the field survey and that of the air photo. However, the data in Table 1 show clearly that the heat output of all fumaroles increased by almost one order of magnitude between 1950 and 1960, namely fiom c. 30 to c. 235 MW. The total output has since decreased to c. 100 MW today. Not all the heat loss data for Karapiti fumaroles listed in the report by Allis (1979, his Fig. 3) for the period 1950 to 1978, could be checked since some data are incomplete or relate to fumaroles with ill-defined steam clouds.

Table 1: Estimates of Karapiti fumarole heat loss (Q_{tot}) fiom relative steam cloud areas (A_i/A_{tot}):

Fumarole (Remarks)	Date Q_i (MW)	Date A_{tot} (m2)	(A_i/A_{tot}) Q_{tot} (MW)
A #1	010550	300846	0.60
0.39 m pipe	18 f 1.5	1300	30
A #2	030660	251060	0.087
open crater	20.5 f 3	5500	235
A #2	160163	230463	0.112
0.51 m pipe	c.30 f 5	10050	265
A #3	160179	100778	0.038
0.4 m pipe	4.6 ± 1	5670	120
E3 #4	160499	160199	0.14
openvent	15 f 1	4200	105
E3 #4	150300	180200	0.13
openvent	12 f 1	5100	88

Notes:
#1) Based on original data by R.L. Ledger, re-interpreted by Hochstein and Bromley (2000),
#2) Based on re-interpretation of original data collected by G.B.Dawson,
#3) Re-interpretation of original data by R. G. Allis,
#4) Based on data cited in Hochstein and Bromley (in press).

The Q_{tot} values in Table 1 do not include the contribution of numerous small steam vents whose steam clouds ($< 5\ m^2$) can not be detected in air photos. Their combined effect is significant since it was found recently (March 2000) that there are, for example, at least c. 150 of such small vents in the Karapiti field which together discharge heat at a rate of at least 12 MW.

3. ASSESSMENT OF THERMAL GROUND AND ASSOCIATED HEAT TRANSFER

The extent of thermal ground in the Karapiti area was assessed initially from ground temperature surveys. Temperatures at 0.15-m depth (T (0.15)) were used to define zones of warm and hot ground. The extent of hot ground in earlier maps (1958 and 1960) contains some errors because of the limited station density. The quality of maps increased when zonation of thermally stressed vegetation was considered. Such zonation and an increase in spot temperature density data improved the quality of the 1964 and 1968 maps for the area (Dawson and Dickinson, 1970). The last ground temperature map of the Karapiti area, based on a combination of ground and aerial surveys, was produced more than 20 years ago (Allis, 1979). The margin between thermal and

non-thermal ground fkom that study is shown in Fig.1.

Renewed interest in monitoring changes in thermal ground led to helicopter-borne surveys of hot ground with raised surface temperature using modem infrared surveys (emissive **8-10 um** spectrum). These surveys started at Karapiti with a trial survey in **1989** and were repeated in **1991, 1997, 1998** and **2000.** The surveys define clearly the extent and intensity of hot ground.

3.1 Changes of thermal ground (visible in air photos):

The few ground temperature maps referred to above are not sufficient to recognize the overall development of thermal ground in the Karapiti area. Such information, however, can be obtained from an inspection of *air* photos. Four examples, illustrating the large changes between **1946** and 2000, are shown in figure **4.** The resolution of these photos is sufficient to recognize clearly the area of hot ground with thermally stressed vegetation with T **(0.15)** >> 40°C, an area which includes bare, steaming ground. The surrounding area is characterized by the appearance of small shrubs, which can still grow at a ground temperature T **(0.15)** between **25** and **40°C.** Such warm ground can not easily be identified from air photos. Furthermore, photos cannot easily differentiate bare ground that is thermal, fiom other causes of vegetation loss, such as pumice ejecta fkom crater eruptions, acidic clays or gully erosion.

Table 2: Area of thermal ground at Karapiti visible in air photos **(1946-2000).**

Date of Air-photo	Visible thermal ground (km^2)	Sub-areas of hot ground (km^2)
300846	c. 0.17	-
050658 #1	0.17	0.175 (1958) >80°
051060 #1	0.27	0.23 (1960) >52°
230463 #2	0.28	0.20 (1964) >52°
100778 #3	0.29	0.12 (1978) >80°
081185	0.30	-
180200	0.33	-

Notes:
#1) Dickinson **(1960)** after scale correction;
#2) Dawson and Dickinson **(1970);**
#3) Allis **(1979)**

The area of visible thermal ground is listed in Table **2.** It remained the same between **1946** and **1958** but increased rapidly fiom **0.17** km^2 in **1958** to **0.27** km^2 in **1960.** Whereas the total steam output of fumaroles declined probably fkom **1968** onwards, visible thermal ground has increased in size slowly and almost linearly with time during the last **40** years. Areas of hot ground with T **(0.15)** >52°C and >80°C from various ground temperature maps are also listed. It appears that hot ground areas in earlier maps were probably overestimates. More representative are the sub-areas of hot ground in the **1964** and **1978** ground temperature maps.

3.2 Changes in hot ground visible in infrared images (1989-2000):

The problems described above concerning the interpretation of air-photos can partly be overcome by the use of thermal infrared (TIR) imagery. Repeat TIR surveys, using a FLIR thermal imaging camera and videotape, have been conducted over Karapiti at night, during autumn, to minimize solar heating and seasonal effects. Typical ground resolution is about 1-m, achieved by flying at about 600m height. Typical temperature resolution is 0.2°C across a surface temperature range of about 10°C to 60°C (when calibrated using water surface temperatures). Examples of **275m** by **145m** images, digitally captured from the May **2000** TIR videotape, are given in figures **5** and **6.** These show the two large craters F and G, located on Figure **1.**

By creating mosaics, using up to **25** individual TIR images, composite thermal TIR maps of Karapiti have been prepared for each of the surveys. Taking into account differences in instrument settings and meteorological conditions, these composite TIR maps are carefully compared for evidence of change. Between **1991** and **2000** the majority **of** the thermal features have not changed significantly. Neither has the general extent of thermal ground. An increase in thermal activity is observed, however, within and adjacent to crater F. This crater was involved in a steam eruption sequence during **25-27th** of March, **2000.** A small increase in activity is also seen at area H to the south. Minor changes in the hillside vents at area B occurred between **1991** and **1998,** and in the E-F area between **1997** and **2000. A** new vent (E3), 20m west of crater E, was created in **1997** and now discharges most of the steam that used to originate from the base of crater E.

3.3 Magnitude of heat transferred by thermal ground:

Estimates of the heat transferred by all thermal ground in the Karapiti area are still subject to large uncertainty. The uncertainty is caused by the lack of detailed information about the spatial distribution of the in-situ thermal conductivity of the ground and of shallow temperature gradients (in the top **0.15-m).**

Details of a recent estimate of heat transfer through thermal ground at Karapiti are given in Table **3.** Four grades are used, based on near-surface temperatures. Heat-flow ratings (KW/m^2) are based on current knowledge of heat transfer processes, and are comparable to those of Allis

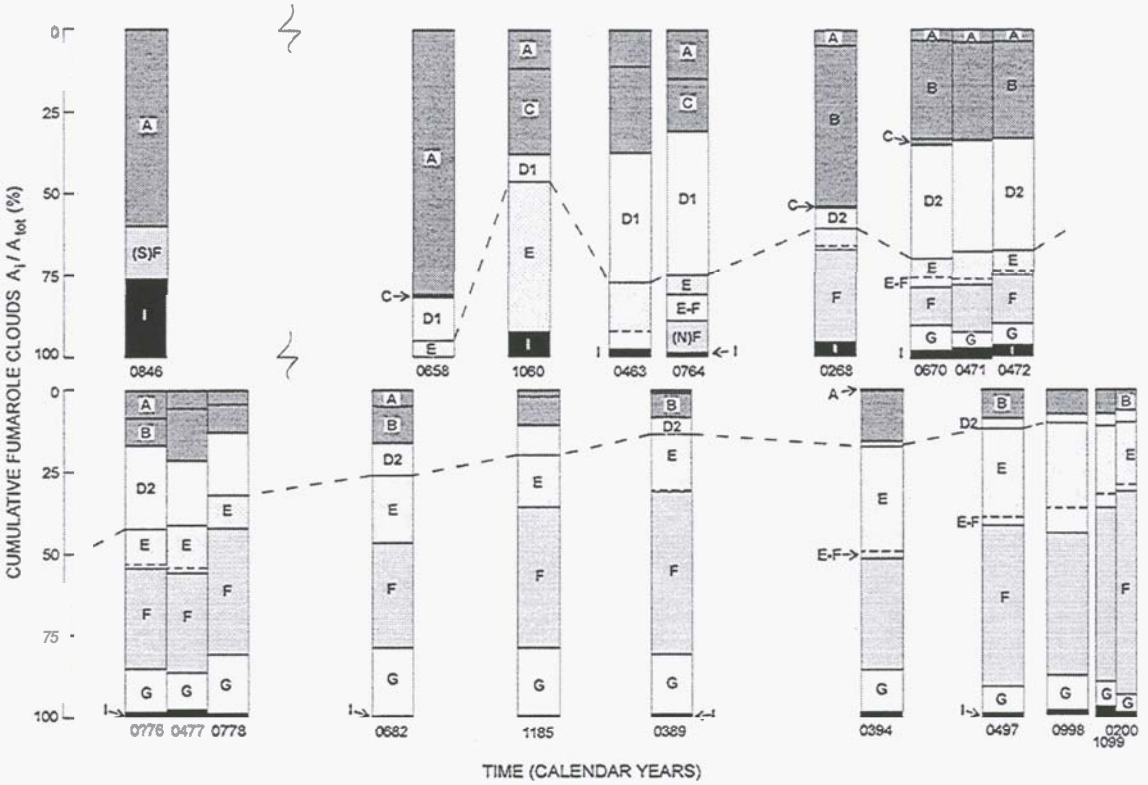


Figure 3: Normalized fumarole cloud areas (A_i/A_{tot}) for all surveys shown in Fig.2.



Karapiti thermal area (Wairakei); changes between 1946 and 1999.

Figure 4: Air-photos of Karapiti

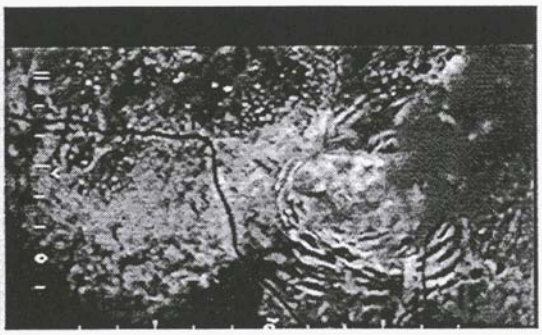


Figure 5: Infrared image (2000) of Crater F (viewed north, 275m*145m) showing cool boardwalk and bright, steaming, concentric fractures.



Figure 6: Infrared image of Crater G (as for figure 5 caption).

(1981). Improved accuracy is achieved through the use of recent infrared imagery to calculate the areas in the upper two grades (>30°C, >40°C), and recent air photos to determine the areas in the lower grades (fiom thermal vegetation). The resulting total conductive heat loss at Karapiti, for February-May 2000, is c.98 MW.

Table 3: Estimates of conductive heat transfer fiom Karapiti thermal ground using infrared and air-photos (Feb-May 2000).

Grade	Temp.Range (°C)	Area (m^2)	Rating KW/m^2	Heat loss MW
1	>40	600	10	6
2	30-40	10000	5	50
3	20-30	58000	0.5	29
4	15-20	260000	0.05	13
	Total	338600 m^2	Total	98MW

The heat discharged by minor steam vents in March 2000 was c.12 MW, and the estimate of large harole heat discharge was c.88 MW, based on air-photo analysis of steam cloud areas, calibrated with several individual fumarole measurements. The total heat loss for March 2000 is therefore c.200 MW. This is similar to the total 1978 Karapiti heat loss of 220 (+/-40) MW (including 2 MW of heat discharged by springs in the nearby Waipouwerawera Stream) calculated by Allis (1981). Assuming that the conductive heat loss fiom visible thermal ground is proportional to its size, magnitudes of c. 98 MW and c. 50 MW are indicated for 2000 and the period between 1946 and 1958 respectively. These figures are only order of magnitude estimates but indicate that for periods with settled conditions, the magnitude of heat transferred by thermal ground is probably similar to that discharged by fumaroles.

4. CONCLUSIONS

Heat loss fiom conduction, evaporation and direct steam discharge can be assessed using air-photos and infrared surveys, when backed up by steam flow measurements fiom several individual vents. Analyses of 22 air-photos since 1946, and 5 infrared surveys since 1989 have been used to map changes in steam discharge, areas of hot ground and areas of thermally tolerant vegetation. The recently observed linear relationship between heat loss and relative steam cloud area has been applied to older fumarole studies and air-photos.

Large and irregular changes occurred at Karapiti during the first 25 years (fiom 1950), but changes have been more gradual since 1975, and no new centres of fumarole activity have formed. The source of deeper vapour flux has apparently migrated southwards over this period (fiom areas A-D to E-G, fig.1). Some compensating interaction between discharge changes from neighbouring centres has been observed. The heat output of all haroles is assessed to have increased fiom about 30 MW (1950) to 235 MW (1960) then decreased gradually to c. 100 MW (2000). The total heat loss for Karapiti in 2000 is assessed to be c. 200 MW, 50% fkom conductive losses and 50% from steam discharges.

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