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Advances in Environmental Management of Geothermal Developments

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ABSTRACT

Over the past five years, advances have been made in environmental management of geothermal developments, worldwide, and particularly within those countries participating in an Environmental Annex of the Geothermal Implementing Agreement of the International Energy Association. This reflects a gradual change that has occurred in the philosophy of geothermal environmental management. The strategies developed include regulatory policies to achieve more efficient and sustainable use of renewable geothermal resources, while avoiding or minimizing adverse effects on the surface environment. Issues such as net changes in CO_2 and H_2S gas emissions, from natural vents and boreholes, are being addressed in terms of the global as well as the local effects. A key objective when undertaking environmental impact assessments is achieving a balance between adverse and beneficial effects through practical mitigation schemes. Production and reinjection strategies have evolved to be more flexible in order to react to adverse effects, such as major reductions in natural surface discharges and subsidence, without compromising the efficient utilization of the resource. The benefits of a well designed environmental monitoring program have been clearly demonstrated. Examples of positive environmental benefits arising from these changes have been documented. They include: hot stream restoration, the creation of new thermal features using waste hot water, subsidence-induced wetlands, increases in steam heated ground resulting from pressure drawdown, and increases in hot spring activity stimulated by shallow reinjection. These increases have subsequently created enhanced ecological habitats for rare thermophilic organisms and thermally tolerant vegetation.

1. INTRODUCTION

Countries that have pioneered the sustainable use of their indigenous geothermal resources have reduced the need to burn hydrocarbons, thereby reducing CO_2 emissions. With declining natural gas reserves, energy planners are increasingly looking to fill the gap in future energy supplies by increased geothermal utilization, as a renewable energy source. This is seen as an environmentally preferable alternative to coal or other fossil fuels. A key factor in achieving this goal is the management of environmental effects, through appropriate regulation. Better and more practical methods of minimizing or mitigating such effects are needed, along with better integrated or “cascaded” uses, and more-efficient and economic direct geothermal energy use, to encourage greater uptake of geothermal technology. Examples of such methods from recent geothermal developments in several countries that are participating in an international collaborative exchange of information under the IEA Geothermal Implementing Agreement are given in this paper, together with a discussion of appropriate and practical geothermal system management policies.

Monitoring of the environmental effects of geothermal resource utilization has, in many recent cases, identified the benefits of appropriate management in terms of production and reinjection strategies. It has been demonstrated that such strategies can minimize, reverse or mitigate the effects on surface thermal activity. Appropriate strategies also have the potential of minimizing adverse effects of subsidence, gas emissions and liquid discharges to the surface environment, while ensuring sustainable use of the resource.

2. EXPERIENCES IN ENVIRONMENTAL GEOTHERMAL RESOURCE MANAGEMENT

2.1 New Zealand Experience

As an example of recent New Zealand resource management experience, at Rotokawa in New Zealand, an environmentally successful strategy of deep production (1500-2500m) and total shallow reinjection (300-600m) for a 30 MWe hybrid steam turbine and binary power plant, has been operating since July 1997. This has resulted in no significant detrimental effects on any thermal features. Monitoring of gas emissions and subsidence has also detected no adverse effects. The power plant is visually and acoustically unobtrusive (surrounded by pine-trees). Gravity and pressure monitoring has shown that reinjection has been re-saturating a shallow aquifer (originally 2-phase) out to a radius of several hundred meters from the injection wells, and pressures have risen by a few bars. A gradual enhancement of an acid chloride spring (“Ed’s Spring”, Fig.1), located 300m from the power station was noted from December 2001. Although its chemistry is distinctly different from that of the reinjected fluid, precluding the possibility of a *direct* fluid connection, the small pressure rise that stimulated its activity is probably related to increased pressures in the underlying injection aquifer. It is therefore considered an indirect effect of development, and an enhancement to the thermal feature environment at Rotokawa, by gradually creating an enhanced habitat for geothermal organisms.

Figure 1. “Ed’s Spring” near Rotokawa Power Station commenced discharge of mineralized geothermal water four years after commissioning.

At nearby Wairakei, over the past 5 years about 30 to 40 % of the waste hot water has been reinjected, and the balance is discharged into the Waikato River. This has caused a 26% increase in the natural chemical loading attributable to geothermal discharges. Wairakei springs contributed 28% of the 'pre-development' total loading (originating from natural discharges of 8 geothermal fields), while Wairakei separated brine now contributes 44% of the total loading (Timperley, 2004). The field operator intends to reduce this back to pre-development loading over the next 10 years by either increasing reinjection or by treatment of separated water to remove the toxic contaminant (arsenic). Bio-technology research aimed at producing economic and efficient methods of arsenic removal has commenced. A separate treatment option is proposed to reduce the quantities of heat, mercury and dissolved H_2S that enter the river from the direct-contact condensers by constructing a cooling water canal.

Several local users are able to take advantage of some of the separated hot water in a way that partly mitigates for the historic loss of geysers at Wairakei Valley during the initial reservoir pressure drawdown of the 1950's. The recent benefits include tourist facilities based on a geothermally-heated prawn farm, and hot stream restoration with an artificial geyser and silica terrace that were developed by Netcor, a local Maori collective (Fig.2).

Figure 2. Wairakei Terraces, a recent example of enhancement using separated geothermal bore water to create a geyser, silica terraces, and hot pools.

The benefits of increased steam-heating, stimulated by early Wairakei pressure drawdown, were enjoyed at Taupo in the adjacent Tauhara Field (Fig.3).

Figure 3. Otumukeke Spring (Spa Stream) discharging into Waikato River at Taupo. This popular bathing area was enhanced by increasing flow and spring temperature (+50^{o}C over 30 years), an indirect result of increased steam heating and local subsidence from Wairakei pressure decline. Stream banks have been populated by rare thermal ferns.

Another benefit is the popular free tourist attraction at 'Craters of the Moon' (Fig.4) a large area of increased steam-heated thermal activity, in a natural setting. Recent research into better methods of quantifying the heat discharged from this area of steaming ground (Bromley and Hochstein, 2005) helps with monitoring the surface discharge effects and will thereby assist future resource management decisions.

Figure 4. Craters of the Moon, (Karapiti), Wairakei, 1988, an example of an enhanced thermal area, where production-induced pressure drawdown caused a large increase in steam activity (within an existing thermal area). There was also an increase in thermal vegetation.

Subsidence is an issue at several locations at Wairakei Tauhara and Ohaaki, but has not yet caused major damage. Effects on pipelines, drains, roads and transmission lines are relatively easily dealt with. Local inundation of the Waikato River banks at Ohaaki is dealt with in a planned and pragmatic manner. Mitigation by targeted reinjection to restore pressures within compacting formations has been demonstrated to be feasible, (Allis et al, 1985) and is a future option if adverse effects on structures become significant, but this must be balanced against the risk of adverse effects of targeted reinjection on the long-term sustainability of the resource, caused by rapid returns of cool water to production wells. Not all occurrences of subsidence in geothermal areas are attributable to deep reservoir pressure drawdown; some are caused by shallow processes such as groundwater level changes (Bromley and Currie, 2003), thermal clays, or poorly-compacted fill placed within thermal gullies and depressions. Before mitigation or avoidance measures are put into place, the correct mechanism must be identified. Placing the blame for adverse effects on the geothermal development, without adequate proof of cause, as has happened in Taupo, does a significant disservice to the community by generating unwarranted negative publicity. A similar issue has recently arisen in the Philippines at the Kidapawan geothermal project, Davao, where elevated arsenic levels found in people living nearby had been unjustifiably attributed to the power plant operation. Investigation by environmental and health authorities as well as the Committee on Ecology of the Philippine Congress in 1995 indicate the presence of elevated arsenic in the natural environment rather than from discharges from the power plant. The presence of elevated arsenic levels in natural hot springs was validated by Webster (1999) in the area.

At Mokai, where a 57 MWe hybrid plant was commissioned in December 1999, total reinjection occurs into a 400m deep aquifer about 4 km from the production area (>800m depth) A comprehensive environmental monitoring programme covering springs, streams, groundwater, vegetation, fauna, subsidence and gas emissions has shown no significant post-production changes due to abstraction or injection of fluids. Temperatures and water levels in groundwater monitor bores have shown no changes that could be attributed to reservoir pressure drawdown or reinjection returns. Monitored ecosystems, consisting of rare thermal ferns associated with hot spring discharges, have not been affected. A small and temporary increase in thermal activity was observed in February 2000 associated with a line of existing thermal craters near the reinjection area (Fig. 5). These craters contain steam-heated mud pools. The increase in steam activity was local, and did not directly include reinjected chloride fluid, but may have been related to a local pressure increase in the underlying aquifer, while it was still 2-phase. Thermal activity around these craters has since returned to normal. A gravity increase around the reinjection wells is attributed to re-saturating of a pre-existing two-phase zone, and a small amount of subsidence (20mm/yr) may be attributed to formation cooling by reinjected fluid.

Figure 5. Mokai, Tirohanga Rd craters, an example of increased steam-heated activity near the reinjection area, which became, for several years, an enhanced habitat for thermal vegetation (particularly mosses).

At Rotorua, management of extraction and reinjection from numerous domestic bores has achieved a significant recovery in hot spring and geyser activity (Scott and Cody, 2000, Fig.6). In places (Kuirau Park) the pressure recovery of boiling liquid has exceeded expectations, causing small hydrothermal eruptions, and rejuvenation of long-forgotten spring vents in a residential area. This illustrates the principal of reversibility of effects on thermal features, but also shows that some rejuvenation effects can be hazardous and even adverse to structures that were built too close to dormant vents.

Figure 6. Geysers at Whakarewarewa, Rotorua, showing increased discharge after pressure recovery from bore closure programme.

The development of geothermal fields and hot spring areas in New Zealand is managed by application of regulatory control through regional policies and plans under the Resource Management Act. Applications for resource development consents are decided in a public hearing process. The plans that provide a framework for this process have recently been undergoing industry-wide review and improvement (Brokelsby, 2003). They attempt to address changes in the philosophy of environmental management, which focuses on issues of importance to local inhabitants, while providing for the national interest of sustaining and growing a future energy supply from a renewable resource, and accommodating international environmental pressure to reduce greenhouse gas emissions.

2.2 Icelandic Experience

Environmental management of geothermal resource use in Iceland is also under review (Kristmannsdottir et al, 2003), as policies and procedures are debated by the geothermal community. Resource development consents are currently issued by the Ministry of Energy, in a process that is not open to public submission. However, there is generally positive public support for new geothermal projects because most people see geothermal energy, particularly in the form of hot water for direct domestic use, as an economic and environmental benefit. For example, nobody opposed the 23 km hot water pipeline from Nesjavellir to Reykjavik when it was proposed. Photographs of the smog from coal fires that used to plague Reykjavik in the 1930's are a reminder of the environmental benefits of geothermal heating. The loss of hot springs traditionally used for laundry purposes at Laugardalur, which was caused by early pressure drawdown, was not strongly lamented in Reykjavik because the amenity value was replaced by hot water piped directly to homes.

A definitive national policy and plan is still needed in Iceland to reduce uncertainty in planning future geothermal developments, and reduce the risk of exploration costs in areas that are unlikely to be permitted for exploitation (Andresdottir et. al., 2003). For new geothermal projects (>1 MWe), full environmental impact assessments are required, and permits under several different laws may also be needed. Separate exploration, utilization and operation permits are usually required along with building permits. Protection of natural features such as springs, geothermal deposits, craters and lava fields must be considered. Development decisions generally take into account the sustainability of the proposed energy extraction rate, and the visual impacts on the natural landscape, as primary considerations. Potential effects on geothermal surface features, noise, subsidence, induced seismicity, thermal and chemical pollution and gas emissions are also important considerations. Environmental issues have resulted in the withdrawal of a proposed power plant at Namafjall, and a revised scheme for discharge of separated water at Heillisheidi. At the Geysir field, the geysers are of sufficient aesthetic and tourist value that the field is generally accepted as requiring protection from large energy extraction. Accordingly, there is reluctance to allow drilling of new wells in this field. Although artificial manipulation of the Great Geysir water level, and the reaming out of the Strokkur geyser vent by drilling, were tolerated many years ago as a means of stimulating more frequent eruptions, changing attitudes to such activities means that they are now forbidden (Pasvanoglu et al. 2000).

Each separate geothermal field in Iceland is developed by one organization or company. Such a single tapper policy is also advocated by New Zealand regulators. This avoids issues such as competitive take, and ensures environmental accountability.

An issue, at present, is the status of a large, but poorly explored, geothermal area to the east of Iceland (Torfajokull). It is in a protected area of great natural beauty and unusual rhyolite geology, but might also contain more than 30% of Iceland's technically-harnessable geothermal energy potential, hence the dilemma for energy planners in deciding on the merits or otherwise of allowing future exploration drilling in this area. Without clear policy on future extraction, there is a large risk faced by development companies that the cost of exploration drilling could not be recovered.

At Svartsengi geothermal field, environmental effects resulting from pressure drawdown of about 30 bars over 27 years have included a small amount of widespread subsidence, up to 13 mm/yr maximum, but with very gradually sloping edges, so the differential effects are negligible. (Eysteinsson, 2000) The pressure drawdown also formed a steam zone which has resulted in a gravity decrease of about 4 μgal/yr, and a small increase in steam-heated surface discharges. H_2S gas emissions result in concentrations reaching about 120 $\mu g/m^3$ near the power-station, but with a broad dispersion pattern that is driven by wind direction and strength (Kristmannsdottir et al, 2003). Separated brine from the power plant ends up in the Blue Lagoon, an artificial pond on the adjacent lava flow. In a sense, this lagoon started as an environmental accident, because fluids were not reinjected, but allowed to soak into the groundwater causing local thermal and chemical contamination. However, inspired marketing has turned it into Iceland's most popular tourist destination. The effects on the groundwater are not considered significant because they are confined to an outflow towards the nearby coastline. Ironically, environmental management decisions in future will need to balance the requirements of the Blue Lagoon, to avoid excess or insufficient brine flow for bathing, versus the needs of the resource to sustain pressures by increased reinjection of the brine without causing premature cooling of the production aquifer.

3. ENVIRONMENTALLY CRITICAL EMISSIONS

An environmental issue that is common to many geothermal countries is the significance of CO_2, Hg and H_2S emissions from geothermal power-plants relative to emissions from natural thermal features. Collaborative research is being undertaken in Iceland, New Zealand, Italy, United States and Mexico to address these issues (Armannsson, 2003, Sheppard and Mroczek, 2004). Carbon dioxide injection possibilities are also being addressed (eg: White et al, 2003). CO_2 emissions from geothermal power plants were surveyed and published by Bertani and Thain (2002) and Armannsson (2003). The worldwide weighted average of emitted CO_2 was 122 g/MWe, but with a large range from 4 to 740 g/MWe. It was argued by Bertani and Thain that this source of CO_2 emission to the atmosphere was of natural origin, and that the power plants merely redirected the flow away from ground based emissions. This was particularly relevant to Larderello, where natural steam emissions (and by implication CO_2 emissions) diminished as a result of geothermal power development. However, in many cases, geothermal development causes an *increase* in steam heated ground as a steam zone develops in response to pressure drawdown. Furthermore, the assumed direct relationship between surface heat and CO_2 discharges is not necessarily correct. Recent measurements in Wairakei and Rotokawa thermal areas suggest that the correlation is weak. Diurnal variations from atmospheric effects and soil bacteria activity appear to be important (Sheppard and Mroczek, 2002). Cold gas emissions at the periphery of thermal areas can be larger than from hot ground where steam condensation occurs beneath a thin layer of low permeability thermal clay. There will be changes induced in total CO_2 discharge to the atmosphere caused by different development strategies (for example extraction from a gas-rich steam zone or from a gas-depleted liquid aquifer). Given that the ultimate source of the gas (recharge from deep magmatic degassing) can be assumed to remain constant, then perhaps the temporary shallow gas flux changes may balance out in the long term. Further research into this issue is warranted.

Studies into H_2S gas emissions in Iceland and Mexico have demonstrated that this geothermal gas does not generally oxidize to SO_2 in the atmosphere and is not a significant contributor to acid rain. (Kristmannsdottir et al, 2000, Verma et al, 2000). H_2S has an unpleasant odour at low concentrations and is toxic in higher concentrations, so removal or remediation measures may be appropriate near urban areas. Recent advances in H_2S abatement technology are discussed by Sonnerville et al (2001), Squires (2002) and Gallup (2003). In most situations, however, (particularly wet and windy climates), the gas is adequately dispersed by the wind, or is dissolved into precipitation, so is only a hazard during specific weather conditions, such as still air beneath a temperature inversion, which can cause local accumulations at ground level near the vent. Research into mercury vapour emissions is also investigating the chemical processes that could lead to elevated concentrations in and around power plants. (Christenson et al, 2002, Mroczek, 2005). The main concerns with mercury are its toxicity, resistance to oxidation, and bio-accumulation properties.

4. ENVIRONMENTAL POLICY CONSIDERATIONS

When establishing environmental compliance procedures it is important to state a clear, balanced, technically sound and objective assessment of likely and possible outcomes of various scenarios. The definition and use of terms in geothermal environmental policy documents can be a source of misunderstanding. In connection with thermal features, some of the relevant terms are: "significant or outstanding", "protection or preservation", "natural or artificial", and "reversible or recoverable". In connection with resource utilization, issues such as "renewable and sustainable" and "adverse or beneficial effects" can cause concern. Some of these effects include subsidence, gas emissions, surface water pollution, and induced earthquakes. The following comments on these issues (summarized from Bromley, 2003) help provide a practical guide for dealing with such environmental concerns by balancing, in an objective and holistic way, the net outcomes of any proposed management strategy.

4.1 Ranking of significant or outstanding springs

It is commonly accepted that there will be *some* risk of losses of individual thermal features in geothermal systems where reservoir pressures are affected by development. Ranking of surface geothermal features in a region identifies, possibly for protection, geothermal systems exhibiting "outstanding" features that could be seriously affected by future resource utilization, and to ensure that a representative range of such features is protected for the enjoyment of future generations. However, the ranking process must be equitable; it is not appropriate to apply the term "significant" to *all* identified natural geothermal features, simply on the basis that they are regionally or nationally unusual. Some springs are easily identifiable as discreet vents, but there are also large thermal areas, many square kilometres in size, that contain dispersed weak steam vents along with large portions of non-thermal ground. Arbitrary application of activity rules to the vicinity of such features could place undue constraints on potential resource users and property owners, with no real environmental benefit.

The term “sinter” also covers a wide range of deposits that form from spring discharges (e.g. amorphous silica, travertine, calcite) and these are not all diagnostic of a direct plumbing connection between the spring and a high temperature geothermal reservoir. Sinters can also form from rock leaching by acidic steam-heated groundwater, which is not directly connected to deep reservoir liquid. Indeed, deep pressure drawdown is likely to enhance such features through additional upward steam flow. Therefore, the presence of “sinter” is quite common and should not be the sole criterion for ranking features for protection on the basis of resilience or rarity.

It is proposed that the environmental significance of surface thermal features should be ranked using at least four grades (eg: outstanding-, high-, moderate-, and low- ranking), partly based on their resilience, variability, and rarity, and on their scientific, aesthetic, cultural and intrinsic values.

4.2 Protection or Preservation

Management plans are sometimes premised by an underlying assumption that protection of natural geothermal features from change is achievable by excluding large-scale resource utilization. However, numerous observations and monitoring records show that nearly all geothermal features vary widely over time-scales that can range from minutes to decades. It is not possible to guarantee their *preservation* in terms of maintaining a constant discharge temperature, flowrate or heatflow. Furthermore, recent experience has demonstrated that large-scale resource development does not necessarily result in loss of surface geothermal features. With innovative resource management strategies, such as shallow injection where appropriate, discharge from thermal features of many types can often be enhanced rather than reduced. Rather than attempting to preserve specific individual features, the principal aim of geothermal management plans and policies should be to promote efficient integrated use of the energy resources, while protecting the *diversity* of thermal features in the region. This can be achieved by designating several geothermal systems to remain undeveloped (except for tourism facilities), as a kind of environmental insurance policy. Properly managed development of all other geothermal resources for sustainable energy utilization should be encouraged, with any significant environmental concerns addressed by imposing reasonable and balanced conditions on development consents. Conditions should encourage enhancement of *any* type of surface thermal feature, by way of mitigation for unavoidable and adverse changes to other thermal features. This recognizes the observed variation behaviour that occurs naturally. Geysers and fumaroles, for example, are both naturally transient features. On this basis, a newly created steam vent could mitigate for the loss of a chloride spring, or vice-versa.

An issue commonly faced by direct users of shallow hot water resources is the “buffer zone” distance from significant thermal features, and other users, that a new user should respect in order to avoid interference effects. A distance of 20m is considered reasonable for relatively small amounts of fluid extraction and injection (<1 kg/s). There should also be some regulatory incentive for the use of down-hole heat exchangers or ground-source heat-pumps, rather than direct fluid extraction, because of the relative benefit to the resource aquifer, in that pressure interference is avoided.

In terms of potential hazards such as subsidence, induced earthquakes, and hydrothermal eruptions, it is reasonable to undertake relative risk assessments associated with any proposed development strategy, in order to minimize the risk wherever possible and practical. However, it is generally unreasonable to adopt the exceptionally precautionary view of zero risk tolerance for such events, because most geothermal fields occur in regions where there is an existing moderate level of risk from similar natural events related to tectonic movement and volcanic activity. Furthermore, changes from such events often accrue secondary benefits such as subsidence-induced wetlands or lakes, enhanced reservoir permeability from induced earthquakes, and tourist attractions at hydrothermal eruption craters.

4.3 Natural or Artificial

A common misperception regarding geothermal features is to regard them in ‘black-and-white’ terms as being either natural or artificial. This can lead to a misappropriate application of rules designed to preserve natural features by actively discouraging artificial features. There is, in practice, a continuum of natural to human influences on thermal features (‘shades-of- grey’). At one end of the spectrum, an artificial geyser and silica terrace, such as at Wairakei Terraces (Fig.2), which uses water from the reinjection pipeline, is indisputably *man-made.* Some geysers, such as Lady Knox “geyser” at Waiotapu are *artificial,* in the sense of being stimulated daily by soap to erupt through a hidden pipe, but after a long period of discharge they can have a very natural appearance and be highly valued. There are also examples of old boreholes that have evolved into discharging springs or geysers (such as the 60 year old “Healy 2 Bore” (Fig. 7) at Tokaanu, NZ, Strokkur Geyser at Geysir and Hverarond fumarole in east-Namafjall, Iceland, and Fly Geyser in Nevada, USA). These features have well-developed sinter-cones, terraces, or thermal ecosystems, and have evolved into a natural setting over many years. Although initially created by *human activity,* they now appear totally natural and deserve some protection.

Figure 7. “Healy 2 bore” at Tokaanu, drilled in 1942, and later abandoned, has since evolved into a natural-appearing geyser-mound, sinter, and associated eco-system.

Another example, the “Craters of the Moon” thermal area at Wairakei, (Fig. 4) has always existed as a natural feature, but the intensity of thermal activity increased dramatically in response to Wairakei pressure draw-down, so it has been *indirectly affected* by human activity. The same could be said of existing geysers and discharging hot springs at

Orakei-Korako that are *indirectly* supported by raised groundwater levels in response to the artificial filling of Lake Ohakuri in 1961. Several hydrothermal eruptions at Kuirau Park, Rotorua, were stimulated by pressure recovery related to the bore closure programme (Fig. 8).

These examples illustrate the point that planning rules need to be made flexible enough to cater for a wide spectrum of scenarios when considering the desirability of human influences on geothermal features. Environmental effects of geothermal developments can be mis-represented as always adverse, when there are often hidden beneficial environmental effects. An example is the silica deposit in the main drain at Wairakei (Fig. 9). Fascinating shapes and patterns are created in these deposits through bacteria-mediated bio-mineralisation (Mountain et al 2002).

Figure 8. Hydrothermal eruption at Kuirau Park, Rotorua (March 2001) caused by increased shallow pressures following the bore closure programme in Rotorua.

4.4 Reversible or recoverable development effects

Many of the assumptions of the likely effects from *new*, large-scale geothermal energy developments are outdated. The modern philosophy is to develop new fields in stages, big enough to create measurable effects on the resource, but not big enough to create large irreversible effects on the surface environment, or to compromise future resource sustainability. Stages are typically about 5 years in duration, and utilization steps are up to 2 times the previous level. Monitoring, and predictions based on regularly-updated reservoir models, provide confidence of the probable effects (out to about 50 years) for each stage. In this way the risks are minimized for all parties, the environmental regulator, the owner, the developer, and the investor.

Recovery from adverse pressure effects on outstanding geothermal features is feasible, as demonstrated at Rotorua, where a change of bore management policy to raise pressure caused a significant recovery of geysers and springs. A similar, but temporary, hot spring recovery effect was observed at Bao Valley, Tongonan, Philippines (Bolanos and Parilla, 2000) in response to specific use of a reinjection well. This demonstrates that such features *can* be recovered, and are not necessarily lost irretrievably when pressures initially decline due to extraction.

4.5 Sustainable and Renewable

An issue for policy makers to ensure a future period of sustainable utilization of geothermal resources is the duration of "reasonably foreseeable use". Most reservoir modelers would not be confident about predicting geothermal reservoir behavior beyond about 50 years, and this is probably a reasonable period to choose for planning sustainable extraction rates. Within that time, technological advances will have provided access to heat resources deeper within the earths crust. Furthermore, a long-term strategy of cyclic use of existing geothermal reservoirs would have the advantage of allowing natural recharge of fluids and heat during a "fallow" period of recovery in between periods of heat extraction. Thus the concepts of renewable and sustainable use of geothermal energy can both be satisfied whilst undertaking cyclic extraction of heat. An extraction rate that is several times greater than the natural surface heat discharge rate is achieved by drawing down reservoir pressure to enhance inflows of hot recharge fluid.

Figure 9. Silica scale deposited in hot-water drains at Wairakei; an example of bacteria-mediated growth patterns.

5. CONCLUSIONS AND FUTURE PLANS

When considering the induced effects of geothermal development on the environment, a balanced view is to weigh up the adverse effects against the beneficial effects to determine a net effect that may be mitigated for. Examples of beneficial effects that are often overlooked include: subsidence induced wetlands; thermal ecosystems enhanced by increased areas of steam-heated ground and surface-disposal of hot water; reduced gas emissions relative to fossil fuel alternatives; and enhanced fracturing from induced seismicity. Regional geothermal plans should adopt the modern approach to utilization of new resources, by allowing staged development of all but a few "protected" systems, in a manner that minimizes risk, and allows for recovery by adjustments to field management. Optimum size increments should be established by considering the resource knowledge acquired during each stage. Monitoring can provide early warning of adverse effects, and remedial measures can be implemented. If adverse effects on thermal features occur, they can usually be reversed by locally managing the subsurface pressures.

Over the next few years, further collaborative research efforts amongst participants in the Environmental Annex of the IEA Geothermal Implementing Agreement are anticipated to include the following:

- Development of improved carbon dioxide and heat flux monitoring techniques in areas of steaming ground.

- Changes to natural thermal features induced by development, and practical methods of controlling or mitigating such effects by subsurface pressure management.

- Improvements in subsidence modeling to provide a more reliable basis for future predictions, and possible mitigation, remediation or avoidance strategies.

- Better understanding of the factors that affect the intensity and distribution of induced earthquakes in developed geothermal fields.

- Advances in understanding of the processes involved in reducing hydrogen sulphide and mercury emissions, and removing arsenic from waste water.

- Investigating the potential for thermophilic bacteria to reduce toxic chemical contaminants from geothermal waste waters by bio-remediation.

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