GEOTHERMAL TRAINING PROGRAMME
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FIVE LECTURES ON ENVIRONMENTAL EFFECTS OF GEOTHERMAL UTILIZATION

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gas and coal are 9.5 and 46.9 Mt for electricity, and 9.9 and 49.0 for direct-use (at 35% plant efficiency). Similar numbers for natural gas, oil and coal can be determined for sulfur oxides (SO_x) and nitrogen oxides (NO_x) at 0, 0.25 and 0.26 Mt and 2.2, 7.6 and 7.6 kt (thousand tonnes) respectively for electricity, and 0, 0.26 and 0.28 Mt and 2.3, 7.9 and 7.9 kt respectively for direct-use. For direct-use, the values would be approximately half if the heat energy was used directly.

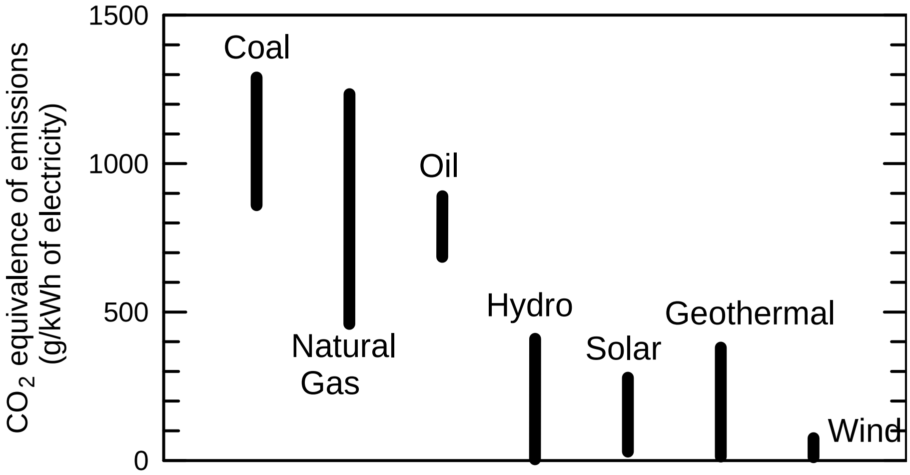

FIGURE 1: Relative amounts of greenhouse gas emissions from various types of electricity generation methods, data expressed as CO_2 equivalents; taken from Geothermal Energy News (May 1998), and geothermal data adjusted on basis of data from ETSU (1998)

In total, the savings from present worldwide geothermal energy production, both electric and direct-use, are summarised in Tables 1 and 2.

TABLE 2: CO_2, SO_x and NO_x savings (annual) from geothermal energy production; taken from Lund (2000)

CO_2 (10^6 t)			**SO_x (10^6 t)**			**NO_x (10^6 t)**		
Natural gas	Oil	Coal	Natural gas	Oil	Coal	Natural gas	Oil	Coal
19.4	82.2	95.9	0	0.51	0.54	4.5	15.5	15.5

2.3 Reduced sulphur gas emissions

The amount of sulphur gases (mainly H_2S) emitted from a geothermal power station (average 0.03 g/kWh) is less than 2% of that emitted from equivalent size coal- and oil-fired power stations (9.23 and 4.95 g/kWh, respectively).

3. ENVIRONMENTAL IMPACTS

Geothermal energy does have some environmental impacts, most of which are associated with the exploitation of high-temperature geothermal systems. In Table 3 the possibilities of environmental effects of geothermal development both for low-temperature areas and high-temperature areas are summarised.

3.1 Drilling operations

Exploitation of both low-temperature and high-temperature systems involves drilling wells to depths of 500-2500 m; this requires large drilling rigs and may take several weeks or months. For high-temperature systems the location of the drilling site is important, although directional drilling techniques have reduced this in recent times. The main environmental effects of drilling are shown here below.

TABLE 3: Possibilities of environmental effects of geothermal development

	Low-temperature systems	**High-temperature systems**	
		Vapour-dominated	**Liquid-dominated**
Drilling operations:			
Destruction of forests and erosion	●	● ●	● ●
Noise	● ●	● ●	● ●
Bright Lights	●	●	●
Contamination of ground-water by drilling fluid	●	● ●	● ●
Mass withdrawal:			
Degradation of thermal features	●	● ●	● ● ●
Ground subsidence	●	● ●	● ● ●
Depletion of groundwater	○	●	● ●
Hydrothermal eruptions	○	●	● ●
Ground temperature changes	○	●	● ●
Waste liquid disposal:			
Effects on living organisms			
surface disposal	●	●	● ● ●
reinjection	○	○	○
Effects on waterways			
surface disposal	●	●	● ●
reinjection	○	○	○
Contamination of groundwater	●	●	●
Induced seismicity	○	● ●	● ●
Waste gas disposal:			
Effects on living organisms	○	●	● ●
Microclimatic effects	○	●	●

○ No effect ● ● Moderate effect
● Little effect ● ● ● High effect

Impact of access and field development
The construction of road access to drilling sites can involve destruction of forests and vegetation which, particularly in tropical areas with high rainfall (Indonesia, Philippines), can result in erosion. Such erosion can result in large amounts of silt being carried by the streams and rivers draining the development area, This silt can affect fish in the river and may even affect fish in coastal waters near the mouth of the river. The silt may also deposit on the river bed where the gradient (flow rate) is less, causing the bed of the river to be raised and make the adjacent land more likely to be flooded during periods of high rainfall.

Effects of drilling operations
Drilling creates noise, fumes and dust which can disturb animals and humans living nearby. Typical noise levels (in approximate order of intensity) are:

- Air drilling – 120 dBa (85 dBa with suitable muffling);
- Discharging wells after drilling (to remove drilling debris) – up to 120 dBa;
- Well testing – 70-110 dBa (if silencers used);
- Heavy machinery (earth moving during construction) – up to 90 dBa;
- Well bleeding – 85 dBa (65 dBa if a rock muffler is used);
- Mud drilling – 80 dBa;

- Diesel engines (to operate compressors and provide electricity) – 45-55 dBa if suitable muffling is used.

The characteristics of the site (e.g. its topography) and meteorological conditions will also have an influence. To put the above noise levels into context, 120 dBa is the pain threshold (at 2-4000 Hz), noise levels in a noisy urban environment are 80-90 dBa, in a quiet suburban residence about 50 dBa and in a wilderness area 20-30 dBa (DiPippo, 1991; Armannsson and Kristmannsdottir, 1993). Noise is attenuated by distance travelled in air; there is approximately 6 dB attenuation every time the distance is doubled, but lower frequencies are attenuated less than higher frequencies. Thus, low rumbling noises from drill rigs and silencers carry much further than high frequency steam discharge noises.

Continuous drilling involves the use of powerful lamps to light the work site at night which can disturb local residents, domestic and wild animals.

Disposal of waste drilling fluid
In the past it was common practice to discharge waste fluids into nearby waterways.

3.2 Mass withdrawal

Large-scale exploitation of liquid-dominated high-temperature geothermal systems involves the withdrawal of large volumes of geothermal fluid. For example, between 1958 and 1991 more than 1700 Mt of fluid were withdrawn from the Wairakei geothermal field (New Zealand); assuming an average temperature of 200°C this represents nearly 2 km^3 of fluid (Hunt, 1995). In geothermal power schemes where the fluid withdrawn is reinjected, the reinjection wells are generally located away from the production wells to reduce the chances of the cooler reinjected water returning to the production wells and reducing the temperature of production fluids. Even if all the waste liquid is reinjected, there may be a large mass loss (up to 30% of that withdrawn) associated with discharge of water vapour into the atmosphere from the power station. A major consequence of the mass loss from parts of the field is the formation of a 2-phase (steam + water) zone in the upper part of the reservoir, and as production continues this zone increases in size and the pressures (both in and below this zone) decrease. At Wairakei, the deep (liquid phase) pressures declined by about 0.5 MPa (5 bar) during exploratory drilling, and a further 1.7 MPa (17 bar) during the first ten years of production, although subsequent pressure declines have been less than 0.5 MPa (Figure 2). Pressure declines in the reservoir, as a result of mass withdrawal and net mass loss, are an important cause of environmental changes at or near the surface.

Degradation of thermal features
In their natural, unexploited state many high-temperature geothermal systems are manifested at the surface by thermal features such as geysers, fumaroles, hot springs, hot pools, mud pools, sinter terraces and thermal ground with special plant species. Often these features are of great cultural significance, as well as being important tourist attractions. The thermal features result from the (upward) leakage of

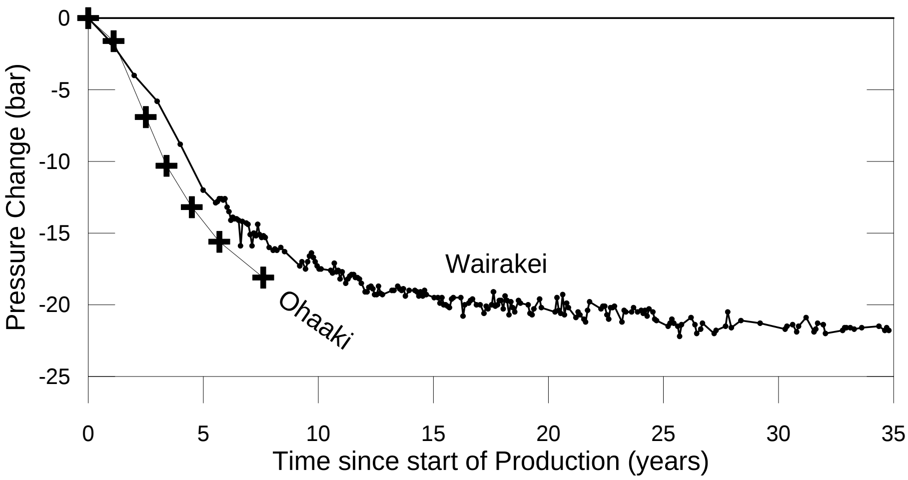

FIGURE 2: Deep reservoir pressure changes since start of production at the liquid-dominated, high-temperature geothermal fields of Wairakei (1958) and Ohaaki (1988), in New Zealand; note the rapid decline in pressure during the first 10 years of production

boiling geothermal fluid from the upper part of the reservoir, through overlying cold groundwater, to the surface.

Historical evidence shows that natural thermal features have been affected, often severely, during the development and initial production stages of most high-temperature geothermal systems. At Wairakei (New Zealand), nearly all the thermal features in the Waiora and Geyser Valleys (including more than 20 geysers) have died. At Ohaaki (New Zealand), the level and temperature of water in the Ohaaki Pool have declined since exploration drilling and reservoir testing began. Such effects are not confined to liquid-dominated systems. At Larderello (Italy) where the original natural activity consisted of numerous steam and gas jets, activity has now largely ceased, and at The Geysers (USA) there has been a decrease in the flow from hot springs since exploitation began.

Scientific evidence shows that the decline in thermal features is associated with the decline in reservoir pressure. As the pressure declines, so also does the amount of geothermal fluid reaching the surface and hence the thermal features decline in size and vigour. If pressures fall further then the features may die and the flow may reverse with cold groundwater flowing down into the reservoir; once this situation has occurred there may be little hope of resurrecting the features, at least within a human lifetime.

Depletion of groundwater

Most high-temperature geothermal systems are overlain by a cold groundwater zone. If exploitation of the system results in a large pressure drop in the reservoir, this groundwater may be drawn down into the upper part of the reservoir in places where there are suitable high-permeability paths (such as faults); such a situation is called a *cold downflow* (Bixley, 1990). If the lateral permeability of the rocks in the groundwater zone is low then a downflow may result in a drop in the groundwater level. For example, at Wairakei, a localised drop of more than 30 m in groundwater level has occurred associated with a cold downflow.

Downflows, and groundwater level changes, may also occur as a result of breaks in the casing of disused wells (Bixley & Hattersley, 1983).

Ground deformation

Withdrawal of fluid from an underground reservoir can result in a reduction of formation pore pressure which may lead to compaction in rock formations having high compressibility and result in subsidence at the surface. Subsidence has also been observed in groundwater and petroleum reservoirs. Horizontal movements also occur. Such ground movements can have serious consequences for the stability of pipelines, drains and well casings in a geothermal field. If the field is close to a populated area, then subsidence could lead to instability in dwellings and other buildings; in other areas, the local surface watershed systems may be affected.

The largest recorded subsidence in a geothermal field (15 m) is in part of the Wairakei field (New Zealand) This subsidence has caused:

- Compressional and tensional strain on pipelines and lined canals;
- Deformation of drill casing;
- Tilting of buildings and the equipment inside;
- Breaking of road surfaces;
- Alteration of the gradient of streams and rivers.

Ground movements have been recorded in other high-temperature geothermal fields in New Zealand, at Cerro Prieto (Mexico), Larderello (Italy), and The Geysers (USA). Subsidence in liquid-dominated fields has been greater than in vapour-dominated fields, because the former are often located in young, relatively-poorly compacted volcanic rocks and the latter are generally in older rocks having lower porosity.

Ground temperature changes

The formation and expansion of a 2-phase zone in the early stages of exploitation of a liquid-dominated geothermal system can also alter the heat flow. Steam is much more mobile than water; it can move through small fractures that are impervious to water and can move much more quickly through larger fractures. The generation and movement of steam can therefore result in increased heat flow and increased ground temperatures so that vegetation becomes stressed or killed.

At Wairakei, heat flow from natural thermal features was about 400 MW prior to the start of exploitation in 1958, increased to a peak of nearly 800 MW by the mid 1960s, and has since declined to about 600 MW (Allis, 1981). Most of this increase was associated with increased thermal activity in the Karapiti thermal area, which is situated 3 km south-west of the main production borefield. These changes have been attributed to steam rising to the surface through fissures that were previously impervious to water.

3.3 Waste liquid disposal

Most geothermal energy developments bring fluids to the surface in order to mine heat contained within them. In high-temperature liquid-dominated geothermal fields the volumes of resultant liquid waste involved may be large: at Wairakei, a medium-sized power station (156 MW), it is currently about 5800 m^3/hr. For vapour-dominated systems it is less, and for low-temperature systems it is very much less: at Chevilly-Larue (France) it is only about 3 m^3/hr. The waste fluid is disposed of by putting it into waterways or evaporation ponds, or reinjecting it deep into the ground. Surface disposal causes more environmental problems than reinjection.

Environmental problems are due not only to the volumes involved, but also to the relatively high temperatures and toxicity of the waste fluid. For example, at Wairakei the waste water has a temperature of about 140°C. The chemistry of the fluid discharge is largely dependent on the geochemistry of the reservoir, and the operating conditions used for power generation and will be different for different fields (Webster, 1995). For example, fluids from the Salton Sea field (USA), which is hosted by evaporite deposits, are acidic and highly saline (pH <5, [Cl] = 155 000 ppm). At the other extreme, those of the Hveragerdi field (Iceland) are alkaline and of very low salinity (pH >9, [Cl] <200 ppm). Most high-temperature geothermal bore waters include high concentrations of at least one of the following toxic chemicals: lithium (Li), boron (B), arsenic (As), hydrogen sulfide (H_2S), mercury (Hg), and sometimes ammonia (NH_3). Fluids from low-temperature reservoirs generally have a much lower concentrations of contaminants.

Most of the chemicals are present as solute and remain in solution from the point of discharge, but some are taken up in river or lake bottom sediments, where they may accumulate to high concentrations. The concentrations in such sediments can become greater than the soluble concentration of the species in the water, so that re-mobilisation of the species in the sediment, such as during an earthquake or flood, could result in a potentially toxic flush of the species into the environment. Chemicals which remain in solution may be taken up by aquatic vegetation and fish (Webster & Timperly, 1995), and some can also move further up the food chain into birds and animals residing near the river. For example, in New Zealand, annual geothermal discharges into the Waikato River contain 50 kg mercury, and this is regarded as partly responsible for the high concentrations of mercury (often greater than 0.5 mg/kg of wet flesh) in trout from the river and high (greater than 200 μg/kg) sediment mercury levels.

Effects on living organisms

If hot waste water from a standard steam-cycle power station is released directly into an existing natural waterway, the increase in temperature may kill fish and plants near the outlet. Release of untreated waste into a waterway can result in chemical poisoning of fish, and also birds and animals which reside near the water because some of the toxic substances move up the "food chain".

Effects on waterways
Release of large volumes of waste water into a waterway may increase erosion, and if uncooled and untreated there may be precipitation of minerals such as silica near the outlet surface disposal

Contamination of groundwater
Release of waste water into cooling ponds or waterways may result in shallow groundwater supplies becoming contaminated and unfit for human use

Induced seismicity
Most high-temperature geothermal systems lie in tectonically active regions where there are high levels of stress in the upper parts of the crust; this stress is manifested by active faulting and numerous earthquakes. Studies in many high-temperature geothermal fields have shown that exploitation can result in an increase (above the normal background) in the number of small magnitude earthquakes (microearthquakes) within the field. It is believed the increase is caused by reinjection because when reinjection is stopped the number of small earthquakes decreases, and when it is restarted the number increases (Sherburn et al., 1990). High wellhead reinjection pressures increase the pore pressure at depth particularly in existing fractures, which allows movement to suddenly release the stress and resulting in an earthquake. This phenomenon occurs in both liquid- and vapour-dominated fields, but has not been observed in low-temperature fields. Detailed studies show that the induced microearthquakes cluster (in space) around and below the bottom of reinjection wells and so the effects at the surface are generally confined to the field (Stark, 1990). To date no serious damage has been caused by such earthquakes, but they do frighten people.

3.4 Waste gas disposal

Gas discharges from low-temperature systems do not usually cause significant environmental impacts. In high-temperature geothermal fields, power generation using a standard steam-cycle plant may result in the release of non-condensable gases (NCG) and fine solid particles (particulates) into the atmosphere (Webster, 1995). In vapour-dominated fields in which all waste fluids are reinjected, non-condensable gases in steam will be the most important discharges from an environmental perspective.

The emissions are mainly from the gas exhausters of the power station, often discharged through a cooling tower. Gas and particulate discharges during well drilling, bleeding, cleanouts and testing, and from line valves and waste bore water degassing, are usually insignificant. The concentration of NCG varies not only between fields but can also from well to well within a field, thus changes to the proportion of steam from different wells may cause changes in the amounts of NCG discharged.

Gas concentrations and compositions cover a wide range, but the predominant gases are carbon dioxide (CO_2) and hydrogen sulphide (H_2S).

Carbon dioxide
Carbon dioxide occurs in all geothermal fluids but is most prevalent in fields in which the reservoir contains sedimentary rocks, and particularly those with limestones. Carbon dioxide is generally the most abundant NCG. It is colourless and odourless, and is heavier than air and can thus accumulate in topographic depressions where there is still air. It is not highly toxic (c.f. hydrogen sulfide) but at high concentrations it can be fatal due to alteration of pH in the blood. A 5% concentration in air can result in shortness of breath, dizziness, and mental confusion. At 10% a person will normally lose consciousness and quickly be asphyxiated. Exposure standards range from 5000 to 30,000 ppm (for 10 min.). There is some evidence that in high-temperature fields the amount of CO_2 discharged (per unit mass withdrawn) decreases with time as a result of de-gassing of the deep reservoir fluid and a decline in heat transfer from the formations occurs.

Hydrogen sulphide
H_2S is characterised by a "rotten egg odour" detectable by humans at very low concentrations of about 0.3 ppm. At such concentrations it is primarily a nuisance, but as the concentration increases, it may irritate and injure the eye (10 ppm), the membranes of the upper respiratory tracts (50-100 ppm), and lead to loss of smell (150 ppm). At a concentration of about 700 ppm it is fatal. Because H_2S is heavier than air it can accumulate in topographic depressions where there is still air, such as well cellars and the basements of buildings near the gas exhausters. The disappearance of the characteristic smell at concentrations greater than 150 ppm is especially dangerous because it leads to people failing to recognise potentially fatal concentrations. Exposure standards range from 10 to 50 ppm (10 min.). In sparsely populated areas, H_2S emissions may not prove a problem, and at many sites, there are already natural emissions from fumaroles, hot springs, mudpots etc. H_2S emissions can vary significantly from field to field, depending on the amount of H_2S in the geothermal fluid, and the type of plant used to exploit the reservoir (Table 4).

H_2S dissolved in water aerosols, such as fog, reacts with atmospheric oxygen to form more oxidised sulphur-bearing compounds; some of these compounds have been identified as components of "acid rain", but a direct link between H_2S emission and acid rain has not been established. U.S. Occupational Safety & Health ceiling level for H_2S is 14 mg/m^3, but an ambient air quality standard of 0.042 mg/m^3 is used in California.

TABLE 4: H_2S emissions from some geothermal plants; taken from ETSU (1998)

Field	H_2S emission (g/kWh)	Reference
Wairakei, NZ	0.5	Barbier, 1991
The Geysers, USA	1.9	Barbier, 1991
Lardarello, Italy	3.5	Barbier, 1991
Cerro Prieto, Mexico	4.2	Barbier, 1991
Krafla, Iceland	6.0	Armannsson and Kristmannsdottir, 1992
Ohaaki, NZ	6.4	Barbier, 1991

Other gases
Geothermal power stations do not emit oxides of nitrogen (NO_x), which combine photochemically with hydrocarbon vapours to form ground-level ozone which harms crops, animals and humans. However, geothermal gases may contain ammonia (NH_3), trace amounts of mercury (Hg) and boron (B) vapour, and hydrocarbons such as methane (CH_4). Ammonia can cause irritation of the eyes, nasal passages and respiratory tract, at concentrations of 5 to 32 ppm. Inhalation or ingestion of mercury can cause neurological disorders. Boron is an irritant to the skin and mucus membranes, and is also phytotoxic at relatively low concentrations. but these metals are generally emitted in such low quantities that they do not pose a human health hazard. The metals may also be deposited on soils and, if leached from there, they may contribute to groundwater contamination.

Binary plants use low-boiling point fluid, commonly iso-pentane, which may escape from the plant over a period of time. The gas phase may be recognised in the steam, and values of up to 4000 ppm have been recorded.

Effects on living organisms
The impacts of H_2S discharge will depend on local topography, wind patterns and land use. The gas can be highly toxic, causing eye irritation and respiratory damage in humans and animals, and has an unpleasant odour. Boron, NH_3, and (to a lesser extent) Hg, are leached from the atmosphere by rain, leading to soil and/or vegetation contamination (Webster, 1995). Boron, in particular, can have a serious impact on vegetation. Contaminants leached from the atmosphere can also affect surface waters and affect

aquatic life. Details of biological impacts of these gases are given by Webster & Timperley (1995).

Microclimatic effects
Even in geothermal power schemes which have complete reinjection, a considerable amount of gas (mainly steam) may be lost to the atmosphere. For example, at Ohaaki, of 70 Mt of fluid withdrawn (1988 - 1993) about 20 Mt (nearly 30%) was discharged to the atmosphere. Such discharges of warm water vapour may have a significant effect on the climate in the vicinity of the power station, depending on the topography, rainfall, and wind patterns. Under certain conditions there may be increased fog, cloud or rainfall. Microclimatic effects are mainly confined to large power schemes on high-temperature fields; exploitation of low-temperature geothermal systems does not cause significant microclimatic effects.

3.5 Landscape impacts

Land use
Power plants must be built on the site of geothermal reservoirs because long fluid transmission lines are expensive, and they result in losses of pressure and temperature. At the site, land is required for well pads, fluid pipelines, power station, cooling towers and electrical switchyard. The actual area of land covered by the total development can be significantly higher than the area required for these components. For example at Cerro Prieto field (Mexico) the area covered by the well pads (12 ha) is only 2% of the total area (540 ha) encompassing all the wells and the 180 MWe power station.

In many cases, the land between the well pads and pipes may continue to be used for other purposes, although at some sites the nature of the development may make this impracticable. For example, at Wairakei, where the development is located in a relatively narrow valley, there are a lot of individual pipelines, separation plants, steam discharges and surface hot water drains which effectively divide the land up into very small parcels. This precludes the land being used for anything else, although it is unlikely the land would have had another productive use. In contrast, the development at nearby Ohaaki (Broadlands) field, the design of the development has resulted in much larger parcels of land between the pipelines and the road system so the land will continue to be used. Areas previously used for stock and arable farming are now used mainly for sheep farming, and land which was mainly self sown pine scrub is worked as a productive forest.

The impact on land use depends on the type of development, and the original use of the land.

Visual intrusion
A geothermal plant must be located close to the resource, so there is often little flexibility in the siting of the plant. Geothermal plants generally have a low profile, and need not have a tall stack like coal and oil fired power plants. However, their visual impact may still be significant, as geothermal fields are often situated in areas of outstanding natural beauty. Any associated natural thermal features (e.g. geysers and hot pools) may be a tourist attraction or of historical and cultural significance. Visual impact may be particularly high during drilling due to the presence of tall drill rigs.

3.6 Catastrophic events

Like any large engineering development, catastrophic events may occur during the construction and operation of a large-scale geothermal power scheme.

Landslides
For schemes in areas of high relief and steep terrain, landslides are a potential hazard. Landslides may be triggered either:

a) Naturally, by heavy rain or earthquake; or
b) As a result of construction work, which may have removed the “toe” of the slide.

Such events are relatively rare but the result may be severe, such as for the landslide on 5 January 1991 in Zunil field (Guatemala), when 23 people were killed (Goff & Goff, 1997).

Hydrothermal eruptions
Although rare, hydrothermal eruptions (also called “hydrothermal” or “phreatic explosions”) constitute a potential environmental hazard in high-temperature liquid-dominated geothermal fields (Bixley and Browne, 1988; Bromley & Mongillo, 1994). Eruptions occur when the steam pressure in near-surface aquifers exceeds the overlying lithostatic pressure and the overburden is then ejected, generally forming a crater 5-500 m in diameter and up to 500 m in depth (although most are less than 10 m deep).

A hydrothermal eruption occurred on 13 October 1990 in the Agua Shuca fumarole area of Ahuachapan field (El Salvador) which killed or injured people living nearby (Goff & Goff, 1997). At Wairakei field, hydrothermal eruptions began (or significantly increased) in the Karapiti thermal area after development of the field began. At least 15 eruptions have occurred here but fortunately nobody has been killed or injured.

4. SUMMARY

- Use of geothermal energy has low environmental impact, particularly when compared with fossil fuels.
- Most environmental impacts are associated with the exploitation of high-temperature systems, particularly in liquid-dominated fields (Table 3).
- Exploitation of low-temperature systems rarely has any significant environmental effects.